ПЛОДОРОДИЕ ПОЧВ

IRSTI 68.05.29; 34.27.21
DOI: 10.51886/1999-740X_2026_4_5

M.K. Tynykulov[1], R.K. Pernebekova[2,3], R.U. Mamykova[4], G.S. Zhakipbekova[3], N.V. Malitskaya[5], A.K. Mukhtarov[1]

AGROCLIMATIC MODELLING OF SOIL BIOLOGICAL ACTIVITY IN KAZAKHSTAN AND ZONING OF THE TERRITORY BY THE POTENTIAL FOR APPLICATION OF MICROBIAL PREPARATIONS

[1]L.N. Gumilyov Eurasian National University, Astana, Kazakhstan
[2]Khoja Akhmet Yassawi International Kazakh-Turkish University, Faculty of Postgraduate Higher Medical Education, Turkestan, Kazakhstan
[3]South Kazakhstan Medical Academy, Faculty of Medicine Shymkent, Kazakhstan
[4]Zhanibekov University, Faculty of Natural Sciences, Shymkent, Kazakhstan
[5]M. Kozybayev North Kazakhstan State University, e-mail: mr.tynykulov@mail.ru

Abstract. The field performance of microbial preparations in Kazakhstan remains unstable, and one of the main reasons is abiotic: introduced microorganisms establish and function only within a narrow range of soil temperature and moisture, which in a sharply continental climate stays open for a short time. The aim of the study was to describe quantitatively the seasonal dynamics of soil biological activity in Kazakhstan and, on that basis, to delineate zones differing in their potential for the use of microbial preparations. A process-based model was developed in which soil temperature at a depth of 10 cm, the daily water balance of the 0–50 cm layer and a daily index of biological activity - the product of the Lloyd–Taylor temperature function and a moisture function expressed through water-filled pore space - were computed from the 1991–2020 climate normals of 16 weather stations. The temperature module was verified against published soil temperature normals for the Astana station (R^2=0.997; standard error 1.0°C) and the carbon module against field measurements of CO_2 efflux at Shortandy and a 261-record subset of the global SRDB-V5 database. The annual index varied 2.5-fold across the country and the computed carbon mineralisation ranged from 254 to 811 g C m^{-2} yr^{-1}. Three biotechnological windows were introduced - inoculation, nitrogen fixation and crop-residue decomposition - lasting 32–75, 0–84 and 0–117 days, respectively. Ward clustering identified four biotechnological zones (silhouette 0.51). Under RCP4.5 and RCP8.5 the index increased by 17.5 and 23.4% by 2040–2059, the inoculation window narrowed and the decomposition window lengthened, which shifts the priority of soil biotechnology from stimulating mineralisation towards conserving soil organic matter.

Keywords: soil biological activity, soil microorganisms, microbial preparations, carbon mineralisation, soil water regime, agroclimatic zoning, climate change.

INTRODUCTION

Soil biological activity is an integral expression of the work of the soil microbiome: it is microorganisms that close the carbon and nitrogen cycles, mobilise poorly available forms of phosphorus, build water-stable structure and govern the rate at which plant residues are converted into humic substances. Any assessment of soil fertility that ignores the biological component therefore remains incomplete, and any technology for restoring fertility relies, in one way or another, on managing microbial activity. For Kazakhstan the problem is particularly acute. On the arable land of the republic, which exceeds 24 million ha, half a century of intensive cropping has caused marked dehumification. According to generalised data, humus content in southern chernozems has decreased by 25–35%, and on the light soils of the former virgin lands locally by more than 40% [1]. Direct comparisons of virgin and arable land confirm the scale of the losses: in the carbonate southern chernozem of Akmola region the humus content of the 0–20 cm

layer is 4.64% under virgin vegetation and only 2.60–3.07% on arable land; in the haplic chernozem of Kostanay region the corresponding values are 5.74 and 3.80–4.42% [2]. Loss of organic matter simultaneously means loss of substrate for the microbiota, that is, a self-sustaining decline in biological activity.

Microbial biotechnology is today regarded as one of the most accessible ways of partially restoring the biological potential of soils. Kazakhstan has established its own culture collection base and obtained convincing laboratory results. From the wheat rhizosphere of Akmola region, strains of *Pseudomonas fluorescens*, *Bacillus cereus*, *Enterobacter cloacae* and *E. ludwigii* were isolated and identified by MALDI-TOF; they increased wheat seedling length from 10.1 cm in the control to 14.7–15.3 cm [3]. Screening of 848 cultures of micromycetes and yeasts from agrocenoses of the republic showed that 24.9% of the isolates mobilised phosphates and 16.4 % possessed cellulolytic activity, while 35 selected strains increased the length and mass of barley seedlings 1.2–1.5-fold [4]. On irrigated saline soils of Turkistan region the halophilic strain *Bacillus* sp. PK-1 gave a maize yield increase of 15–35% [5]. Isolates of the genera *Pseudomonas* and *Agrobacterium* from agrocenoses of Almaty region increased alfalfa seedling length from 12.6 to 70.1 mm [6].

The reproducibility of these effects under production conditions nevertheless remains low, and the reason is by no means always biological. A population introduced into the soil must not only withstand competition with the indigenous community but also arrive within the period when soil temperature and moisture simultaneously permit its growth. In the sharply continental climate of Kazakhstan this period is short, shifts in the calendar from zone to zone and varies strongly between years. Yet agronomic regulations for the use of microbial preparations usually contain no zonal reference and are transferred from regions with an entirely different hydrothermal regime. A quantitative basis for such a reference is still lacking. Conventional agroclimatic indicators - the sum of active temperatures and the Selyaninov hydrothermal coefficient - characterise conditions for plants rather than for microorganisms: they take into account neither the temperature of the soil itself nor the fact that microbial activity is suppressed both by desiccation and by waterlogging. Direct measurements of soil respiration within the republic are isolated [7].

The aim of the present work was to build a process-based model of the seasonal dynamics of soil biological activity in Kazakhstan, relying on published response functions of the microbial community to temperature and moisture, to verify it against independent data and to use it for zoning the territory by the potential for application of microbial preparations, as well as for assessing how this potential will change by the middle of the century. The scientific novelty lies in the transition from a descriptive characterisation of soil-climatic zones to the calculation of specific biotechnological windows - periods during which the use of a particular group of preparations is physically justified.

MATERIALS AND METHODS

Input data. Calculations were performed for 16 weather stations covering all the main soil-climatic zones of Kazakhstan, from the haplic chernozems of North Kazakhstan region to the grey-brown desert soils of the Aral Sea area and the piedmont sierozems of Zhetysu. The 1991–2020 climate normals (mean monthly maximum and minimum air temperatures, monthly precipitation totals) of World Meteorological Organization stations were used. Soil-zonal parameters - humus content of the plough layer, field capacity, wilting point and bulk density - were adopted from [2] and from reference values for the corresponding textural classes [8]. The list of stations and the parameterisation adopted are given in table 1.

Conversion from air to soil temperature. Soil surface temperature exceeds air temperature during the period of radiative warming and is slightly lower in the presence of snow cover. This excess was described as a linear function of air temperature above a threshold of 5°C, the coefficient of which was calibrated against the published soil temperature normals of the Astana station [9]:

$$T_s = T_a + 0.31 \cdot \max(0; T_a - 5) - 1.0 \cdot I(T_a < 0) \quad (1)$$

where T_s is soil surface temperature, °C; T_a is mean daily air temperature, °C; and I is an indicator function. The transition to a depth of 10 cm was made using the analytical solution of the heat conduction equation for the annual harmonic: at a thermal diffusivity of $0.5 \cdot 10^{-6}$ m^2 s^{-1} the damping depth is 2.24 m and the amplitude of the annual wave at 10 cm is attenuated by a factor of 0.956. The approach corresponds to that adopted in continental soil temperature models [10]. Daily series were obtained by interpolating monthly normals with a cyclic spline.

Water regime. Potential evapotranspiration was calculated by the Thornthwaite method [11] with a correction for day length at the latitude of the station. The daily water balance of the 0–50 cm layer was reproduced using the Thornthwaite–Mather scheme: when precipitation exceeded evapotranspiration, soil water storage was replenished up to field capacity, and under a deficit it decreased exponentially with a constant equal to the available water range. Four iterations of the annual cycle were performed to remove the effect of initial conditions. Volumetric water content was converted into water-filled pore space (WFPS) through porosity determined from bulk density and a particle density of 2.65 g cm^{-3}. *Response functions.* The thermal response of microbial respiration was described by the Lloyd–Taylor function [12] normalised to 10°C:

$$f_T = \exp[E_0 \cdot (1/(T_{ref} - T_0) - 1/(T - T_0))] \quad (2)$$

where T is soil temperature, K; T_0 = 227.13 K; Tref = 283.15 K; E_0 = 308.56 K. Below −2°C activity was set to zero. The moisture function was specified as piecewise linear: a linear increase from a lower WFPS limit of 0.05 to an optimum of 0.60 and a decrease to 0.55 at full saturation. The position of the optimum was adopted from a generalisation of experimental data [13, 14], according to which the maximum heterotrophic respiration of mineral soils occurs at 0.60–0.63 of saturation. The daily index of biological activity was defined as the product fT·fW, and the annual index (BAI) as its yearly sum. BAI is expressed in standard days: unity corresponds to one day with a soil temperature of 10°C and optimum moisture.

Calibration and verification. Absolute values of carbon mineralisation were obtained by multiplying BAI by a substrate factor $\sqrt{(H \cdot \rho)}$, where H is humus content, %, and ρ is bulk density, g cm^{-3}. The square root reflects the fact that the rate of decomposition is not proportional to the entire stock of organic matter, a considerable part of which is stabilised. The scaling coefficient (1.213) was determined from four field measurements of annual CO_2 efflux on a southern chernozem at Shortandy (51.6° N, 71.1° E): 366, 428, 487 and 551 g C m^{-2} yr^{-1}, with a mean of 458 g C m^{-2} yr^{-1} [7]. For independent verification an empirical climatic regression was built using the global soil respiration database SRDB-V5 [15, 16]; a "dry continental" subset was selected from it 261 records for grassland, agricultural, shrubland and desert ecosystems with annual precipitation of 150–500 mm and a mean annual temperature from −2 to 14°C:

$$\ln R_s = -2.998 + 1.529 \cdot \ln P + 0.0211 \cdot T, \quad R^2 = 0.25 \quad (3)$$

Biotechnological windows. Three periods relevant to the practical use of microbial preparations were introduced. The inoculation window is the spring period (before 1 July) with a soil temperature of 8–25°C and WFPS of at least 0.30, when mesophilic bacteria introduced at sowing are able to establish. The nit-

rogen-fixation window is the period with a soil temperature of 15–30°C and WFPS of at least 0.35, corresponding to the operating conditions of symbiotic and associative diazotrophs. The decomposition window is the period from 1 August to 30 November with a soil temperature of at least 5°C and WFPS of at least 0.25, during which cellulolytic preparations applied to stubble can decompose straw.

Zoning and scenarios. The stations were grouped by Ward hierarchical clustering [18] using five standardised variables (BAI, mean moisture function and the durations of the three windows); the number of clusters was chosen by the maximum mean silhouette [19]. Spatial interpolation was performed as a combination of a linear trend in coordinates and inverse-distance-weighted interpolation of the residuals, masked by the state border. Climate projections for 2040–2059 were constructed by the delta-change method using the CMIP5 ensemble for the RCP4.5 (+2.2°C, precipitation +3%) and RCP8.5 (+2.8°C, precipitation +4%) scenarios [17], with subtraction of the observed warming of 0.28°C between the midpoints of the baseline periods. The calculations were carried out in Python 3 using the NumPy and Matplotlib libraries; all algorithms were implemented by the authors.

Table 1 – Weather stations, soil-zonal parameterisation and climatic characteristics (1991–2020 normals)

Station	Latitude / longitude, °	Elevation, m	Soil zone	Humus, %	AWR, mm	T, °C	Precipitation, mm	PET, mm
Petropavl	54.83 / 69.15	142	Haplic Chernozem	4.10	80	2.7	387	587
Kostanay	53.22 / 63.62	171	Haplic Chernozem	4.10	80	4.0	352	616
Astana	51.13 / 71.37	350	Southern Chernozem	2.85	75	4.1	338	608
Oral	51.25 / 51.40	35	Southern Chernozem	2.85	75	6.7	337	667
Aktobe	50.28 / 57.15	219	Dark Kastanozem	2.40	70	5.9	316	652
Pavlodar	52.30 / 76.95	122	Dark Kastanozem	2.40	70	3.6	311	610
Oskemen	49.95 / 82.62	285	Dark Kastanozem	2.40	70	4.3	477	604
Karaganda	49.80 / 73.15	553	Kastanozem	2.00	65	4.2	381	590
Semey	50.40 / 80.25	206	Kastanozem	2.00	65	4.4	303	615
Zhezkazgan	47.80 / 67.72	346	Light Kastanozem	1.60	60	6.2	183	669
Atyrau	47.12 / 51.92	-22	Brown desert soil	0.80	55	10.7	187	789
Kyzylorda	44.85 / 65.50	130	Grey-brown desert soil	1.35	55	11.5	146	828
Turkistan	43.30 / 68.25	207	Light Sierozem	1.10	75	13.5	206	871
Taraz	42.85 / 71.38	653	Typical Sierozem	1.70	80	11.5	357	736
Shymkent	42.32 / 69.70	604	Typical Sierozem	1.70	80	13.4	617	811
Almaty	43.23 / 76.93	847	Dark piedmont Sierozem	2.30	80	10.9	674	720

Note: AWR is the available water range of the 0–50 cm layer; T is mean annual air temperature; PET is annual potential evapotranspiration after Thornthwaite.

RESULTS AND DISCUSSION

Model verification. The annual course of soil surface temperature calculated from Equation (1) reproduced the published normals of the Astana station with a coefficient of determination of 0.997, a standard error of 1.0°C and a systematic bias of +0.2°C (Figure 1c). The largest discrepancies occurred in March and October (+1.7 and +1.4°C) and were related to the effect of snow cover and delayed thawing, which the model does not describe explicitly. For

quantities integrated over the year this accuracy is sufficient, as confirmed by a sensitivity analysis: a shift of the calculated soil temperature by ±2°C changed the annual index by −14.4 and +16.4%, respectively, so that an error of 1°C corresponds to about 8 % uncertainty in BAI.

An independent check of the carbon module was provided by comparing two fundamentally different estimates of mineralisation - the process-based one (the model) and the empirical-climatic one (Equation 3 based on SRDB-V5). The correlation coefficient between them across the 16 stations was 0.80, with a mean difference of only 5 g C m^{-2} yr^{-1}, although the mean absolute difference reached 177 g C m^{-2} yr^{-1}. There is thus no systematic bias, and the discrepancies are substantive; they are examined below.

Spatial structure of biological activity. The annual index of biological activity varied 2.5-fold across the republic, from 167 standard days in Karaganda region to 421 in Shymkent (figure 2a, table 2). The distribution is distinctly latitudinal, yet it cannot be reduced either to heat supply or to moisture supply alone. The maximum occurs neither at the warmest nor at the wettest point but on the piedmont sierozems of the south, where abundant winter and spring precipitation coincides with early and prolonged soil warming. The minimum is formed in the dry-steppe zone of Central Kazakhstan, where moderate heat supply is combined with deep summer desiccation. It is notable that the BAI series and the humus content series are almost in antiphase. The haplic chernozems of Northern Kazakhstan, the richest in organic matter (humus 4.1%), occupy only seventh to eleventh places by index, whereas sierozems with a humus content of 1.1–1.7% lead.

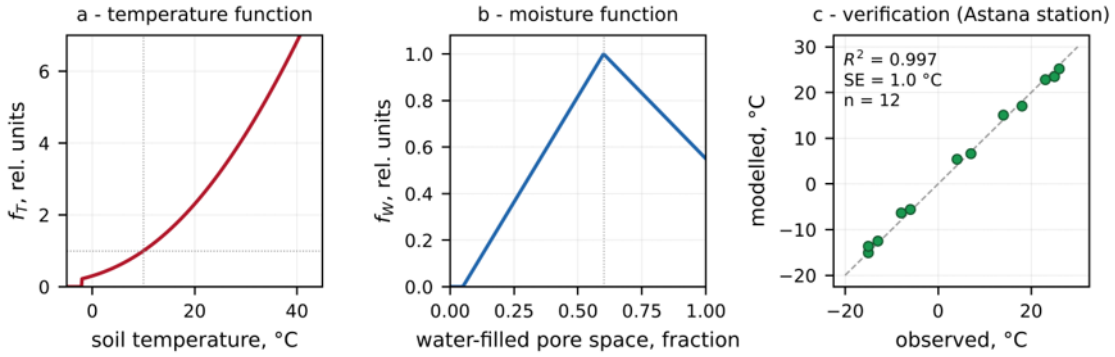


Figure 1 – Response functions of the model and verification of the temperature module: a - Lloyd–Taylor temperature function; b - moisture function; c - comparison of calculated and observed mean monthly soil surface temperatures (Astana station)

This is not a contradiction but a direct consequence of the fact that the large humus stocks of the northern chernozems were historically formed precisely because of the brevity of the period of biological activity: organic matter accumulates where mineralisation is retarded by cold. The relationship becomes obvious when absolute values are considered: taking the substrate factor into account, the calculated carbon mineralisation at Kostanay (604 g C m^{-2} yr^{-1}) is higher than at Turkistan (516 g C m^{-2} yr^{-1}) despite a substantially lower index.

Table 2 – Calculated indicators of soil biological activity by station

Station	Zone	BAI, standard days	R_s (model), g C m^{-2} yr^{-1}	R_s (SRDB), g C m^{-2} yr^{-1}	Biologically active period, days	Soil T in July–August, °C	WFPS in July–August, fraction
Petropavl	III	203.1	535	475	181	21.4	0.32
Kostanay	III	229.5	604	423	188	23.3	0.31
Astana	III	204.2	458	399	189	23.2	0.29
Oral	III	244.4	548	419	202	26.2	0.28
Aktobe	III	226.2	475	373	198	26.0	0.27
Pavlodar	III	187.6	394	347	187	23.4	0.27
Oskemen	III	207.3	436	677	192	23.2	0.28
Karaganda	IV	167.5	328	480	190	22.5	0.25
Semey	IV	170.9	334	340	192	23.8	0.24
Zhezkazgan	IV	186.4	330	163	201	27.1	0.22
Atyrau	IV	194.3	254	185	227	31.6	0.18
Kyzylorda	IV	233.4	392	129	236	32.4	0.19
Turkistan	II	355.7	516	228	259	33.3	0.24
Taraz	I	336.8	603	507	248	29.2	0.26
Shymkent	I	420.9	753	1217	269	31.5	0.26
Almaty	I	399.1	811	1321	241	28.6	0.32

Note: BAI is the annual index of biological activity; R_s is annual carbon mineralisation according to the process-based model and to the empirical regression (3); the biologically active period is the number of days with a soil temperature above 5°C and WFPS above 0.15; WFPS is water-filled pore space.

Seasonal dynamics and the leading limiting factor. The seasonal course of the indicators for four contrasting stations is shown in figure 3. In all zones except the piedmont one the curve of the daily index is markedly asymmetric: a rapid rise in spring as the soil, still wet after snowmelt, warms up, and a protracted decline in summer caused by exhaustion of soil water. At Petropavl and Karaganda the maximum falls in June, at Shymkent in May, while at Kyzylorda the curve is almost flat: at a July soil temperature of 33–34°C the water-filled pore space falls to 0.19, and the thermally favourable period proves to be biologically almost waterless. Of fundamental importance is the fact that at none of the 16 stations does water-filled pore space reach the optimum value of 0.60 at any time of the year: the maximum is 0.58 in the chernozems of Northern Kazakhstan, 0.55–0.57 in the southern chernozems and piedmont sierozems, and only 0.42–0.43 in the Caspian and Aral Sea areas.

Moreover, the highest moisture content everywhere occurs from November to April, when soil temperature is close to zero or negative. In other words, throughout Kazakhstan heat and soil water are systematically separated in time, and biological activity is realised only within narrow transitional intervals. This is the main structural finding of the study, and it directly determines the logic of applying microbial preparations.

On the discrepancy between the process-based and empirical estimates. The largest differences between the two ways of calculating mineralisation were obtained for stations with a winter precipitation maximum: at Shymkent and Almaty the empirical regression gave 1217 and 1321 against 753 and 811 g C m^{-2} yr^{-1} from the model, whereas at Turkistan and Kyzylorda, conversely, 228 and 129 against 516 and 392. The reason is that regression (3) relies on annual precipitation, whereas what matters for the microbial community is the coincidence of precipitation with the warm period. Under the Mediterranean-type moisture regime of southern Kazakhstan the annual total systematically overestimates the biologically available water, while in the desert zone, where a consi-

derable part of the activity occurs in short spring periods, it underestimates it. The process-based model, which works with a daily water balance, is free of this distortion; the discrepancy should be regarded as an argument in favour of the process-based approach when zoning arid territories.

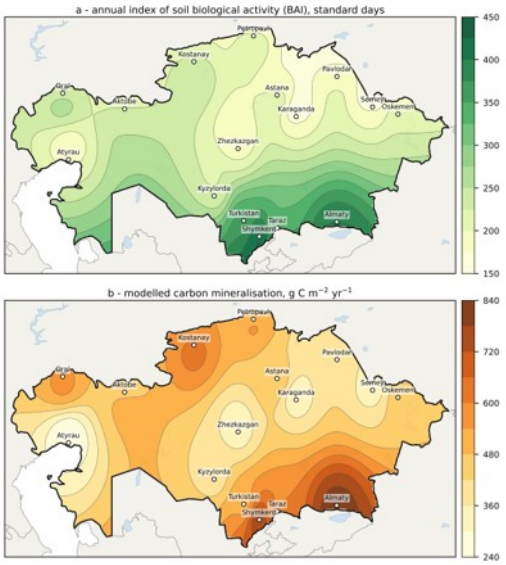


Figure 2 – Spatial distribution of the annual index of soil biological activity and of calculated carbon mineralisation over the territory of Kazakhstan

A fundamental limitation should also be noted. Analysis of the SRDB-V5 subset shows that in a dry continental climate annual precipitation correlates with carbon efflux (r=0.43), whereas mean annual temperature practically does not (r=−0.05).

The model, in an experiment with single perturbations, gives the opposite picture: a temperature increase of 1°C raises BAI by 8.1–9.8%, while a 10% increase in precipitation raises it by only 0.4–2.1%. The contradiction is explicable: at a fixed humus content the model describes the direct abiotic control of the mineralisation rate, whereas in nature moisture also governs plant productivity, that is, the input of fresh substrate.

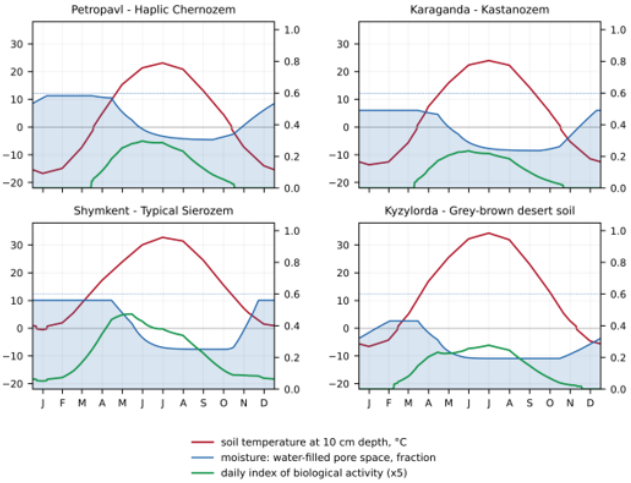


Figure 3 – Seasonal dynamics of soil temperature, moisture and the daily index of biological activity under contrasting soil-climatic conditions

This feedback loop is not reproduced in the present version of the model and must be taken into account when interpreting the scenario estimates.

Biotechnological windows. The calendar position and duration of the three windows identified are shown in figure 4. The inoculation window is open everywhere, but its duration differs more than twofold - from 32 days at Atyrau to 75 at Oskemen - and its timing shifts by almost one and a half months: at Shymkent and Turkistan it opens in the first ten days of March, at Petropavl only in the second ten days of April. The practical conclusion is straightforward: a single nationwide regulation for pre-sowing seed treatment with microbial preparations is impossible, and in zones with a short window (the Aral Sea area, the Caspian area, Central Kazakhstan) a delay of ten days in sowing means the loss of one third of the period suitable for establishment.

The nitrogen-fixation window is distributed far more unevenly - from zero at Atyrau and 4–7 days at Zhezkazgan and Kyzylorda to 84 days at Almaty. Over a considerable part of the dry-steppe and desert zone, conditions for diazotroph activity in rainfed crops are in fact absent, and the use of preparations based on nitrogen-fixing bacteria without irrigation is physically meaningless there. In the piedmont zone, by contrast, the duration of the window is comparable with the length of the growing season of grain legumes.

The most contrasting picture is given by the crop-residue decomposition window. In the steppe zone it lasts 75–85 days owing to autumn rains while soil temperatures are still positive, in the piedmont zone 103–117 days, while at five stations of the dry-steppe and desert zone (Karaganda, Semey, Zhezkazgan, Atyrau, Kyzylorda) it is completely closed: by August soil water storage is exhausted, and autumn precipitation falls when temperatures are already low. This explains the poor straw decomposition in Central Kazakhstan long known to practitioners and shows that the application of cellulolytic preparations to stubble there has little prospect without water-conserving practices.

Biotechnological zoning. Ward clustering by five variables gave the best partition at four clusters (mean silhouette 0.51; figure 5). The resulting zones have a clear geographical and pedological interpretation (table 3).

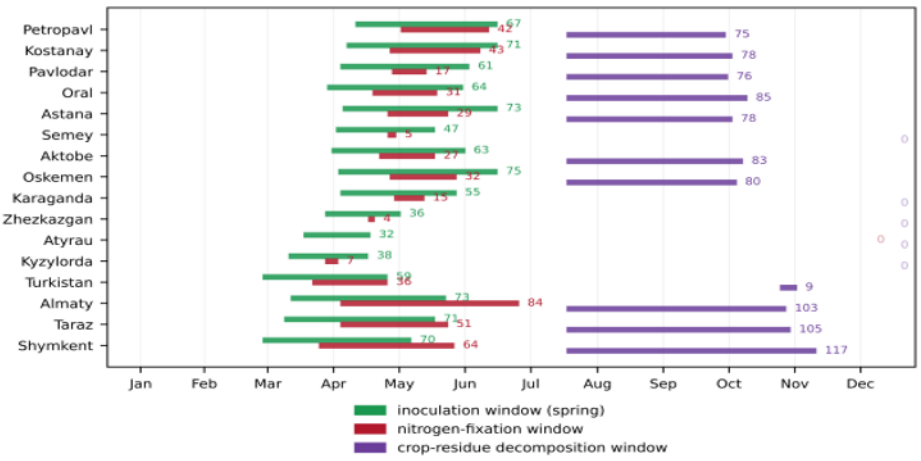


Figure 4 – Calendar of biotechnological windows by station (bars show the calendar position of each window, figures its duration in days; stations are ordered from north to south)

Zone I (Taraz, Shymkent, Almaty) comprises piedmont sierozems with the highest index (386 standard days) and the longest windows of all three types. With a low humus content (1.9%) the calculated mineralisation here is the highest - 722 g C m^{-2} yr^{-1} - that is, the turnover of organic matter is intensive while its stocks are small. This is a zone in which microbial preparations can work throughout almost the whole warm season but in which the task of returning organic matter to the soil is also the most acute.

Zone II is represented by a single station, Turkistan, and its separation is meaningful. The combination of high heat supply (index 356) with a severe water deficit gives a long inoculation window (59 days, from the beginning of March) with an almost complete absence of a decomposition window (9 days). This is an independent type of conditions requiring osmotolerant strains; it is precisely for such soils that results have been obtained with the halophilic *Bacillus* sp. PK-1 [5].

Zone III is the main agricultural belt of the republic (seven stations, chernozems and dark kastanozems). With a moderate index (215) it has the highest humus content (3.0%) and a stable autumn decomposition window (79 days). It is here that a domestic strain base also exists - isolates from the wheat rhizosphere of Akmola region [3].

Zone IV (dry-steppe and desert) is characterised by the lowest index (190), a short inoculation window (42 days), an almost zero nitrogen-fixation window (6 days) and a complete absence of a decomposition window. The use of microbial preparations here is confined to a narrow spring interval or requires irrigation.

Comparison of the zones with the published characteristics of Kazakhstani strains (table 4) shows that the existing collection base is distributed extremely unevenly among the zones: active isolates of local origin have been described for zones I–III, whereas for zone IV, which occupies the largest area, such data are practically absent. This indicates a priority direction for further work - a targeted search for drought-tolerant and osmotolerant strains in the soils of the dry-steppe and desert zones.

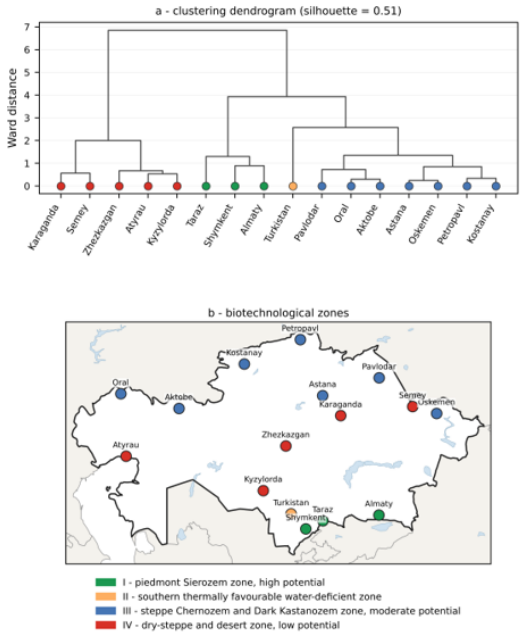


Figure 5 – Biotechnological zoning of the territory of Kazakhstan: a - dendrogram of Ward clustering of the stations; b - spatial position of the zones

Scenario estimates. By 2040–2059 the annual index of biological activity increases on average by 17.5% under RCP4.5 (from 16.1 to 19.2% across stations) and by 23.4% under RCP8.5 (from 21.4 to 24.9%); the calculated carbon mineralisation increases correspondingly (figure 6, table 5).

The increase is due almost entirely to the temperature component: the sum of the thermal function grows by 22–28%, whereas the mean moisture function decreases by only 0.5–2.7%, since the 12–18% rise in potential evapotranspiration is partly compensated by increased precipitation, and at the driest points soil water is already fully exhausted in the baseline period.

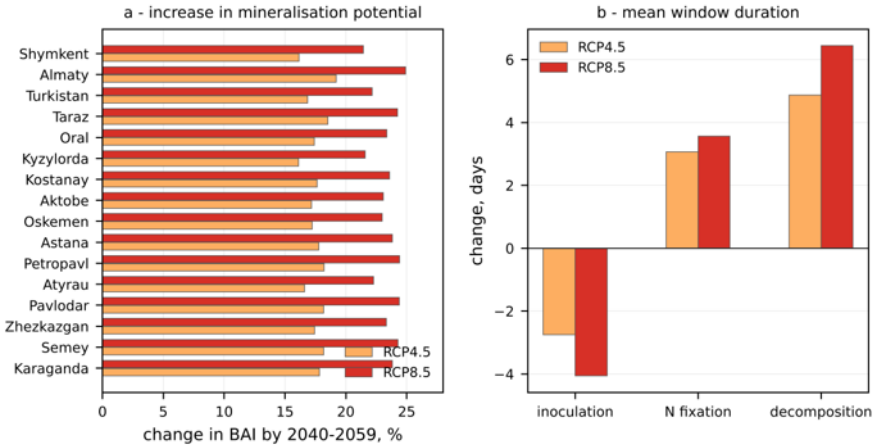


Figure 6 – Changes in the indicators of soil biological activity by 2040–2059 under the RCP4.5 and RCP8.5 scenarios

The biologically active period lengthens on average by 14 (RCP4.5) and 18 (RCP8.5) days. The changes in the individual windows are, however, of opposite sign. The crop-residue decomposition window increases by 5–6 days and the nitrogen-fixation window by 3–4 days, whereas the inoculation window, on the contrary, is shortened on average by 3–4 days, and at Kostanay and Astana by 12–15 days. The reason is that the spring crossing of the upper limit of the mesophilic optimum (25°C) by soil temperature occurs earlier, while the lower limit shifts only slightly. Thus, in the main agricultural belt of the republic the period suitable for the establishment of mesophilic cultures introduced at sowing will contract, and the need for thermotolerant strains will increase.

The picture obtained has a quite definite agroecological consequence. An increase in mineralisation potential with an unchanged or declining input of plant residues means accelerated dehumification, that is, a continuation of the trend already recorded for the chernozems of the republic [1, 2]. Under these conditions the main task of soil biotechnology becomes not so much the stimulation of mineralisation as the management of the organic matter balance: the use of decomposers must be combined with straw return and green manuring, and inoculation with practices that increase the input of root exudates and root biomass.

Table 3 – Biotechnological zones of Kazakhstan and recommended directions for the application of microbial preparations

Zone	Stations	Humus, %	BAI, standard days	R_s, g C m^{-2} yr^{-1}	Inoculation window, days	N-fixation window, days	Decomposition window, days	Priority directions of biotechnology
I - piedmont Sierozem zone	Taraz, Shymkent, Almaty	1.90	386	722	71	66	108	Full range: pre-sowing inoculation, associative and symbiotic diazotrophs, cellulolytic preparations applied to plant residues
II - southern thermally favourable water-deficient zone	Turkistan	1.10	356	516	59	36	9	Inoculation with halotolerant and osmotolerant strains; decomposers only under irrigation or when residues are incorporated into a moist layer
III - steppe Chernozem and Dark Kastanozem zone	Petropavl, Kostanay, Astana, Oral, Aktobe, Pavlodar, Oskemen	3.01	215	493	68	32	79	Pre-sowing inoculation and autumn stubble decomposition; nitrogen fixers for grain legumes in the wettest subzones
IV - dry-steppe and desert zone	Karaganda, Semey, Zhezkazgan, Atyrau, Kyzylorda	1.55	190	327	42	6	0	Inoculation with drought-tolerant strains within a short spring period; preparations based on nitrogen fixers and decomposers only in irrigated farming

Table 4 – Published characteristics of strains isolated from the soils of Kazakhstan and their correspondence to the biotechnological zones identified

Strains	Source of isolation	Zone	Main established effect	Reference
Pseudomonas fluorescens AK-4, *Bacillus cereus* TB-1, *Enterobacter cloacae* KB-2, ShB-2, T-3, *E. ludwigii* TB-2, *Staphylococcus epidermidis* ChK-4	Wheat rhizosphere, Akmola region	III	Wheat seedling length 14.7–15.3 cm against 10.1 cm in the control	[3]
44 strains of micromycetes and yeasts, including *Aspergillus* sp. T17, *Penicillium* sp. AC 14, *Cryptococcus* sp. K3	Agrocenoses of cereal, fodder and oil crops	III	Phosphate mobilisation in 24.9 % of isolates, cellulolytic activity in 16.4 %; barley biomass increase of 1.2–1.5-fold	[4]
Bacillus sp. PK-1 (halophilic)	Irrigated saline soils, Turkistan region	II	Maize yield increase of 15–35 %	[5]
Isolates of the genera *Pseudomonas*, *Agrobacterium*, *Bacillus*, *Arthrobacter*	Agrocenoses of fodder crops, Almaty region	I	Alfalfa seedling length 70.1 mm against 12.6 mm in the control; germination 65–85 %	[6]

Table 5 – Projection of soil biological activity indicators by zone for the period 2040–2059

Zone	BAI, baseline	BAI, RCP4.5	BAI, RCP8.5	R_s, baseline	R_s, RCP4.5	R_s, RCP8.5	Δ inoculation window, days	Δ N-fixation window, days	Δ decomposition window, days
I	386	455	476	722	852	892	-4	-2	+11
II	356	416	435	516	603	630	-3	+7	+12
III	215	252	265	493	580	609	-10	+4	+8
IV	190	223	234	327	384	403	+3	+6	+0

Note: BAI is expressed in standard days; R_s in g C m^{-2} yr^{-1}; Δ is the change in window duration under RCP8.5 relative to the baseline period.

Limitations of the study. The model operates with climate normals and describes mean long-term conditions, without reproducing the interannual variability that is very large in Kazakhstan. Snow accumulation and spring snowmelt are taken into account implicitly, through the replenishment of soil water storage at zero winter evaporation. Soil-zonal parameters were averaged for each zone and do not reflect intrazonal heterogeneity, in particular solonetzicity and salinity, which suppress microbial activity in their own right. Humus content was assumed constant, so that the feedback "moisture - productivity - substrate input" is not reproduced; as shown above, this is precisely what explains the divergence from the empirical relationships of the SRDB-V5 database. Finally, the boundaries of the biotechnological windows were set according to generalised physiological requirements of mesophilic soil bacteria and must be refined experimentally for particular strains.

CONCLUSION

A process-based model of soil biological activity in Kazakhstan was developed and verified, linking climate normals, the hydrophysical properties of soil zones and published response functions of the microbial community to temperature and moisture. The temperature module reproduced the observed annual course of soil temperature with a coefficient of determination of 0.997 and a standard error of 1.0°C; the calculated carbon mineralisation agreed with field measurements at Shortandy and with an independent empirical estimate based on the global SRDB-V5 database (r=0.80). It was established that the annual index of biological activity varies 2.5-fold across the republic and the calculated carbon mineralisation ranges from 254 to 811 g C m^{-2} yr^{-1}, the spatial series of the index being almost in antiphase with that of humus content. It was shown that at no station does water-filled pore space reach the optimum of 0.60, and that the period of highest moisture everywhere falls in the cold season, as a result of which biological activity is realised only within narrow transitional intervals in spring and autumn. Three biotechnological windows were introduced and calculated - inoculation (32–75 days), nitrogen fixation (0–84 days) and crop-residue decomposition (0–117 days). Ward clustering identified four biotechnological zones (mean silhouette 0.51), for each of which priority directions for the application of microbial preparations were substantiated. It was established that in the dry-steppe and desert zone the decomposition window is completely closed, which makes the application of cellulolytic preparations to stubble there unpromising without water-conserving practices. Under the RCP4.5 and RCP8.5 scenarios the index of biological activity increases by 17.5 and 23.4% by 2040–2059, the biologically

active period lengthens by 14 and 18 days, the nitrogen-fixation and decomposition windows widen, while the inoculation window in the main agricultural belt contracts by 12–15 days. This implies a growing mineralisation pressure on soil organic matter together with a narrowing of the period suitable for the introduction of mesophilic strains, and it defines two practical priorities: the search for thermo- and drought-tolerant strains of local origin, above all for the dry-steppe and desert zones, and the obligatory combination of microbial preparations with practices that return organic matter to the soil.

REFERENCES

1. Belgibayev M.E. Problemy sokhraneniya pochv stepnoj zony Kazakhstana. – Semej: Universitet imeni Shakarima, 2021. – S. 120–124. – DOI: 10.24412/cl-36359-2021-120-124.

2. Kuryshbayev A.K., Zvyagin G.A., Yaroslavtseva N.V., Kogut B.M. Agrogennaya transformatsiya organicheskogo veshchestva chernozemov Kazakhstana // Samarskij nauchnyj vestnik. – 2016. – T. 5, № 3. – S. 35–39. – DOI: 10.17816/snv20163107.

3. Bisenova G.N., Sadykova B.Zh., Mussabayeva B.K., Tekebayeva Zh.B., Sarmurzina Z.S., Temirkhanov A.Zh. Otsenka roststimuliruyushchej aktivnosti mikroorganizmov, vydelennykh iz pochvy Akmolinskoj oblasti // Vestnik Evrazijskogo natsional'nogo uni-versiteta imeni L.N. Gumileva. Seriya: Biologicheskie nauki. – 2022. – № 3(140). – S. 47–59. – DOI: 10.32523/2616-7034-2022-140-3-47-59.

4. Brazhnikova E.V., Mukasheva T.D., Ignatova L.V. Skrining shtammov mikromitsetov, perspektivnykh dlya stimulyatsii rosta sel'skokhozyajstvennykh kul'tur // Eksperimental'naya biologiya. – 2019. – № 3(80). – S. 40–47. – DOI: 10.26577/eb-2019-3-b4.

5. Karabaeva I.Z., Ultanbekova G.D., Sydykbekova Zh.K., Saparov S.S., Tokseitov N., Serikbay G.B., Abay A.K. Vliyanie galofil'nykh mikroorganizmov Bacillus sp. PK-1 na rost i razvitie kukuruzy v usloviyakh oroshaemykh zasolennykh pochv Turkestanskoj oblasti // Eurasian Journal of Ecology. – 2020. – Vol. 62, № 1. – P. 18–26. – DOI: 10.26577/EJE.2020.v62.i1.02.

6. Zhumagalieva Zh., Aimagambetova Zh., Nesterova A., Shukeshova S., Tokesh B., Berzhanova R.Zh., Mukasheva T.D. Otsenka roststimuliruyushchej aktivnosti mikroorganizmov, vydelennykh iz razlichnykh substratov // Vestnik KazNU. Seriya ekologicheskaya. – 2014. – № 2(41). – S. 199–203.

7. Perez-Quezada J.F., Saliendra N.Z., Akshalov K., Johnson D.A., Laca E.A. Land use influences carbon fluxes in northern Kazakhstan // Rangeland Ecology & Management. – 2010. – Vol. 63, № 1. – P. 82–93. – DOI: 10.2111/08-106.1.

8. Shein E.V. Kurs fiziki pochv. – M.: Izd-vo Moskovskogo universiteta, 2005. – 432 s.

9. Kozhakhmetova E.P., Kozhakhmetov P.Zh. O klimate i ego izmenenii v gorode Astane // Gidrometeorologiya i ekologiya. – 2011. – № 2. – S. 7–14.

10. Zheng D., Hunt E.R. Jr., Running S.W. A daily soil temperature model based on air temperature and precipitation for continental applications // Climate Research. – 1993. – Vol. 2. – P. 183–191.

11. Thornthwaite C.W. An approach toward a rational classification of climate // Geographical Review. – 1948. – Vol. 38, № 1. – P. 55–94.

12. Lloyd J., Taylor J.A. On the temperature dependence of soil respiration // Functional Ecology. – 1994. – Vol. 8, № 3. – P. 315–323.

13. Linn D.M., Doran J.W. Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils // Soil Science Society of America

Journal. – 1984. – Vol. 48, № 6. – P. 1267–1272. – DOI: 10.2136/sssaj1984.03615995004-800060013x.

14. Moyano F.E., Vasilyeva N., Bouckaert L., Cook F., Craine J., Curiel Yuste J., Don A., Epron D., Formanek P., Franzluebbers A., Ilstedt U., Kätterer T., Orchard V., Reichstein M., Rey A., Ruamps L., Subke J.-A., Thomsen I.K., Chenu C. The moisture response of soil heterotrophic respiration: interaction with soil properties // Biogeosciences. – 2012. – Vol. 9, № 3. – P. 1173–1182. – DOI: 10.5194/bg-9-1173-2012.

15. Bond-Lamberty B., Thomson A. A global database of soil respiration data // Biogeosciences. – 2010. – Vol. 7, № 6. – P. 1915–1926. – DOI: 10.5194/bg-7-1915-2010.

16. Jian J., Vargas R., Anderson-Teixeira K., Stell E., Herrmann V., Horn M., Kholod N., Manzon J., Marchesi R., Paredes D., Bond-Lamberty B. A restructured and updated global soil respiration database (SRDB-V5) // Earth System Science Data. – 2021. – Vol. 13, № 2. – P. 255–267. – DOI: 10.5194/essd-13-255-2021.

17. Climate Risk Country Profile: Kazakhstan. – Washington: World Bank Group; Manila: Asian Development Bank, 2021. – 32 p.

18. Ward J.H. Jr. Hierarchical grouping to optimize an objective function // Journal of the American Statistical Association. – 1963. – Vol. 58, № 301. – P. 236–244.

19. Rousseeuw P.J. Silhouettes: a graphical aid to the interpretation and validation of cluster analysis // Journal of Computational and Applied Mathematics. – 1987. – Vol. 20. – P. 53–65.

ТҮЙІН

М.К. Тыныкулов[1], Р.К. Пернебекова[2,3], Р.У. Мамыкова[4], Г.С. Жакипбекова[3], Н.В. Малицкая[5], А.К. Мухтаров[1]

ҚАЗАҚСТАН ТОПЫРАҚТАРЫНЫҢ БИОЛОГИЯЛЫҚ БЕЛСЕНДІЛІГІН АГРОКЛИМАТТЫҚ МОДЕЛЬДЕУ ЖӘНЕ АУМАҚТЫ МИКРОБТЫ БИОПРЕПАРАТТАРДЫ ҚОЛДАНУ ӘЛЕУЕТІ БОЙЫНША АЙМАҚТАРҒА БӨЛУ

[1]Л.Н. Гумилев атындағы Еуразия ұлттық университеті, Астана, Қазақстан

[2]Қожа Ахмет Яссауи атындағы Халықаралық Қазақ-Түрік университеті, жоғары оқу орнынан кейінгі медициналық білім беру факультеті, Түркістан, Қазақстан

[3]Оңтүстік Қазақстан медицина академиясы, медицина факультеті, Шымкент, Қазақстан

[4]Жәнібеков Университеті, Жаратылыстану ғылымдары факультеті, Шымкент, Қазақстан

[5]М. Қозыбаев атындағы Солтүстік Қазақстан мемлекеттік университеті, Петропавл, Қазақстан, e-mail: mr.tynykulov@mail.ru

Қазақстанның дала жағдайында микробтық биопрепараттардың тиімділігі тұрақсыз болып қалуда, оның басты себептерінің бірі - абиотикалық шектеулер: енгізілген микроорганизмдер топырақ температурасы мен ылғалдылығының тар ауқымында ғана тамырлана алады, ал күрт континенттік климатта бұл ауқым ұзаққа ашылмайды. Жұмыстың мақсаты - Қазақстан топырақтарының биологиялық белсенділігінің маусымдық динамикасын сандық түрде сипаттау және осының негізінде биопрепараттарды қолдану әлеуеті бойынша ерекшеленетін аймақтарды бөліп көрсету. 16 метеостанцияның 1991–2020 жж. климаттық нормалары бойынша 10 см тереңдіктегі топырақ температурасы, 0–50 см қабатының тәуліктік су балансы және Ллойд–Тейлордың термиялық функциясы мен сумен толтырылған кеуек кеңістігінің үлесі арқылы берілген ылғалдану функциясының көбейтіндісі ретінде биологиялық белсенділіктің тәуліктік индексі есептелетін процестік модель әзірленді. Температуралық блок Астана станциясының жарияланған топырақ

температурасы нормалары бойынша тексерілді (R^2=0,997; стандартты қате 1,0°C), көміртектік блок - Шортандыдағы CO_2 эмиссиясының далалық өлшемдері және жаһандық SRDB-V5 базасының 261 жазбасы бойынша. Жылдық индекс аумақ бойынша 2,5 есе, ал көміртектің есептік минералдануы 254-тен 811 г С/(м^2·жыл) дейін өзгереді. Инокуляция, азотфиксация және өсімдік қалдықтарын ыдырату деген үш биотехнологиялық терезе енгізілді; олардың ұзақтығы тиісінше 32–75, 0–84 және 0–117 тәулікті құрайды. Уорд әдісімен кластерлеу төрт биотехнологиялық аймақты бөліп шығарды (силуэт 0,51). RCP4.5 және RCP8.5 сценарийлері бойынша 2040–2059 жж. индекс 17,5 және 23,4%-ға артады, инокуляция терезесі қысқарады, ал ыдырату терезесі ұзарады, бұл биотехнологияның басымдығын минералдануды ынталандырудан топырақтың органикалық затын сақтауға қарай ығыстырады.

Түйінді сөздер: топырақтың биологиялық белсенділігі, топырақ микроорганизмдері, микробтық биопрепараттар, PGPR, көміртектің минералдануы, топырақтың су режимі, агроклиматтық аймақтарға бөлу, климаттың өзгеруі, ГАЖ.

РЕЗЮМЕ

М.К. Тыныкулов[1], Р.К. Пернебекова[2,3], Р.У. Мамыкова[4], Г.С. Жакипбекова[3], Н.В. Малицкая[5], А.К. Мухтаров[1]

АГРОКЛИМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ БИОЛОГИЧЕСКОЙ АКТИВНОСТИ ПОЧВ КАЗАХСТАНА И ЗОНИРОВАНИЕ ТЕРРИТОРИИ ПО ПОТЕНЦИАЛУ ПРИМЕНЕНИЯ МИКРОБНЫХ БИОПРЕПАРАТОВ

[1]Евразийский национальный университет им. Л.Н. Гумилева, Астана, Казахстан

[2]Международный Казахско-Турецкий университет им. Ходжи Ахмета Яссауи, Факультет последипломного высшего медицинского образования, Туркестан, Казахстан

[3]Южно-Казахстанская медицинская академия, Медицинский факультет, Шымкент, Казахстан

[4]Университет им. Жанибекова, Факультет естественных наук, Шымкент, Казахстан

[5]Северо-Казахстанский государственный университет им. М. Козыбаева, Петропавловск, Казахстан, e-mail: mr.tynykulov@mail.ru

Эффективность микробных биопрепаратов в полевых условиях Казахстана остаётся нестабильной, и одной из главных причин этого являются абиотические ограничения: интродуцированные микроорганизмы способны приживаться и работать лишь в узком диапазоне температуры и влажности почвы, который в резко континентальном климате открыт недолго. Цель работы - количественно описать сезонную динамику биологической активности почв Казахстана и на этой основе выделить зоны, различающиеся по потенциалу применения биопрепаратов. Разработана процессная модель, в которой по климатическим нормам 1991–2020 гг. 16 метеостанций рассчитываются температура почвы на глубине 10 см, суточный водный баланс слоя 0–50 см и суточный индекс биологической активности как произведение термической функции Ллойда–Тейлора и функции увлажнения, заданной через долю занятого водой порового пространства. Температурный блок верифицирован по опубликованным нормам температуры почвы ст. Астана (R^2=0,997; стандартная ошибка 1,0°C), углеродный - по полевым измерениям эмиссии CO_2 в Шортандах и по выборке из 261 записи глобальной базы SRDB-V5. Годовой индекс изменяется по территории в 2,5 раза, а расчётная минерализация углерода - от 254 до 811 г С/(м^2·год). Введены три биотехнологических окна - инокуляции, азотфиксации и деструкции растительных остатков; их длительность составляет соответственно 32–75, 0–84 и 0–117 суток. Кластеризация методом Уорда выделила четыре биотехнологические зоны (силуэт 0,51).

По сценариям RCP4.5 и RCP8.5 к 2040–2059 гг. индекс возрастает на 17,5 и 23,4%, окно инокуляции сокращается, а окно деструкции удлиняется, что смещает приоритет биотехнологии от стимуляции минерализации к сбережению органического вещества почв.

Ключевые слова: биологическая активность почв, почвенные микроорганизмы, микробные биопрепараты, PGPR, минерализация углерода, водный режим почв, агроклиматическое зонирование, изменение климата, ГИС.

INFORMATION ABOUT THE AUTHORS

1. Tynykulov Marat Korganbekovich, Candidate of Agricultural Sciences, associate professor, the main author, https://orcid.org/0000-0002-4878-4030,
e-mail: tynykulov@list.ru.

2. Pernebekova Rakhat Karimbekovna, Candidate of Biological Sciences, associate Professor, Faculty of Postgraduate Higher Medical Education, https://orcid.org/0000-0002-9652-1729, e-mail: rakhat_71@mail.ru

3. Mamykova Roza Ubaidyalayevna, Candidate of Biological Sciences, associate Professor., Faculty of Natural Sciences, https://orcid.org/0000-0002-0085-6744,
e-mail: roza.mamykova@mail.ru

4. Zhakipbekova Galiya Saparovna, Candidate of biological sciences, professor, https://orcid.org/0009-0008-1842-4561, e-mail: zhakipbekova.1974@mail.ru

5. Malitskaya Natalya Vladimirovna, Candidate of Agricultural Sciences, Associate Professor of the Department "Agronomy and forestry", e-mail: natali_gorec@mail.ru

6. Mukhtarov Abilkhas Kapizovich, Candidate of chemical sciences, associate professor, https://orcid.org/0000-0001-9020-2551, e-mail: Abilkhas@mail.ru