The control model of arid plant communities

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Abstract. The paper is devoted to simulation modelling of the arid plant communities (APC) behaviour. Such systems belong to the class of agro ecological systems and include a large number of interacting natural factors that contribute to the system’s degradation. We propose a model of APC behaviour based on a weighted oriented graph. The values of weights and other coefficients reflecting the exposure of factors and their mutual relationship are acquired by expert assessments. The proposed model allows predicting the behaviour of APC in response to various biogenic control actions.

1. Introduction

Plant communities are open biological systems, which are extremely complex. Control of such systems is complicated by difficulties in selection of proper control actions and in forecasting their results [1, 2].

Arid plant communities (APC) have some specific features. In particular, they have limited restoration abilities and a lot of natural destabilizing factors. Human activity changed the plants at the arid agriculture zone. It now consists of agrosystems and androgenous transformed APCs with violated natural ground relief, vegetation, and soil quality [3]. Such APCs have reduced species compositions, affect adjacent agroecosystems, and contribute to the violation of consort connections in them. Their areas form specific microrelief that changes the watering and transfers the pollutants, which are accumulating in the “Soil – Plant” subsystem [4].

The interpretation of heterogeneous data acquired by comparing the information about the ecosystem and its environmental conditions is quite difficult. One of the prospective ways to research such systems is the scenario approach. It helps to predict the behaviour of complex systems with heterogeneous, incomplete, and partially distorted data, as is often found in systems with a high human factor weight [5].

Let us note that the obtained research data, as expected, were insufficient for building the reliable quantitative dynamic forecast of the APC’s impact on the adjacent agroecosystem. However, we were able to predict the direction of this influence and to compare the system dynamics under different initial conditions.

The study proposes the control model of APC which can predict the result of various control action combinations. To achieve this, we use the apparatus of weighted directed graphs [6] with elements of
scenario analysis of complex systems behaviour [7, 8]. The ranking of the strength of action of individual groups of control factors was obtained by the method of expert assessments.

2. Arid plant communities as a research subject

The data used in this study are the summarized results of numerous studies in the arid zone. In particular, a detailed study of APC in the Southern Federal District in 2017-2019 was performed by one of the co-authors [9, 10]. This study allowed us to make the necessary generalizations regarding APC’s internal structure, relationships, and impact on adjacent agroecosystems.

The common characteristics of any plant community are the stability of its territory, biodiversity, the structure of dominant/subdominant plant species, and the community’s average projective cover. These characteristics are compared with the landscape, geomorphological data, and characteristics of the soil. Some characteristics could be determined using high-precision video recordings and hyperspectral sensing with drones, airplanes, and space probes [11; 12; 13].

Arid plant communities show comparative species poverty, but often differ from each other in the species composition and presence of invasive ones. These differences are usually explained by the stochastic nature of species distribution in the technologically disturbed territories. The distribution of plants largely depends on the anthropogenic factor – seeds migrate with equipment, transport, and clothing of field workers. In this regard, annual and biennial anemochores and zoochores with abundant small seeds, often having special adaptations-hooks, spikes, and a sticky, slimy shell, gain a great advantage [14, 15, 16, 17].

As a result, a typical arid APC has from 8-10 to 65 species of higher vascular plants, about 20 species of which could be dominants or subdominants on their own tier or in a specific vegetative phase. Among the dominant species of APC are _Artemisia absinthium_, _Artemisia lerchiana_, and _Lactuca tatarica_; the composition of subdominants also varies widely: _Crepis teutorum_, _Descurainia sophia_, _Elytrigia repens_, _Euphórbia seguieriana_, _Euphórbia helioscopia_, _Tripleurospérmum inodórum_, and _Xanthium albinum_. The general trend of plant interaction in APCs is forming the stable community “core” consisting of productive perennial plants adapted to the conditions of the southern dry steppe. The interaction of dominants and subdominants within such “core” produces typical structures in which the material and energy balance is based on their competition [4; 18].

The actual problem in agroecology is to assess and forecast the APC’s impact on adjacent agricultural systems. Such assessments are made by comparing the morphological and phenological indicators of the cultivated crop and the prevailing weeds in the area immediately adjacent to APC (APC shadow) and at a distance of at least 50 m from it deep into the field. The quantitative indicators of APC’s impact on agroecosystem are differences of the average height of plants and of their density in these areas, expressed as a percentage.

According to our observations, APCs with a significant impact on the adjacent agroecosystem have relatively higher variability in tiering, greater projective coverage, and more diversity of species. These APCs also have relatively high NDVI (Normalized Difference Vegetation Index) values (see Fig. 1, solid line). Their negative impact on the field is noticeable at a depth of at
least 40-50 m from the border of the APC. Similar plant communities with weak influence on the adjacent agroecosystem show opposite properties (see Fig. 1, dotted line) [10].

The most important factors (or consorts) that are considered when analysing the dynamics of APC we should identify and consider in the subsequent modeling are the following: 1) climate trends and the level of insolation [19, 20]; 2) water supply and salt concentration in the soil [21, 22]; 3) the content of key nutrients and toxic agents (including metals) in the soil, the status of the soil microbiota [23, 24, 25, 26]; and 4) the degree of external aggression of phytophages and invasive plants [27, 28, 29].

3. Materials and methods

The earlier study [30] proposed the control model of APCs directly adjacent to agroecosystems. It made possible to find an economically optimal solution to support the agrocenosis, which consists in the combined introduction of mobile forms of microelements and microbiota subdominants into the soil. The natural way to evolve the model is to generalize it from this particular case (phytocenosis in technogenic intrusion) to APC as a whole.

The main goal of the study is to develop a simulation model of APC behaviour based on expert assessments of comparative severity and mutual influence of both biotic and abiotic factors. Such model will allow predicting the direction of APC development under various control actions.

3.1. Developing the model of APC behaviour

At the first stage of the research, we surveyed 20 experts – agroecologists. We asked them to assess the degree of seven negative factors’ impact on two APC state indicators – species diversity and the life span of perennial plants. The degree of impact was represented on a 5-point scale. Since that previous study to identify key impact factors [4] was carried out in the South of Russia, expert assessments refer to plant communities in arid zones.

At the second stage, we asked the experts who have responded to fill out a matrix of the mutual influence of factors on each other, ranking it on a three-point scale (weak, may be indirect influence, moderate one, and high direct influence). The results of the expert survey are presented in Table 1.

### Table 1. Mutual influence of the arid plant communities’ development factors

| Factor ↓ influences the factor → | (SS) | (IE) | (ML) | (WL) | (PC) | (IC) | (IS) |
|---------------------------------|------|------|------|------|------|------|------|
| Soil salinity (SS)              | 0    | +1   | -1   | +2   | -1   | -1   | -1   |
| Excessive insolation (IE)       | +2   | 0    | 0    | +3   | -1   | -1   | -1   |
| Lack of minerals in the soil (ML)| 0    | +1   | 0    | 0    | 0    | 0    | 1    |
| Lack of water (WL)              | +2   | +3   | +1   | 0    | -1   | 0    | +1   |
| Contamination by phytophages (PC)| 0    | 0    | 0    | 0    | +1   | +2   | +1   |
| Contamination by insect pests (IC)| 0    | 0    | 0    | 0    | +1   | +1   | +1   |
| Settlement of invasive plant species (IS) | 0    | 0    | 0    | +1   | 0    | +1   | +1   |
The weighted digraph of the mutual influence of changes in factors is shown in Fig. 2. Note that the weight coefficients on the edges were assigned based on general biological considerations — a weak effect corresponds to a coefficient of 0.1, moderate — 0.4, high — 1.0. The weight sign indicates the direction of influence: a positive coefficient means the supporting influence on another factor, a negative one means that the certain factor suppresses another one.

The minimum impulse values at the vertices \( SS, PC, IC, IS \) are limited to zero. The impulse values at the other vertices are not limited.

The value of the impulse at the \( i \)-th vertex of the graph at time \( t \) is calculated by the formula:

\[
\psi_i(t) = v_i(t) + e_i \sum_{k \in K_i} v_k(t - 1)
\]

where \( e_i \) is a parameter characterizing the severity of the factor corresponding to the \( i \)-th vertex at the particular territory, and \( K_i \) is the set of vertices adjacent along the edges of \( i \).

4. The results and discussion

The Figure 3a, 3b shows the results of simulation modelling of the APC behaviour in two cases: without control and with a control action in the form of irrigation. The steps of the impulse process are plotted on the horizontal axis. Fluctuations of the impulse value at the target vertices are approximated by a linear function. Its increase or decrease identifies the type of APC dynamics. In this case, we can see confirmation of the well-known fact of the need for artificial irrigation of plants in arid zones.

Another example is shown in Fig. 3c, 3d. The result of APC behaviour simulation modelling under the settlement of invasive species (weeds) shows a decrease in species diversity while maintaining the
life span of perennial plants. This result is in good agreement with practice — although invasive species compete with APC for resources, they do not infect other plants such as phytopathogens. In this case, over time, the plot will be completely occupied by weeds.

One could fight such an invasion mechanically (weeding). However, this method is too expensive for industrial farming. The analysis of APCs behaviour under various control actions shows that the introduction of complementary microelements into the soil will be effective. This method is significantly cheaper and, moreover, is successfully applied in practice [11].

5. Conclusion
The result of the study is a simulation model, which can predict the APC behaviour in response to various biogenic control actions.

Based on the model, we obtained the hypothetical formula that allows controllable changing the APC properties such as adverse effect on the adjacent territories with a minimum impact on its biosystem.

The modelling results could be used to control APC by changing, for example, the soil composition and properties to ensure the necessary level of environmental management and achieve the optimal economic effect. The economic value of the model is in the possibility of quick and low-cost forecasting the possible damage due to APC, as well as modulating their processes to reduce the negative impact on crops.

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