ROLE OF IRRIGATION FOR SUSTAINABLE FOOD PRODUCTION IN RUSSIA

Liudmila Kireycheva

ABSTRACT

The current macroeconomic conditions in Russia pose certain risks for the insurance of the country’s food security. Russia is situated in the area of risky agriculture: 80% of the arable lands suffer from the precipitation shortage, while excessive waterlogging is observed in 10% of the farmland. This situation is deteriorated due to the aridization of the climate. It is almost impossible to grow high-yield crop species, as well as to apply intensive agricultural technologies and adaptive-landscape systems of agriculture without land reclamation in dry years.

Now there are 4.27 million hectares (Mha) of irrigated lands and 4.8 Mha of drained lands in Russia. The average yield in the irrigated lands is 2.9 tons in grain units/ha, which is 3-4 times lower than the productive potential of soils.

The methodology basing on the energy approach which helps to increase the production potential of soils using irrigation and drainage measures has been proposed. The energy estimation includes the following calculations: bioclimatic potential; energy accumulated in the soil and in the vegetation cover. A new parameter – turbulent energy output, which is calculated as the difference between the radiation balance, energy of soil formation and energy accumulated in humus and in the crops, is used to estimate land reclamation efficiency.

This enables to predict the production potential of the agricultural land depending on the input energy in the case of land reclamation and makes it possible to use more general energy estimations instead of non-energy approach.

Using the developed technique the calculations of the soil productivity for the different natural zones of the European part of Russia were fulfilled. The greatest production potential was obtained in chernozems. It reaches 7.7 thou.grain-u/ha, and can be increased up to 10 - 12 thou.grain-u/ha under irrigation. The productivity of sedge-podzolic and gray forest soils does not exceed 1.3 to 2.0 thou.grain-u/ha under natural conditions, but their productivity can be increased up to 6-8 thou.grain-u/ha under irrigation. Up to 5 times soil productivity increase can be obtained under irrigation in semi-arid and arid zones of the European part of Russia.

The suggested methodology makes it possible to allocate land reclamation projects in the zonal soils more efficiently as well as to select the most high-productive crops. The paper shows that food security can be achieved both under excess and insufficient soil moisture due to the development of land reclamation.

Keywords: food security of Russia, production potential, land reclamation, irrigation, drainage, climate change, energy approach, the forecast of yield.

1 Vice-director, All-Russian Research Institute for Hydraulic Engineering and Land Reclamation, build.44, B. Academicheskaya street, Moscow, 127550, Russia, e-mail: kireychevalw@mail.ru
1. INTRODUCTION

Growth of the world population and the demand for food will continue in the foreseeable future. Russia with its land and water resources has a potential to become a significant exporter of agricultural products to the world’s market. In Russia the area of arable land is about 0.85 ha per capita, which is higher than the world average, and water resources amount rank the second place after Brazil. The largest part of the water resources is located in the Siberian region. A major part of all reclaimed land 62.4 % is situated in the European part of Russia, where the shortage of water for irrigation is detected in the South of the territory, particularly in Kalmykia and the Caspian lowland. Irrigation is the determining factor in increasing crop productivity in this region.

Up to 70% of vegetables, more than 20% of coarse and succulent fodder, 100% rice and the significant amount of other crops are produced in the reclaimed lands which occupy 9.1 million hectares in Russia now. The main projects of water management and land reclamation which were constructed in the 60s of the 20th century are practically lost the operating capacity or efficiency. Their further operation is risky due to the increasing number of the emergency situations, the equipment failures, deterioration of irrigated and drained land. All the above mentioned led to the decrease in crop yield and agricultural gross harvesting being obtained from the reclaimed land.

Crop yields in Russia are 4 times lower than in the UK and Germany, and 2 times lower than in China now (Figure 1). This is due to the extensive farming and inadequate area of reclaimed land. At present the issue on the restoration of the existing drainage systems which were built before the 80s years, as well as the innovative development of the irrigation sector is being considered.

![Figure 1. The dynamics of the wheat yields in Russia and in other countries (Data base Faostat, A report on the status and use of the agricultural land.2014)](image_url)

Federal goal-oriented program “The Development of Land Reclamation of farming lands in 2014-2020” has been joined into force in Russia since 2014. The goal of the Program is to increase the productivity and sustainability of agricultural production and soil fertility on the base of land reclamation taking into account global and regional climate change. The program should provide the growth of crop production by 128 %, putting into operation 840, 96 ha of the former reclaimed land, 343,13
thousand hectares of agricultural land, protection of 1 Mha from wind erosion and desertification by 2020.

In 2015 available in Russia 4.26 Mha of irrigated land in agricultural production was actually used to 3.27 Mha, and from 4.78 reclaimed lands in agricultural turnover used 3.38 Mha.

Actually only 3.15 Mha among the 4.26 Mha of the available irrigated lands are actually used as farm lands in 2015. Only 3.38 Mha among the 4.78 Mha drained lands are used for agricultural purposes now. Close to 1.35 Mha are actually irrigated, using water to the extent of 7.2 km³.

Reclaimed land being used in agriculture is less than 5.8% of the total arable land area. The average yield is 2.9 tons in grain units/ha in the irrigated lands, 2.2 tons in grain units/ha in the drained lands.

To fulfill the tasks of the program of land reclamation it is necessary to expand the reclaimed area and to increase the production potential of the irrigated and drained lands. The study of production potential of agricultural land by the use of reclamation measures based on the energy estimation was carried out, recommendations on the development and the allocation of the irrigated and the drained lands were prepared.

2. METHODS

2.1 Estimation of the energy state of the natural object

Management of crop productivity using a new theoretical approach is based on the energy estimation of the soil condition and the vegetation cover. This allows prediction of the production potential of the agricultural land depending on the amount of income energy when carrying out agrotechnical, hydrotechnical or other reclamation activities. Entering the natural system (agricultural landscape) energy is stored in the soil humus and phytomass of plants supports hydrological and nutrient cycles in the ecosystems, creates mechanisms sustaining the stability of the system and provides the exchange with adjoining systems.

During the agricultural activities the most part of energy is withdrawn with the harvest. Some energy is dissipated. The less energy is dissipated, the more efficiently is the system (Prigogine and Kondepudi. 2009).

With regard to land reclamation, the major components of energy flux are: solar energy, soil formation energy, energy of chemical bonds of organic substances in green plants that accumulate solar energy during photosynthesis, and the energy of chemical relations of organic matter in the soil.

As the main indicator of the energy estimation of the land reclamation in the agricultural landscape we have proposed a new indicator – the effective turbulent energy.

The effective turbulent energy \( J \) is determined as the difference between the radiation balance; soil formation energy; energy which is maintained in the humus and energy accumulated in the crops:

\[
J = R - Q_n - \beta \varepsilon \Pi - \beta \varepsilon \Pi_p.
\]
where J is the effective turbulent energy flux from the soil and vegetation into the environment, kJ/cm²; R – radiation balance, kJ/cm²; Qn – soil formation energy, kJ/cm²; БЭПг – energy, which is maintained in the humus, kJ/cm²; БЭПр – energy accumulated in the plants, kJ/cm².

The value of the effective turbulent energy flux from the soil and vegetation into the environment determines the efficiency of the incoming solar energy, i.e. in fact it is the amount of energy which is dissipated and is not involved in the agro-ecosystem.

The smaller the value of the effective turbulent energy, the more efficient is the natural system. Schematic diagram of the energy balance is shown in the Figure 2.

Figure 2. Scheme of the energy balance in the «atmosphere – vegetation– soil

The main energy flux coming into the soil is a flux of radiant energy of the sun which is transformed to thermal energy at the soil surface. The difference between the solar radiation absorbed by soil surface, and the effective radiation of this surface, represents radiation balance which is described by the following formula (Budyko. 1971):

\[ R = Q \cdot (1 - \alpha) - I, \]  

(2)

where Q – total short wave radiation, KJ/cm²; \( \alpha \) – albedo, in shares of units; I – effective radiation, KJ / cm².

As the main characteristic of energy condition of soils as well as its alteration "the dryness index" on Budyko, which defines dependence of heat and precipitation under natural conditions is wildly used:

\[ \overline{R} = \frac{R}{L \cdot O C}, \]  

(3)

where L – the latent heat of steam formation, constant equals 2,256 KJ/cm²; OC – mean annual precipitation, cm; other designations are given above.

Among the most significant energy consumers, Volobuyev (1974) defines water and heat cycles (95%), biological cycle of matte (1%), physical and chemical rock weathering (0,01%). In spite of the fact that about 1% of the general energy of soil
formation is spent in the biological cycle of matte, as a result the organic substance and soil humus are formed. Work of system is expressed in expenditure of energy for soil formation and estimated according Volobuyev (1974):

\[ Q_n = R \cdot e \cdot \frac{E}{O_C}, \]

(4)

where \( R \) – radiation balance, KJ/cm\(^2\); \( E \) - evaporability, mm; \( O_C \) – average annual precipitation, mm.

According to a goal, the assumption that reclamation has to provide preservation or increase in humus content in different soil zones it is advisable to consider the energy accumulated in humus, estimated on the base of bioenergy potential of organic compounds.

Under irrigation and drainage which create an optimal water regime for the growth of the leading agricultural crops, \( O_c \) is equal to the water consumption of the crops.

Soil formation energy is spent for: evaporation and transpiration – 95 – 99,5 %; processes of the biological cycle – 0,5 – 5,0 %; weathering - about 1 % (Volobuev, 1974).

Bio-energy parameter of humus (БЭПГ) and crops (БЭПР) is determined according to the procedure described below.

2.2 The procedure for determining of the bioenergy potential

The energy having been accumulated in the soil humus and in the crops could be estimated using bioenergy potential (БЭП). Bioenergy potential is the potential energy of any organic matter, including soil organic matter (БЭПГ) and phytomass of plants (БЭПР).

Having the elementwise composition of the organic molecule one can calculate БЭП with the help of the following stoichiometric formula (Khokhlova, 2007):

\[ \text{БЭП} = 183C + 45,75H - 91,5O, \text{ (kJ/mol)}, \]

(5)

where \( C, H \) and \( O \) – atomic fractions or molecular indicators of the carbon, hydrogen and oxygen in the molecule of the organic substrate.

If the mass fractions of the elements in the substance are known, the formula (4) is converted to:

\[ \text{БЭП} = (15,25C + 45,75H - 5,72O) / (C+H+O), \text{ (kJ/g)}, \]

(6)

where \( C, H \) and \( O \) are given in %.

Elementwise compositions of the humic acids and the fulvic acids in the various soils are rather similar, so we use the average values of ratios of carbon, hydrogen and oxygen.

Elementwise composition of the humic acids in mass fractions is: \( C \) - 50-62%; \( N \) – 2,8-6,6%; \( O \) - 31-40%; for the the fulvic acids – \( C \) 40-52; \( N \) - 4-6; \( O \) - 40-48% (Khokhlova, 2007).
The fulvic acids have much less carbon and more oxygen, so their bioenergy potential will be less. The average value of the БЭП calculated by the formula (6) is: 8.98 kJ/g for the humic substances; 7.14 kJ/g - for the fulvic acids. To estimate the energy of the soil humus, it is advisable to take into account the energy of humus that accumulated in the humic acids and in the fulvic acids. Depending on the type of the humus (the ratio of the humic acids and the fulvic acids) bioenergy potential for the labile part of the soil humus was calculated for the main types of soils (table 1).

### Table 1. Bioenergy potential for the labile part of the soil humus in the different types of soil (taking into account data of Orlov et al., 1985)

<table>
<thead>
<tr>
<th>Soils</th>
<th>БЭП of the humic acids, kJ/g</th>
<th>БЭП of the fulvic acids, kJ/g</th>
<th>The type of humus Cha/Cfa</th>
<th>The share of the fraction-sponsored humus,%</th>
<th>БЭП the fraction-sponsored humus, kJ/g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sod-podzol soils</td>
<td>8,98</td>
<td>7,14</td>
<td>0,6-0,8</td>
<td>50</td>
<td>3,95</td>
</tr>
<tr>
<td>Gray forest soils</td>
<td>8,98</td>
<td>7,14</td>
<td>1,0-1,1</td>
<td>70</td>
<td>5,64</td>
</tr>
<tr>
<td>Chernozems</td>
<td>8,98</td>
<td>7,14</td>
<td>1,5-2,5</td>
<td>70</td>
<td>5,80</td>
</tr>
<tr>
<td>Chestnut soils</td>
<td>8,98</td>
<td>7,14</td>
<td>1,5</td>
<td>60</td>
<td>4,95</td>
</tr>
<tr>
<td>Brown desert-steppe soils</td>
<td>8,98</td>
<td>7,14</td>
<td>0,8-1,0</td>
<td>60</td>
<td>4,80</td>
</tr>
</tbody>
</table>

The amount of energy accumulated in the crops (БЭПр) due to photosynthesis was calculated by the grain. The content of the dry matter in grain is 88%; mass fraction of the carbon is 45%, oxygen - 42%, hydrogen - 6.5%, the nitrogen -1.5% (Yagodin et al. 2002). According to the formula (6) БЭП of the grain equals 4.8 GJ/t.

### 2.3 Procedure of the of the determination of the efficient potential

The efficient potential equals the maximum productivity of agricultural crops in the particular soil and climatic conditions. Yield capacity depends on the natural radiation balance; rainfall and natural fertility of zonal soils. In the natural biocenoses crop yields can be determined by the formula Pegov and Khomyakov (1991):

$$ P = S \cdot CL, $$

(7)

where P - potential productivity of biomass of vegetation in these soil and climatic conditions, t/hectare (in dry matter) ; S – soil index; CL – coefficient of favorable climatic conditions;

Under irrigation land radiation balance is changed due to the additional watering or draining of the territory changes the dryness index, and soil fertility increases as the result of land reclamation.

The soil index – as an integrated indicator of soil fertility, is calculated on dependence:

$$ S = 6,4(G_{fk} + 0,2G_{фк}) / 600 + 8,5 \sqrt[3]{NPK} + 5,1e^{-\frac{H_{с} - 1}{4}}, $$

(8)
where 6,4; 8,5; 5,1 – weight coefficients; Гук and Гфк – the content of gumatny and a fulvatny humus respectively, th/ectare; N, P, K-the content in the soil of nitrogen, phosphorus and potassium respectively, a share from their optimum value for this type of crop; Hр – hydrolytic acidity, mg-ekv/100 of the soil.

The considered model has a rather wide application and can used for almost all types of zonal soils, because it takes into account a large set of characteristics and basic soil properties.

The calculations showed that the model well correlates as compared to the field experiments. (Kireicheva and Karpenko, 2015).

3. RESULTS AND DISCUSSION

3.1 Calculation of the turbulent

The calculations of the turbulent energy-conversion efficiency in the natural conditions and under irrigation and drainage having been fulfilled using the equations (1-4) showed that higher yield can be obtained in the case of the reduction of the turbulent energy-conversion efficiency: by use of drainage in the waterlogged area, and due to the irrigation in the arid zones (Figure 3).

![Figure 3. The turbulent energy in natural conditions and under irrigation in the zonal soils of the European part of Russia](image)

The figure shows that the largest efficiency of hydro-amelioration was observed for the zonal chestnut and brown semi-desert soils. Energy-conversion efficiency decreases from 118,3 - 144,79 to 60,83 kJ/cm² under irrigation in these soils. Energy-conversion efficiency equals 62-52 kJ/cm² for the most productive soil (typical chernozem) under natural conditions, which indicates a large energy reserve of the soil. Irrigation is required only in some years for these soils, when natural precipitation is insufficient. To provide the sustainability of agriculture the energy-conversion efficiency under land reclamation should be lower as compared with the initial state, i.e., the efficiency of the incoming solar energy will be increased. We can provide this...
in the case of the management of the geological, biological and anthropogenic cycles of water and chemicals, including biogenic elements, which create the necessary ameliorative modes to increase of production potential. During crops cultivation the amount of outgoing energy in the ecosystem increases while the amount of energy being returned to the soil reduces. To solve the issue of the sustainable increase of the soil fertility it is required to provide the increased amount of energy which is returned to the soil and to maintain the steady ratio of energy fluxes.

Thus, the proposed approach gives an opportunity to choose soil and climatic conditions in which irrigation and drainage are the most efficient and to estimate the scope of land reclamation. In the European part of Russia the following zonal soils are the most sensitive to the land reclamation: soddy-podzolic, chestnut and brown semi-desert soils. Chernozems require special substantiation of the irrigation application.

3.2 Calculation of the production potential

Calculations of the crops productivity were carried out in natural conditions and under irrigation for the leading crops in the specific soil and climatic conditions. As it was shown above, hydrothermal mode is changed and the energy of the soil formation is increased under irrigation. The amount of humus as well as the main nutrient elements (nitrogen, phosphorus, potassium) have reached their optimum values in the zonal soils under land reclamation. To estimate the fertility of the agricultural land the particular properties of the specific crops and the farming systems were taking into account. The calculations were fulfilled for the crop rotation in the grain units for the zonal soils of the European part of Russia. The production potential obtained according to equations (7-8) under natural conditions and under irrigation for the zonal soils of Russia is shown in Figure 4.

Figure 4. The change of the production potential under irrigation in the zonal soils

The calculations showed that chernozems are the most productive under natural conditions, their production potential reaches 7.7 - 8 thou. g. u./ha, and it can be increased up to 9.7 ... 10.2 thou. g u./ha under irrigation. Productivity of sod-podzol and gray forest soils under natural conditions does not exceed 1.3 to 1.6 thou. g
u./ha, however, their production potential can be increased up to 6-8 thou. g u./ha in the case of land reclamation.

In the European part of Russia the waterlogged soils are the most sensitive to the drainage while soils of the semi-desert and desert zones are the most sensitive to irrigation which provides 5 times increase in their production potential.

For example, in Klyuchevsky district of Altai in 2011 a yield of green mass of corn silage under irrigation (irrigated area - 1,800 ha) was 47.6 t/ha, which is 4.7 times more than in the dry-farming land.

On the farm "Uzeffov" in Rostov region 70 t/ha of onions (irrigated area - 230 ha) and 60 t/ha of vegetables were obtained (irrigated area - 260 ha), which are 4 to 5 times higher than in the dry-farming lands.

The possible average increase in productivity of fodder crops in the irrigated lands is up to 6 thou.g.u./ha; up to 4 thou.g.u./ha - in the drained areas; and in some regions up to 8-10 thou.g.u. - under irrigation and up to 5 - 6 thou.g.u - in the drained areas.

In order to ensure food security of Russia the expansion both of the irrigated land up to 6.0 million hectares and drained areas up to 5.3 million hectares is required.

4. CONCLUSIONS

For the implementation of the food security Doctrine of Russia it is required to increase the gross crop harvest more than by 20% and to guarantee forage in the amount of 90 million tons in the feed units for livestock development. Land reclamation should play an important role.

In the arid conditions, which are typical for the 80% of the arable land this is possible only under development of irrigation, and in conditions with excessive moisturizing - in the case of the drainage expansion.

To substantiate the development and allocation of the irrigation and drainage projects the method of the production potential and the procedure of the estimation of the land reclamation efficiency are proposed.

The technique is based on the energy approach, which takes into account the flow of radiant energy in the biocenosis and its expenditure on the processes of soil formation and yield formation.

It is shown that the efficiency of incoming energy is different depending on soil and climatic conditions.

Chernozems are the most favourable soils for the growing crops so as their production potential reaches up to 8 t/ha (in the g.u) without irrigation and production potential can be increased to 10-12 t g. u./ha under irrigation.

In the zone of excessive moisturizing to obtain yield 5-6 t/ha g.u. drainage is required. In the southern steppe and semidesert zone it is possible to increase productivity up to 6-8 thou. g.u./hectares under irrigation, which is 3-5 times higher than without irrigation.

To ensure food security in Russia the increase in the reclaimed area up to 9-10% of the arable land is required.
REFERENCES

Data base Faostat (www.fao.org)


