Mathematical Model of Long - Term Dynamics of Phytocenoses in the Eastern Part of the Dry Bottom of the Aral Sea

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1. Introduction

The Aral Sea crisis, along with global warming, planetary environmental pollution, deforestation and desertification, is one of the most significant environmental problems that threaten regional and global security.

Large-scale changes in the ecosphere of Central Asia, occurring as a result of the anthropogenic reduction in the flow of the Amudarya and Syrdarya, have been attracting the attention of the world community for over 60 years. The Aral Sea problem is a multitude of ecological and socio-economic destructive processes and the wind removal of toxic salts from the drained bottom stands out among them. This process has a number of negative forcings, such as provoking pathologies of the respiratory tract (up to oncological), soil salinization [1], degradation of vegetation [2], climate change [3]. The danger of salt removal is aggravated by its scale. Different researches, scientific and technical projects are being carried out to weaken this process. Large experimental works with phytomelioration prevalence are being held [4].

This work, carried out in this direction with the use of mathematical modeling, is aimed to identify the main patterns of the evolution of the phytocenosis of the dried bottom of the Aral Sea (DBA) and its survival. In the work the authors [5] presented the main conditions of modeling are stated and a model of the dynamics of phytocenoses for the western part of the DBA. This article is a continuation of this work, and presents the results of modeling the dynamics of phytocenoses for the eastern part of the DBA.

The scientific novelty of the research lies in the fact that the long-term dynamics and features of overgrowing of the eastern part of the DBA are first studied by the methods of mathematical modeling with a high degree of spatio-temporal aggregation.

2. Research Methods

Modeling the long-term dynamics of any natural process involves aggregation, simplification, alignment of data series and approximation of the mathematical expectation trajectory by analytical functions. In this case, the aggregation consists of the statistical averaging over decades and by plant species of such characteristics as projective cover and salt tolerance. The average aggregation error, in general, over the modeling period was 13% and 27%, respectively. The main simplification in modeling in this work is the assessment of the quantitative dynamics (total projective cover) of the phytocenosis without taking into account species differences. However, it should be noted that the proposed models can be implemented for individual species if there are representative data for these species.

The adequacy of the real dynamics of the total projective cover was validated by field research data and remote sensing data processed by the LpSquare program.

For the eastern part of the DBA, a system of regression models is used. It is obtained by approximating the results of systemic simulation of the long-term (1966-2005) dynamics of the water-salt regime of the Aral Sea, the salinity of the post-aquatic land and the total projective cover (TPC) of vegetation cover in working process [3]. The macro model presented in work [6] is essentially nonlinear, since it reflects the feedbacks existing between soil salinity, salt removal and vegetation cover. The factor of soil moisture enters into the equations implicitly and is taken into account in the numerical model of the salinity of the post-aquatic land. Since this macro model was used to solve other, multipurpose problems, we selected the approximated results of the implementation of only submodels of DBA salinity and salt removal to construct a model of phytocenoses of DBA.

Salt reserves in the surface layers (average level of root habitat) of the post-aquatic land are determined by the sum of three processes: 1) the transfer of salts from groundwater during evaporation, 2) the deposit of water-soluble salts during sea regression, and 3) the wind removal of salts:

$$S_{PS}(N) = S_{SDB}(N) + S_{SALT}(N) - 0{,}4[V(N)/S_{sol}(N)], \quad (1)$$

where N is the number of the decade in the modeling period, $S_{SDB} = 6.2547\exp(0.8499N)$ is the amount of salts remaining in the surface of soil horizon when the coastline recedes, S_{SALT} is the salts evaporating from groundwater, calculated using the formula and averaged over decades:

$$S_{SALT}(t,T) = A(t)T^4 + B(t)T^3 + C(t)T^2 + D(t)T + E(t), \quad (2)$$

where T = 1, 2, 3 ... is the drying time of the design point of the PS, t is the transformation (drying out) time of the Aral Sea.

With an average confidence score R^2 = 0.911, the following expressions for the coefficients of equation (1) are obtained:
$A(t)$=-0,00001, $B(t)$=0,00002t + 0,0007,
$C(t)$=-0,00069t - 0,01455, $D(t)$= 0,0116t + 0,0434,
$E(t)$=0,0419t + 0,094.

The dynamics of the phytocenosis at point *A*, depending on the drainage time *T* and the drying time of the Aral Sea *t*, as well as on soil salinity and wind transfer of salts, is expressed by the formula:

$$\delta_f(T, t) = -0.0002x^3+0.0334x^2-2.0651x+100 - C(N)/C_{cr} \quad (3)$$

where x = S_{PS}, $C(N) = 3{,}3kV$ is the average annual concentration of salts in the near-surface layer of the atmosphere (μg / m^3), *C* is the critical concentration of salts at which the plant dies.

3. Results and its Discussion

We will preface the presentation of the modeling results with a brief description of the dynamics of salinity in the eastern part of the DBA, as the main factor in the development of phytocenoses in this region.

One of the most important factors in the formation of unstable landscapes on the dried bottom is the geomorphology of the post-aquatic land of the Aral Sea. Salt marshes are formed by intensive evaporation of sufficiently moist soil in areas exposed to the sun, i.e. positive landforms. The leading factor in this process is the proximity of highly mineralized groundwater.

The coastal line is characterized by groundwater depths of up to 0.5 meters. In the immediate vicinity of the coastline, the groundwater level merges with the surface of the day. The water-soluble salts carried away by the capillary current form here, on the surface, a moist crust with a salt content of up to 15%. With a minimum salinity of 4%, the salt reserves in the evaporite horizon and the subcrustal layer are 25-30 t / ha, and with the maximum salinity (27%), the salt reserves reach 200 t / ha [3].

Crusty and crusty-plump salt marshes, thenardite fluff, which is one of the main sources of salt storms in the Aral Sea region, are characteristics of semi-automorphic salt marshes [4]. Along the eastern coast, malignant, silty, crusty-plump salt marshes are developed. Due to the sulfate-chloride-sodium type of salinity, soil warming in the spring-summer season causes the formation of a 1-2 cm layer of thenardite-clay powder. By the period of autumn precipitation, formed during the summer period, the powder is almost completely carried away by the wind from the surface, but then self-regenerates [7, 8]. Such an intermittent regime of soric salt marshes makes them the most powerful source of salt and dust flow.

On gently sloping, smoothed sections of the sea coast, surge waves form marching salt marshes. In 1968-1977, as a result of the washout regime, the formation of salt crusts was not observed here, but with an increase in water salinity in the next decade of the modeling period, salt crusts became ubiquitous (Fig. 1A). The deflationary-accumulative relief of the post-aquatic land was characterized by mobile or weakly fixed hilly-dune sands up to four meters high, on which xerophytic vegetation was dispersed [9] (Fig. 1B).

Figure 1: Post-aquatic land of DBA
A) salt crust in 1 year of drainage in 1978-1986; B) sandy relief for 15 years drainage in 1978-1986; C) coastal drainage in 2008-2017; D) almost complete absence (TPC less than 0.1%) of vegetation cover in 2012.

The water-salt regime of the Eastern basin of the Aral Sea, starting from the first incident of drying in 2009, acquired an oscillatory character. The water area irregularly either decreases or increases in accordance with the interannual dynamics of river flow. It is known that the alternation of drying and moistening intensifies the processes of capillary rise of salts to the surface. Thus, the process of salt accumulation on the soil surface intensifies, which provokes an increase in the danger of the wind carry-over of salts.

The first settler on the drained line is *Salicornia*. At 60–80 meters from the water's edge, the amount of *salicornia* sharply increases and sea blide appears (*Suaeda: S. prostrata S. microphylla*). Reed appears as single spots on the border of the community of hydromorphic solonchaks with semi-hydromorphic ones. As the sea recedes and the groundwater level decreases, the conditions for salicornia worsen, since the maximum of salts due to the effusion regime shifts to the upper horizons of deposits. The saltwort community is dying out. On sediments of clay and loamy texture, vegetation is practically not renewed. Vegetation appears after the surface is covered with a layer of sand as a result of aeolian movement of the sand mass. The vegetation of the eastern part of the DBA is represented by a number of halophytes, such as: *Atriplex dimirphostegia*, *Salicornia europea*, *Salsola micranthera*, *Suaeda*, *Tamarix hispida*, *T. laxa*, *T. Pentadra*, etc.

Sand dunes serve as a transition to landscapes with more abundant vegetation, where *Halaxylon persicum*, *Halaxylon aphullum*, *Salsola arbuscula*, *Salsola richteri*, *Artemisia santolina*, *Artemisia diffusa*, *Artemisia terrealbae*, *Ceratocarpus arenarius*, *Carex physodes* and others. The dunes are interspersed with pits, which are saline blinders with a crust-saline covering, in which the following species are recorded: *Halaxylon aphullum*, *Tamarix elongata*, *Tamarix laxa*, *Halostfachys belungeriana*, *Salicornia europea*, *Suaeda salsa*, etc.

In addition to the salinity of the soil, a significant factor in the deterioration of the state of the vegetation cover is the wind removal of salts from DBA. The effect of this factor is manifested in the fact that salt particles precipitated during dust storms penetrate into the stomata of leaves and partially clog them, as well as excise and damage the entire supra-root part of plants. At present, during the growing season, on average, 250 kg / ha of salts fall out. At the same time, the decrease in TPC (total projective cover) reaches 20-30% [3, 5].

In order to demonstrate the significant contribution of the factor of wind-induced salt carryover, this article presents two variants of calculations using model (1) - (3):

1) On the assumption that the only factor in the dynamics of phytocenosis is soil salinity (Table 1);
2) Taking into account the effect of the wind carry-over of salts on the degradation of the vegetation cover by impulse stimulation of the plant root with salt particles and an increase in soil salinity during the infiltration of salt particles with precipitation (Table 2).

In the Tables 1 and 2, the first column indicates the numbers of the decades into which the modeling period is divided: $N = 1$ corresponds to the drying zone 1968-1977, $N = 2$ - 1978-1987 etc. Further, in pairs, the soil salinity (g / kg) in the T-th year of drainage and the corresponding projective cover (%) for each of the decades are given.

Table 1: Spatio-temporal dynamics of the TPP of the phytocenosis of the eastern part of the DBA (%) depending on soil salinity (g / kg)

N	T=1		T=5		T=10		T=20	
	$S_{PS}(N)$	$\delta_f(T, t)$	$S_{PS}(N)$	$\delta_f(T, t)$	$S_{PS}(N)$	$\delta_f(T, t)$	$S_{PS}(N)$	$\delta_f(T, t)$
1	14,32	76,7	10,51	81,7	6,77	87,5	0,73	98,5
2	33,34	60,9	28,96	63,3	24,95	66,2	16,11	74,6
3	76,90	47,8	69,00	50,8	65,03	52,0	55,72	54,0
4	166,01	11,1	158,60	13,2	155,00	14,9	146,77	16,3
5	372,32	0	364,09	0,2	360,54	0,5	351,84	0,9

Table 2: Dynamics of the phytocenosis of the phytocenosis of the phytocenosis of the eastern part of the DBA (%) depending on soil salinity (g / kg) and wind carry-over of salts

N	T=1		T=5		T=10		T=20	
	$S_{PS}(N)$	$\delta_f(T, t)$	$S_{PS}(N)$	$\delta_f(T, t)$	$S_{PS}(N)$	$\delta_f(T, t)$	$S_{PS}(N)$	$\delta_f(T, t)$
1	14,33	67,3	7,61	76,8	6,77	78,1	0,73	89,2
2	33,34	42,6	26,19	47,0	24,95	47,9	18,41	53,8
3	76,90	19,7	66,37	23,5	65,03	23,9	57,90	25,5
4	166,01	8,6	156,10	11,8	155,00	11,3	148,84	12,8
5	372,32	0	361,72	0	360,54	0	353,79	0

Comparative analysis with the data of field studies [8, 9, 10, 11] of the modeling results for both options showed a greater adequacy of the second option and, consequently, the importance of the factor of the wind removal of salts (tables 3 and 4). We also note that the field data is extremely insufficient.

Table 3: Comparative analysis of the dynamics of phytocenosis in the eastern part of DBA plots (%) depending on soil salinity (g / kg) based on field studies and modeling results

N	T=1			T=5			T=10		
	$H\delta_f(t)$	$P\delta_f(t)$	k	$H\delta_f(t)$	$P\delta_f(t)$	k	$H\delta_f(t)$	$P\delta_f(t)$	k
1	-	76,7	-	72	81,7	9,7	88	87,5	-0,5
2	48	60,9	12,9	58	63,3	5,3	42	66,2	24,2
3	33	47,8	14,8	42	50,8	8,8	38	52,0	14
4	-	11,1	-	5	13,2	8,2	9	14,9	5,9
5	-	0	-	-	0,2	-	0	0,5	-

Note: $H\delta_f(t)$ - field data, $P\delta_f(t)$ - calculated data, k-residual

Table 4: Comparative analysis of the dynamics of phytocenosis in the eastern part of DBA plots (%) depending on soil salinity (g / kg) and wind carry-over of salts based on field studies and modeling results

N	T=1			T=5			T=10		
	$H\delta_f(t)$	$P\delta_f(t)$	k	$H\delta_f(t)$	$P\delta_f(t)$	k	$H\delta_f(t)$	$P\delta_f(t)$	k
1	-	67,3	4,3	72	76,8	4,8	88	78,1	-9,9
2	48	42,6	-5,4	58	47,0	-11	42	47,9	5,9
3	33	19,7	-13,3	42	23,5	-18,5	38	23,9	-14,1
4	-	8,6	-	5	11,8	6,8	9	11,3	2,3
5	-	0	-	-	0	-	0	0	-

Note: $H\delta_f(t)$ - field data, $P\delta_f(t)$ - calculated data, k-residual

In the first variant of calculations, the average discrepancy indicator for the entire observation period was k = 10.6,

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while in the second variant of calculations this coefficient turned out to be small and amounted to k = -4.3.

Note that the data of field studies were obtained on very different and a small number of individual sections of the DBA, which have their own specific features of the level of soil salinity, climatic conditions, amount of precipitation, soil moisture content, etc. Therefore, the model values of TPC obtained in accordance with the purpose of the study with a high degree of aggregation may differ from the data of field studies.

In general, the average error of the model is about 13.8%, which makes it possible to judge about a satisfactory imitation of physical reality in natural processes and substantiates the adequacy of the revealed patterns of dynamics of the phytocenosis of the eastern part of the DBA.

In addition to the regularities of the dynamics of soil salinity (Eq. (2)) established in analytical expression, the dynamics of the TPC of phytocenoses in the eastern part of the DBA in terms of drainage time for dryings of different years was revealed:

$$\delta_f(t_1) = -20{,}99n + 101{,}6$$
$$\delta_f(t_5) = y = -1{,}0214n^2 - 15{,}181n + 98{,}62$$
$$\delta_f(t_{10}) = y = -22{,}53n + 111{,}81$$

Note that for the periods of 1 and 10 years of drying, a linear trend was revealed towards a sharp decrease in the dynamics of TPC, for periods of 5-year drying, a polynomial trend was revealed towards a decrease in the dynamics of TPC of phytocenoses in the eastern part of the DBA.

4. Conclusions

1) The order parameters of the ecosystem in the eastern part of the DBA are soil salinity, geomorphology, and wind regime. These parameters serve as the main factors of the spatio-temporal distribution of the vegetation cover, taking into account that the wind regime determines the scale of the wind carry-over of salts, which affects the state of plants.
2) For each decade of the modeling period, the dynamics of phytocenoses is positive; with an increase in the drying time, there is an increase in the TPC
3) The differences between field and model data on TPC can be explained by the fact that the model does not take into account adaptation processes, as a result of which, during successions, halophytes become dominant species, the projective cover of which on saline soils significantly differs from TPC.
4) The regularity of the dynamics of the formation of vegetation in the eastern part of the DBA is manifested in the fact that with an increase in soil salinity for the entire period under consideration (1968-2017), there is a decrease in the TPC of phytocenoses in this area at an increasing rate.

References

[1] Mukasheva B.G. Influence of climate on the health status of the population of the Aral Sea region // Occupational hygiene and medical ecology.- 2015.- No. 4 (49) .- P.20-27.
[2] Chumachenko S.I., Palenova M.M., Pochinkov S.V., Kukharkina E.V. Simulation modeling of the dynamics of plantations FORRUS-S - a tool for choosing a strategy and planning for forestry // Lesnoy Vestnik.- 2007.- No. 5.- P.143-152.
[3] Tleumuratova B.S. Mathematical modeling of the impact of ecosystem transformations in the Southern Aral Sea region on soil and climatic conditions // Diss. … Dr. Phys.-Math. sciences. - Tashkent, 2018. –209 p.
[4] Kurbaniyazov A.K. Evolution of dry bottom landscapes Aral Sea. - Moscow. - 2017. - 148 p.
[5] Tleumuratova B.S., Kublanov J.J., Kochkarova S.A., Mambetullaeva S.M. Modeling of the Processes of Formation and Development of Phytocenoses of the Dried Bottom of the Aral Sea // International Journal of Science and Research (IJSR) .- 2020.- Volume 9.- Issue 10.- P.1066-1071.- www.ijsr.net.
[6] Plyatsuk L. D., Chernysh E.Yu. Synergetics: nonlinear processes in ecology / Sumy: SSU publishing house, 2016.- 237 p.
[7] Goryshina T.K. Plant ecology: Textbook. allowance.- M.: Higher School. - 1979. - 368 p.
[8] Dimeeva L.A. Regularities of the primary successions of the Aral coast // Arid ecosystems. Sectoral problems of the development of dry lands.- 2007.- T.13.- No. 33-34.- P. 89-100.
[9] Battalova G.S. Assessment of anthropogenic disturbances of vegetation in the eastern Aral Sea region. - Almaty. - 1993. - 28 p.
[10] Vukhrer V. Primary overgrowing of the drying up coast of the Aral Sea // Problems of the development of deserts.- 1979.- No. 2.- Part 1.- P.66-69.
[11] Dimeeva L.A. Primary successions of the Aral and Caspian coastal plains // Development of geobotany: history and modernity: material of Russian Conference. Saint-Petersburg. - 2011.- P. 40.