Journal of Positive School Psychology
2022, Vol.6, No.4, 1630-1638

http://journalppw.com

Modeling of the Long-Term System Dynamics of Salt Removal of Wind and Plant Cover on the Dry Bottom of The Aral Sea

B.S.Tleumuratova[1], Zh.Zh.Kublanov[1], S.M.Mambetullaeva[3]

[1,2,3]Karakalpak Scientific Research Institute of Natural Sciences of Karakalpak Branch of the Academy of Sciences of Uzbekistan, Uzbekistan, 230100, Nukus, Berdakh Avenue, 41

E-mail: tbibigul@mail.ru, kublanov90@list.ru, svetmamb@mail.ru

Abstract

The article involves the results of the study by methods of mathematical modeling of the interactive dynamics of the wind removal of salts and vegetation cover at the drained day of the Aral Sea in the period 1968-2017. A quantitative assessment of the reduction of the overall projective coating of vegetation was given under the influence of a sulphate salt aerosol during dust storms. Quantitatively estimated the reverse negative bond, which consists in the fact that the vegetation cover depending on its density reduces the wind speed and thereby the power of the removal of salts.

In the model representation, the system dynamics of the wind removal of salts and vegetation cove SR depends except the specified nonlinear relationship from the dynamics of the land and the increasing total salt marshes land. Therefore, the patterns of saline on the dried day and the dynamics of the foci of the wind removal of salts are traced separately.

The modulation results indicate the directional dynamics of the degradation of the ecosystem of the drained bottom of the Aral Sea, which can be classified as an atypical desertification due to the specificity of the factor of the large-scale wind removal of salts.

Keywords: Aral Sea, dried bottom, wind removal of salts, vegetation cover, long-term dynamics, mathematical model, approximation.

1. INTRODUCTION

The Aral Sea problem is a set of environmental and socio-economic destructive processes, among which the wind removal of toxic salts from the drained bottom stands out, since it has a number of such negative forcing as provoking respiratory pathologies [9], soil salinization, degradation of vegetation cover, climate change [11]. Its scale exacerbates the danger of salt removal: the visible part of the plume occupies hundreds of thousands of square meters' kilometers in plan and several km in height. In this regard, it seems very relevant to study the vegetation cover, which is currently the only measure to weaken this process. The actuality of the theme of overgrowing the dried bottom of the Aral Sea (DBA) is evidenced by many studies carried out on phytocenoses and phytomelioration of the DBA [8, 4, 5, 6, 7]. For the time being, such aspects of the interaction of vegetation cover (VC) and wind removal of salts (SR) as the aerodynamics of forest plantations, the effect of SR on plants, MPC of salt aerosol during pulverization for various plant species, quantitative assessment of the effectiveness of PC as protection against SR. These uncertainties cause the lack of scientific substantiation of scientific and technical projects and experimental work carried out on the afforestation of the DBA.

In addition to the salinity of soil grunt, a significant factor in the deterioration of the state of the vegetation cover is the wind removal of salts. The effect of this factor is manifested in the fact that salt particles deposited during dust storms penetrate into the stomata of the leaves and partially clog them, as well as excise and damage the entire root part of the plants. This impact is a direct connection of the "SR→PC". The "PC→SR" feedback is that the vegetation cover, depending on its density, reduces the wind speed [2] and, thus, the dust emission power of the underlying surface.

The purpose of this study is to prove the significance of these nonlinear relationships "SR↔PC" and to identify by mathematical modeling the regularities of the system dynamics of the removal of salts and vegetation on the dried bottom of the Aral Sea in the period 1968-2017.

The study of the long-term dynamics of any natural process involves aggregation, simplification, alignment of actual data series, approximation, etc. It should be noted that the high degree of aggregation is also due to the lack of spatial representativeness of the factual data on DBA and the weak structuring of the Aral Sea problem as a whole.

When developing a mathematical model of the systemic dynamics of the removal of salts and vegetation on the dried bottom of the Aral Sea, taking into account their interactions (hereinafter, for brevity, referred to as the "SR↔PC" model), we used the results of our modeling of the dynamics of salinity of the DBA [11], wind removal salts [12], long-term dynamics of phytocenoses of DBA depending on soil salinity and SR [20].

An aggregated quantitative assessment of the systemic dynamics of SR and PC on DBA was obtained for the first time. The results of the study give a new, quantitative expression of the patterns of development of the relationships between the biotic and inert components of the geosystem of the Aral Sea and the dried bottom.

The scientific significance of this study lies in clarifying the mechanism of self-organization of draining salty water bodies of the planet, such as the Great Salt Lake (USA), Lake Poopo (Bolivia), Lake Eyre (Australia), Lake Urmia (Iran), etc.

The practical significance of the work lies in the fact that the results obtained, providing the choice of the optimal variant, should be an important part of the scientific substantiation of projects on phytomelioration of the DBA.

2. CONDITIONS AND METHODS OF RESEARCH.

The need for synchronization and spatial alignment of the processes of sea drying, salt accumulation and overgrowing of SA, as well as their interactions, determines the use of mathematical modeling as a powerful tool for processing large data sets.

The territory of the dried bottom of the Aral Sea has significant lithological and orographic heterogeneity. Therefore, the entire post-aqueous land is divided in the model representation into the western (causal beaches) and eastern (the rest of the territory of the BDA) parts.

In addition, the BDA areas adjacent to the Kokaral dam, forest plantations and partially regulated reservoirs of Muynak, Rybatsky and Zhyltyrbas fall out of the modeling area, as they have the specifics of anthropogenically formed ecosystems.

Due to differences in the slope of the western ($\approx 15^{o}$) and eastern ($<10^{o}$) parts of the BDA, the processes of salinization/desalinization of soils in the SR↔PC model are formalized by different time functions, but at the same time, the calculation scheme for both parts of the BDA is the same, as well as quantization in time and space.

Modeling period - 1968-2017 years - divided into decades, as this is the minimum time for significant natural transformations. Decades are numbered chronologically: N=1 for 1968-1977, N=2 for 1978-1987. etc. In addition, the time is identified as the dehumidification time of the calculated point of the BDA (T=1, 2, 3…), i.e. the number of years that have elapsed since this point came to the day surface and how the drying time of the Aral Sea (t), counted in years since 1961.

Spatial quantization corresponds to the division of the modeling period into decades: the drained bottom is divided into drainage bands in 1968-1977, 1978-1987. etc. At the same time, it is assumed that the processes of salinization/desalinization and overgrowing develop along the normal to the coastline of the corresponding year and are identical along the entire length of the drainage strip.

The SR is identified when assessing the relationship "SR→PC" by the near-surface average annual concentration of salt aerosol, and when estimating the feedback "PC→SR" - the power of salt removal sources from the underlying surface.

Identification of PC only by the common projective cover (CPP) without species differences requires a more detailed justification. The results of numerical experiments on the sensitivity of models of the impact of PC on the environment to such parameters as projective cover, transpiration and leaf area index [11] showed that the dominant (70-90%% of the contribution to a particular environmental impact) is CPP without species differences. A sufficiently large sample (180 cases with different plants) substantiates the validity of the choice of CPP as a quantitative characteristic of the plant layer. This conclusion is also confirmed by similar model studies of PC without species differences [16; 21; 18].

The mathematical model "SR↔PC" consists of 4 blocks. The first two blocks contain regression equations describing the BDA salinity dynamics and SR dynamics, respectively. In the third block, the PC dynamics is calculated under the condition that the only factor is soil salinity. The fourth block serves to describe the actual systemic dynamics of the SR and PC using the results of blocks 1-3.

Most of the relationships in the "SR↔PC model were obtained by approximating the results of the implementation of the models [11]:

1) BDA salinity, described by the quasi-linear parabolic equation of vertical brine transport [1], as well as by the equations of horizontal and vertical infiltration (Hanks and Ashcroft, 1985; Hillel, 1971);

2) salt removal (the equation of turbulent diffusion and atmospheric physics);

3) PC interaction with the environment (energy balance model).

1 block. Formalization of the BDA salinity dynamics, as the main factor in the dynamics of both SR and PC, is carried out at the first stage of research. The average annual salt accumulation during the drying of the N th decade in the surface layers of the eastern part of the post-aquatic land is determined by the sum of three processes: 1) the transfer of salts from groundwater during evaporation, 2) the deposit of water-soluble salts during the regression of the sea, and 3) the wind removal of salts:

$$S_{sg}(N)=S_{sdb}(N)+S_{salt}(N)-0{,}4[V(N)/S_{salt}(N)] \quad (1)$$

Where $S_{sg}(N)$ – soil salinity (g/kg), N – decade number in the simulation period, S_{sdb} – the amount of salts remaining in the surface soil horizon when the coastline recedes, S_{salt}– salts evaporating from groundwater, $V(N)$ – average annual removal of salts from the entire drying, $S_{salt}(N)$ – total area of sources of SR.

On the right side of equation (1), the first two terms are calculated by the formulas [11]:

$$S_{SDB}(N) = 0{,}5 C_d h_d \cos a \quad (2)$$

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

where C_d– salinity of the Aral Sea water in the reference year, h_d – average decadal drop in sea level, α_i – dry bottom slope, T=1, 2, 3… – dehumidification time of the calculated point BDA, t – drying time of the Aral Sea in years counted from 1961.

With an average confidence level R^2= 0,911, the following expressions for the coefficients of equation (3) were 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 formalization of the third term of equation (1) is given in the description of the second block of the "SR↔PC" model.

For the western part of the BDA, the dependence of soil salinity on the drying time T is expressed by the function:

$$S_{sg}(N)=(0{,}1943N^2-2{,}1103N+1{,}916)T-3{,}4286N^2+48{,}229N-35{,}6 \quad (4)$$

where $S_{sg}(N)$ – soil salinity (g/kg), T – drying time.

2 block. The basic characteristic of the SR is the capacity of the source of salt removal Q(g/s/m2), calculated by the following formula (Hua Lu, Yaping Shao, 2001):

$$Q=\frac{0{,}12C_H g}{\rho_s p}Q' ,$$

$$Q'=\frac{c\rho u_*^3}{g}\left[1-\left(\frac{u_{*кр}}{u_*}\right)^2\right] \quad (5)$$

Where Q' - impurity consumption, ρ - air density, ρ_s– particle density, p – deformation pressure exerted by the soil surface on aerosol particles moving along it (3.4x10^5n/m^2), g– gravitational constant, u_* – dynamic friction speed, c=0.25+0.33w_g/ u_*□ Owen coefficient (Owen, 1964), d – particle diameter, u_{*cr} – critical friction speed, C_g ground concentration of salts [11],w_g – speed of gravitational settling of particles (2cm/s).

The stream of salts emitting with BDA contains mainly sulfates [13], the average density and particle diameter of which are 1.8 g/cm3 and 30 µm, respectively.

At high wind speeds, there is a simple dependence of the friction velocity u* on the average wind speed u_2 at the anemometer level [10]:

$$(u_* - u_{*c})=0{,}04(u_2 - u_{2c}), \quad (6)$$

where u*c =45 cm/s, u_{2c}=1000 cm/s are the critical values at which intensive soil dusting begins.

To quantitatively express salt removal per year per unit area under a given wind regime, the work [11] introduced the concept of salt removal potential (SRP), which is determined by the product of the source power Q and the duration of energy-active wind speeds, the range of which is (5-30 m/s) is divided into 5 gradations:

$$P_B=\sum_{i=1}^{4} f_i Q_i U_i \quad (7)$$

f_i is the frequency of gradation in the reference year, Q is the average power of the source for this gradation. Multiplying the SRP by the total area of solonchaks S_{sol} in the corresponding year, we obtain the annual volume of salt removal from the entire drying of the N-th and previous decades:

$$V= P_в S_{sol} \quad (8)$$

The area of solonchaks S_{sol} is calculated from the ratio [11]:

$$S_{sol}(N)=0{,}0042(S_{oc})^2+0{,}073S_{oc} \quad (9)$$

where S_{os} (N) is the total area of the bottom dried in the N-th and previous decades.

The dynamics of the near-surface average annual concentration of salt aerosol depending on the SR in the N th decade was approximated in [11] by the relation

$$C(N)=kV(N) \quad (10)$$

for the western part of the BDA k=2,1·10^{-6}м$^{-3}$, for the eastern part k=7,6·10^{-6} м$^{-3}$.

3 block. The dependence of PC dynamics on BDA salinity is considered to be invariant for the entire BDA and is expressed courtesy of Prof. P.O. Zavyalov regression equation obtained on the basis of data from expeditions of the Institute of Oceanology named after P.P. Shirshov of the Russian Academy of Sciences to the Aral Sea:

□□□□□□□□□□$\delta_f(T,t) = -0{,}0002x^3+0{,}0334x^2-2{,}0651x+100$ (11)

where $x=S_{SA}$,$\delta_f(T,t)$ – general projective cover.

4 block. The influence of SR on PC, despite the relevance of the issue, remains poorly understood. Therefore, the influence of “VS→RP” in the first approximation is estimated by the ratio:

$$\Delta\delta = C(N)/C_{кр} \quad (12)$$

where C(N) is calculated by formula (10), C_{cr} is the average annual MAC, determined by us approximately, by analogy with the known MACs of other pollutants, as 1500 µg/m3.

The impact of “PC→SR” is determined by a decrease in ΔQ, due to a decrease in wind speed in the vegetation layer. To calculate the degree of wind attenuation by the vegetation cover, the following formula is used [2]:

$$u_r = 0{,}83\delta_f c_{Hh}^{0,5} u_a + (1-\delta_f)u_a \quad (13)$$

here u_a is the background wind speed, c_{Hh} is the heat transfer coefficient at the upper boundary of the vegetation layer - 0.023 W/m.K.

Calculating $\Delta Q = Q(u_a) - Q(u_r)$ and substituting into formulas (7) and (8), we obtain the desired decrease in ΔV by the plant layer.

Thus, the system dynamics of SR and PC, taking into account their interactions, is expressed by the equations:

$$\delta_f(T,t)= -0{,}0002x^3+0{,}0334x^2-2{,}0651x+100-\Delta\delta \quad (14)$$

$$V(N)= P_в S_{sol} - \Delta V \quad (15)$$

whose parameters are calculated from relations (1)-(13).

Since the SR→PC model does not contain differential and integral equations, the MS Excel environment (macros) turned out to be sufficient for the implementation of the model.

Validation of the simulation results was carried out according to the available actual data on the EPC, spatial (area) comparison of the model and real data was carried out by processing satellite images using the Lp Square program.

3. RESEARCH RESULTS

Since the causal beaches (the western part of the BDA) make up a small part of the entire dry land and due to the limit on the size of the article, the results of the study are presented below only for the eastern part.

The significance of the factor of wind salt removal for the PC dynamics is proved by performing calculations for two options: without taking into account the effect of salt removal on the PC and taking into account the SR. Comparison of the modeling results **δ_2 and δ_1**, respectively) with the data of field studies showed that taking into account the dynamics of phytocenosis of wind removal of salts in the models reduces the average relative error of calculations for the eastern part of the BDA from 22.9 to 5.4% (Table).

Table 1
The results of modeling the dynamics of PC without taking into account the aircraft (δ_1) and taking into account SR (δ_2) for the eastern part of the BDA

	1968-1977 years	1978-1987 years	1988-1997 years	1998-2007 years	2008-2017 years
δ_1	61.1	51.6	36.3	6.4	0
δ_2	59.4	48.9	32.8	1.5	0
f.d.	58.1[1]	50.2[2]	34[3]	1.9[4]	0[2]
n_1	-3.0	-1.4	-2.3	-4.5	0
n_2	-1.3	0.4	1.2	0.4	0

Note: 1-Kabulov, 1990; 2,5-Kuzmina, Treshkin, 2011; 3-Dimeeva, 2011; 4-Shomuradov, Adilov, 2019, n_1=F-δ_1, n_2=F-δ_2 – residuals.

Increasing the accuracy of the model in this way depends on the degree of influence of the VS on the RP. The dynamics of the "PC→SR" and "SR→PC" relationships, interpreted as a percentage decrease in the object of influence, is presented graphically in Fig. 1.

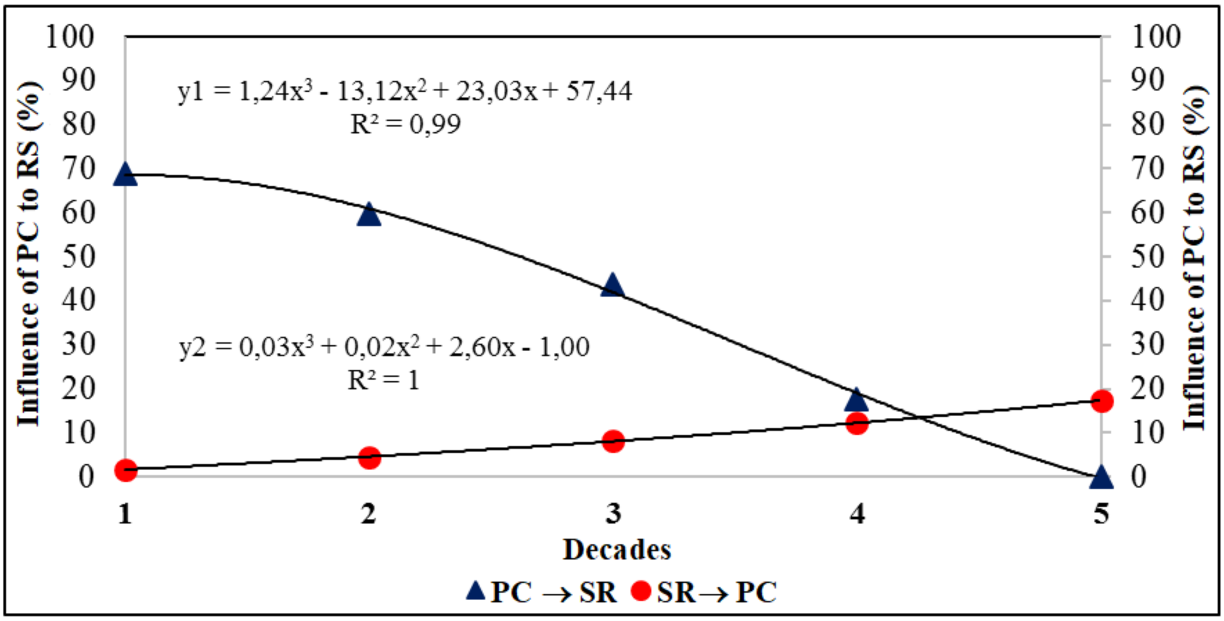

Fig.1. The dynamics of the "PC → SR" and "SR→ PC" connections for the eastern part of the BDA

As we can see, the dynamics of the interactions of SR and PC is given out by the regularities of a monotonous exponential decrease in "PC→SR" and an almost linear increase in "SR→PC". The long-term system dynamics of PC and SR is a homomorphic reflection of this regularity
(Fig. 2). The graph clearly shows that the MAC, averaged over the entire drainage band, falls from 60% in the first decade of the simulation period (1968-1977) to zero in the last decade (2008-2017). Wind removal of salts from the entire drying, on the contrary, increases from 4 to 56 million tons/year. The negative dynamics of the vegetation cover MAC and the positive dynamics of the SR are in themselves clear

indicators of the degradation of the “Aral-Drained Bottom” geosystem. The predominance of the direct impact of “SR→PC” over the reverse one reinforces the existing imbalance in the structure of the geosystem, leading to its accelerating degradation, which can be classified as atypical desertification, inherent only in drying up salt-water bodies with similar climatic conditions.

The simulation results significantly refine the structure of the factors of formation of phytocenoses on the dried bottom of the Aral Sea, quantitatively expressing the relationship between the main factor - the growing salinity of soils - and its consequences, such as wind removal of salts and degradation of vegetation.

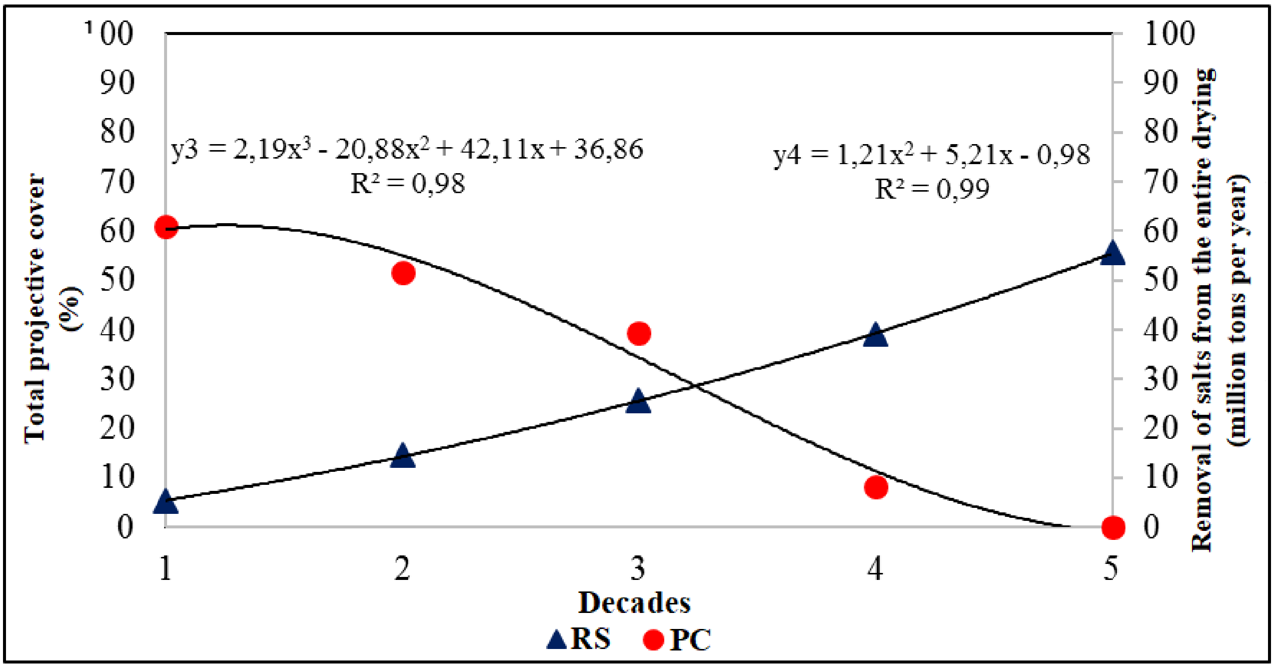

Fig.2. System multi-year Dynamics of PC and SR for the eastern part of BDA

4. CONCLUSION

As we have seen, wind removal of salts plays an important role in the dynamics of BDA phytocenoses, significantly damaging the root part of plants during salt dust storms and increasing soil salinity during precipitation. Salt resurfacing during dust storms contributes to an increase in salinity and old drying, which slows down the processes of desalinization and overgrowing.

The magnitude of the wind salt removal and its effect on plants, as well as the need to take into account the interactions of SR and PC during the afforestation of BDA was analyzed. To determine the relevance of studying the physiological mechanisms of the effect of salt aerosol on plants, as well as the need to organize regional monitoring of vegetation cover and atmospheric pollution by wind removal of salts were defined.

The effectiveness of the use of mathematical modeling in environmental studies is especially evident in the derivation of patterns of development of natural processes and their presentation in a formalized form. Given that the regularities of dynamics are necessary in forecasting and believing that the history of the Aral Sea crisis should be presented not only verbally, but also formally, using quantitative methods, we conducted this study.

Thanks. The authors express their deep gratitude to Prof. P.O. Zavyalov (deputy director of the Institute of Oceanology named after P.P. Shirshov, Russian Academy of Sciences) for providing the regression equation for the formation of vegetation cover dynamics on the BDA.

Financing. The study was carried out within the framework of the topic of the State task of Uzbekistan under the project “Research by methods of mathematical modeling of the dynamics of environmental and climatological processes in the South Prearal”.

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