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An Empirical Framework of Washing Salinity by Irrigation to Maintain Soil Quality in Hetao Irrigation District

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Abstract [**Objectives**] To summarize the characteristics of washing salinity by irrigation in Hetao Irrigation District, and propose the empirical framework of washing salinity by irrigation to maintain soil quality, and provide a theoretical basis for maintaining the sustainable development of soil in Hetao Irrigation District. [**Methods**] The methods of experiment, questionnaire, on-the-spot investigation and literature review were used. [**Results**] This study proposed the empirical framework of washing salinity by irrigation to maintain soil quality in Hetao Irrigation District. Seven factors of the framework, including flood irrigation, land leveling, plastic film mulching, fertilization, soil organic matter, pH and salinity, and their relationships were determined. The characteristics of these factors in Hetao Irrigation District were investigated (flooding irrigation with a large amount of irrigation water, high amount of fertilizer application, low organic matter, high pH, large variation of salinity, *etc.*). The mechanisms and effects of various factors affecting soil quality in Hetao Irrigation District were analyzed (the mean soil organic matter (SOM) and pH were kept in the range of 10.9 - 13.9 g/kg and 8.0 - 8.15 in recent 35 years, respectively, and increased slightly, *etc.*). [**Conclusions**] The empirical framework can be used as a theoretical norm for evaluating soil quality under the condition of washing salinity by irrigation. Under the condition of washing salinity by irrigation, the agricultural soil quality in Hetao Irrigation District showed a stable trend over time. Using this framework, we can find soil problems, and adjust some unbalanced factors to maintain the stability of soil quality in Hetao Irrigation District, and can also provide a reference for other areas.

Key words Washing salinity by irrigation, Empirical framework, Soil quality, Hetao Irrigation District

1 Introduction

Hetao Irrigation District is located in Bayannur City in the west of Inner Mongolia (Fig. 1), which belongs to the arid northwest plateau of China. It is an agricultural area completely dependent on irrigation. It is one of the largest irrigation areas in Asia and one of the three super-large irrigation areas in China. It is also an important commercial grain and oil production base in China[1]. The Yellow River provides abundant water resources for this area, but the soil in this area has a general phenomenon of interannual periodic secondary salinization[2]. To reduce secondary salinization, "autumn irrigation" and/or "spring irrigation" (locally known as "washing salinity by irrigation") must be carried out every year, which has become the key irrigation system in this area[3-4]. However, washing salinity by irrigation can also leach some soil nutrients, including major nutrients and trace elements and soil organic carbon (SOC), and change the soil structure[5-6]. Will washing salinity by irrigation lead to the unsustainability of agricultural soil quality? It is extremely important to answer this question, because the unsustainability of soil quality will lead to desertification in Hetao Irrigation District, thus losing the barrier to ecological security in Northern China[7]. However, there are few reports on the systematic evaluation of washing salinity by irrigation and its effect on the maintenance of soil quality. Therefore, this study proposed an empirical framework related to washing salinity by irrigation to assess this effect.

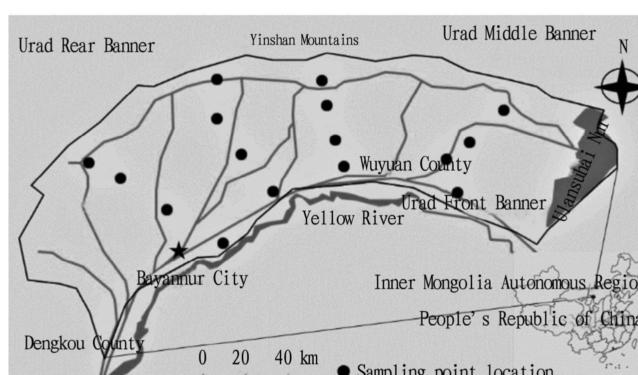

Fig. 1 Map of Hetao Irrigation District in Inner Mongolia and 16 soil sampling points in this study area

A framework refers to a structure interrelated factors that achieve specific objectives and support a particular approach, which can be used as a guide for achieving its aim[8]. Accordingly, the framework in this study refers to the structure supported by interactive factors, which are intrinsically related to washing salin-

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ity by irrigation and soil quality in the "crop-soil" ecosystem. It is used to understand and evaluate the effect of washing salinity by irrigation on soil quality. The key to this framework is to reveal the changes in washing salinity by irrigation and soil quality characteristics, and to reflect the internal relationship between washing salinity by irrigation and soil quality. This framework is based on the previous practice of washing salinity by irrigation and the changes of soil quality, so it is called an empirical framework.

Therefore, the objectives of this study were to summarize the basic characteristics of washing salinity by irrigation in Hetao Irrigation District, and to propose the empirical framework of washing salinity by irrigation to maintain soil quality according to the soil characteristics of Hetao Irrigation District. It is expected provide a theoretical basis for maintaining cultivated land fertility and soil sustainable development in Hetao Irrigation District.

2 Materials and methods

Hetao Irrigation District (40°13′–42°28′ N, 105°12′–109°53′ E; altitude above sea level: 900–1 200 m) is close to the north bank of the Yellow River (Fig. 1), and has a temperate continental climate. From 1960 to 2010, the average annual precipitation and average daily temperature were 159.8 mm and 7.56 ℃, respectively, and the annual evaporation was about 2 200 mm[9]. The agricultural soil is classified as Irrigation Silting Soil by China Soil System Classification. The texture of plough layer includes sand soil, sandy loam, light loam, medium loam, heavy loam and clay. The main crops are corn (*Zea mays* L.), sunflower (*Helianthus annuus* L.), spring wheat (*Triticum aestivum* L.)[10] and melons, fruits and vegetables with local characteristics[11].

The methods adopted are experiment, questionnaire survey, on-the-spot investigation and literature review. Among them, the experiment method is to collect soil samples and laboratory analysis. From October 7 to 8, 2020, 64 soil samples at the depth of 0–20 cm were collected at 16 points (Fig. 1; 8 in corn fields and 8 in sunflower fields) in the irrigation area (4 soil samples were collected at each point, and each soil sample was mixed with 3 repeated samples). The SOM was determined by Walkley and Black's dichromate oxidation method[12], and the pH[13–14] was determined by the 1∶2.5 soil-water method. It was used to investigate the soil SOM and pH factors in the empirical framework proposed in this study.

A face-to-face Q & A survey was conducted among 239 agricultural producers in Hetao Irrigation District from July to August 2019, including: (i) management of fertilization, irrigation and pesticides in the past year; (ii) the changes of soil quality with time in the past 20 years and the problems and causes; (iii) the effects of irrigation, fertilization and pesticides on soil quality.

On-the-spot investigation is: (i) to observe the situation of crops and soil in every township in the whole Hetao Irrigation District; (ii) to interview 12 growers in-depth to investigate the actual changes of irrigation and soil; (iii) to interview 6 local water conservancy and agronomy experts in-depth to investigate the development process of irrigation and land construction, soil change and crop planting history in Hetao Irrigation District.

3 Characteristics of soil and washing salinity by irrigation in Hetao Irrigation District

The agricultural soil in Hetao Irrigation District originates from the sedimentary layer of saltwater lake formed by the diversions of the Yellow River many times[15], and was cumulated irrigation silting soil[16]. The content of soil organic matter (SOM) is low, the distribution of nutrients is uneven, and the soil has the characteristics of interannual periodic salinization. The soil is alkaline (the average pH > 8), and the soil quality is low and heterogeneous. Therefore, soil organic matter, pH, salinity and nutrients are the basic indexes of soil quality in Hetao Irrigation District.

Under the condition of widespread use of chemical fertilizer, the soil nutrients and chemical fertilizers are used more frequently, so fertilization has become an alternative factor of soil nutrients. Under the conditions of the above soil characteristics and the application of chemical fertilizer, washing salinity by irrigation in Hetao Irrigation District has gradually matured in agricultural production and irrigation practice. At the beginning of the 20^{th} century, the irrigation system of Hetao Irrigation District began to be established. At that time, the natural waste river was used as the main irrigation channel, connecting several branch canals, and there were no other auxiliary canals[18]. Only flood irrigation could meet the agricultural production at that time. However, as the area of flood irrigation increased, so the groundwater level rose. Under drought conditions, high groundwater level causes groundwater to rise to the surface through soil capillarity and evaporation of groundwater, and salt in groundwater accumulates on the soil surface with evaporation, resulting in soil secondary salinization[19–20]. The first thing that producers pay attention to is the salt spot problem on their land, which is caused by uneven land, that is, the low-lying land has high salt content, and the higher land has lower salt content, so leveling the land becomes the key. Producers divide their land into smaller lands (usually 0.10–1.33 ha), which is called "land leveling" in Hetao Irrigation District, in order to reduce the amount of labor on the flat land. Then, the producers put up weirs about 50 cm high around these small lands for flood irrigation, and the irrigation water stays in the land, and through natural infiltration, the salt accumulated in the first layer is leached to the soil and even groundwater below the plough layer, namely the irrigation system of "washing salinity by irrigation"[21]. In the early 1980s, plastic film mulching technology was introduced into Hetao Irrigation District[22]. Although the initial aim of this technology is to increase yield, it is quickly used to reduce water evaporation and maintain soil moisture, thereby enhancing the effect of washing salinity by irrigation.

To sum up, washing salinity by irrigation includes three inherent characteristics: (i) flood irrigation; (ii) land leveling; (iii) plastic film mulching.

4 Empirical framework and the influencing factors of soil quality

In Hetao Irrigation District, seven factors (flood irrigation, land leveling, plastic film mulching, SOM, pH, salinity and fertilization) interact with each other, and the impacts on soil quality are closely related to the sustainability of agriculture in Hetao Irrigation District. These seven factors form an empirical framework to help us understand and evaluate the effects of washing salinity by irrigation on soil quality (Fig. 2).

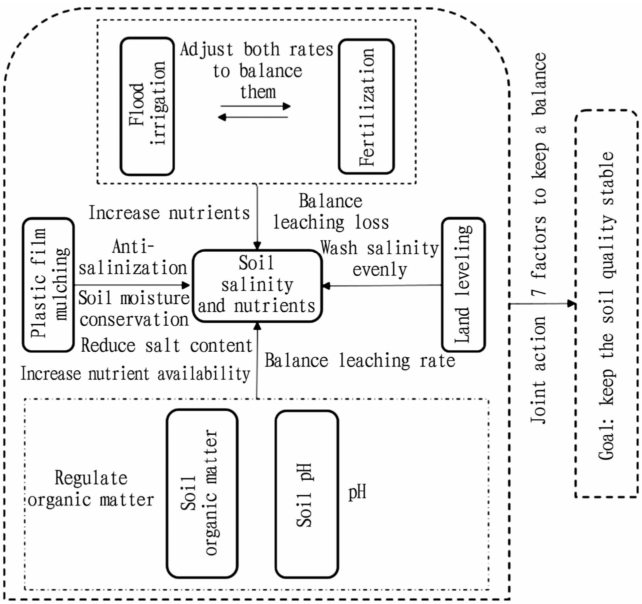


Fig. 2 Empirical framework of washing salinity by irrigation to maintain soil quality in Hetao Irrigation District, Inner Mongolia

The roles of the factors in this framework are: (i) Flood irrigation can leach soil salinity and nutrients, and fertilization can make up for the loss of nutrients. However, if the fertilizer application is too high, more nutrients will be lost. Therefore, the rates of irrigation and fertilization should reach a dynamic balance in order to ensure not only the effect of salinity washing, but also ensure the nutrients needed by crops, and ensure that nutrients or fertilization are not leached too much, so as to avoid environmental pollution. (ii) Plastic film mulching can prevent groundwater salinity from returning to the tillage layer, maintaining the effect of washing salinity by irrigation. (iii) The land leveling can ensure the uniform infiltration of soil salt, so as to improve the effect of washing salinity by irrigation. (iv) SOM and pH can affect the speed and amount of soil salinity and nutrients. Adjusting the soil pH to an appropriate value can increase the availability of soil nutrients and reduce the salt content. Maintaining or increasing SOM can maintain or enhance the ability of soil to provide nutrients. If SOM is reduced to a certain extent, the crops can not grow properly.

The characteristics of these factors in Hetao Irrigation District are as follows: (i) Flood irrigation with a large amount of water was carried out every year. According to Liu Yuanchao, the average annual irrigation volume for washing salinity by irrigation in Hetao Irrigation District was 4 050 m^3/ha from 2013 to 2016, which was significantly higher than the actual water for crops[23]. The questionnaire survey of this study shows that 88.99% of the respondents think that the amount of irrigation has not changed significantly year by year over the past 20 years. This means that it is over-irrigated for nearly 90% of farmers every year. (ii) The land leveling was completed in the 1990s. After that, in order to keep each piece of cultivated land flat, the growers leveled the land every 2 to 3 years. (iii) Plastic film mulching has become a necessary technology in this area (except for a few crops not suitable for plastic film mulching), but the residue of plastic film in soil has a negative impact on soil quality. (iv) There is higher amount of Fertilization. According to the results of the questionnaire survey of this study, the average amount of nitrogen fertilizer applied in the whole irrigation area in 2018 was 25.91 kg/667 m^2, which was higher than that in other areas of the country[24]. (v) There is low SOM. In 2020, the average content of SOM measured in this study was 11.31 g/kg. (vi) The average value of soil pH is more than 8. The average pH measured in this study was 8.07 in 2020. (vii) The fluctuating soil salt content is mainly due to the annual change of climate and irrigation: the salt content of soil tillage layer increases with the increase of air temperature; it decreases with the increase of precipitation and irrigation[11].

These seven factors keep balance and work together to maintain the stability of soil quality. If these factors are out of balance, even one factor is out of balance, it may hinder the sustainable development of agriculture. Once there is an imbalance, one or more of the "irrigation amount, fertilizer application, SOM and pH" can be adjusted to restore it to a new balance.

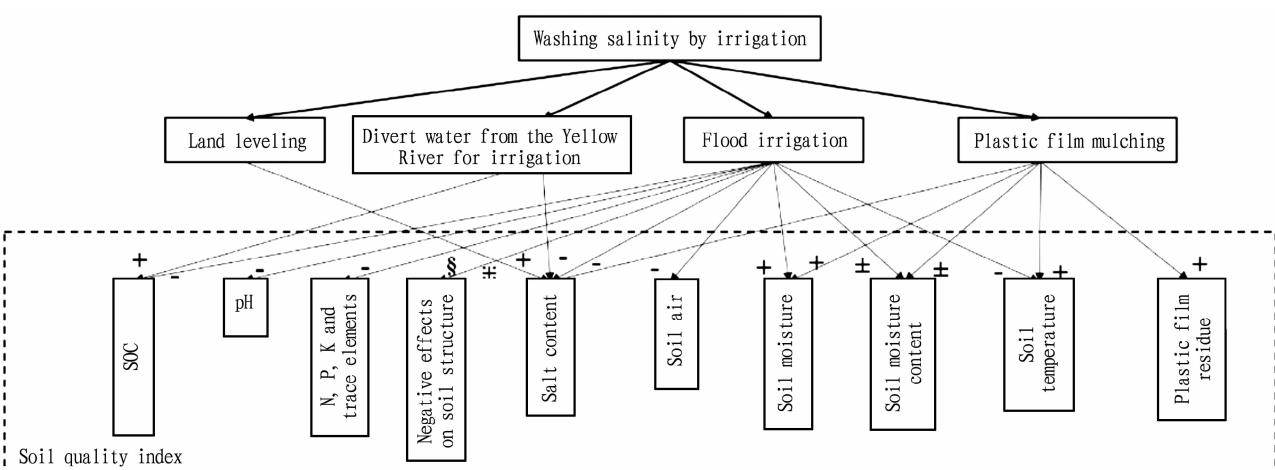
5 Mechanism analysis of influencing factors of soil quality

Flood irrigation can wash the salt in the tillage layer of the soil, but it can also cause nutrient leaching. Irrigation water has the characteristics of vertical movement of "infiltration downward and evaporation upward". In the process of washing salinity by irrigation, gravity makes irrigation water move downward through the pores of the soil. After salt leaching, under drought conditions, the capillary force causes the groundwater to rise along the soil capillary, that is, the groundwater evaporates upward[19]. The solute in the soil moves up and down with the movement of irrigation water. Soil solutes include various salts and nutrients needed by crops, such as nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca) and magnesium (Mg), as well as numerous trace elements (TEs). The direction, speed and size of transport depend on the interaction of soil solute between solid phase and liquid phase. The main types of interaction include adsorption, desorption, dissolution, immobilization and mineralization. In general, SOM and pH can explain a significant change in the activity of total metal ions or free metal ions in soil[25-28]. The amount and rate of soil solute transport with water are different[29], so the amount of soil N, P, K and TEs leached with water is also different. The nutrient ions that can be absorbed by the soil, such as P, K, Ca and Mg, are difficult to be leached into groundwater[30-31]. However, nitrate ions that cannot be adsorbed by the soil can easily be leached with water in the soil[30,32]. Therefore, after washing salinity by irrigation each time, nitrogen fertilizer must be applied. However, due to the different nutrient losses in washing salinity by irrigation, the amount of fertilizer application (including N, P, K, S, Ca, Mg and TEs) should be determined according to the content in the soil and the demand of crop varieties each year. Flood irrigation not only leaches salts and nutrients, but also transports all dissolved components of soil aqueous solutions, such as soil minerals, compounds[33], pesticides and herbicides[34-35]. Leaching salinity, insecticides, herbicides and some toxic compounds have positive effects on soil quality, but have negative effects on groundwater and natural water system.

Flood irrigation will also leach part of the SOC and reduce the soil pH value[3,36]. However, irrigation water from the Yellow River contains a large amount of sediment, which can increase SOM, thereby increasing SOC[37]. After flood irrigation, some salts, nutrients and other substances in groundwater return to the topsoil through evaporation in arid climate, which may increase the pH of the tillage layer[38-39]. During the period of flood irrigation, soil oxygen deficiency caused by long-term water storage in soil may reduce the number of soil microorganisms and adversely affect the microbial community[40-41]. Flood irrigation will also decompose soil aggregates, disperse clay, reduce soil porosity, and have a negative impact on soil structure[42-43]. However, some or all of these negative effects can be offset by appropriate land management methods, such as deep ploughing, rotary ploughing, land leveling and plastic film mulching.

Land leveling can maintain the same groundwater depth in each piece of land. The same groundwater depth can ensure that the land has the same degree of soil salinity, so that the land can be managed effectively. The plots at different elevations have different groundwater depth, and the flood irrigation in the high altitude plots can lead to the increase of the groundwater depth in the low altitude plots, which leads to the higher salt content in the tillage layer of the low altitude plots than that of the high altitude plots.

Plastic film mulching can retain soil moisture and reduce groundwater evaporation. However, the plastic film used to cover the land remains in the soil every year, which has a negative impact on soil quality and ecosystem[44]. The effect of washing salinity by irrigation on soil quality is shown in Fig. 3. Flood irrigation has the greatest impact on soil quality, and land leveling and plastic film mulching are also necessary to maintaining soil quality, but plastic film residues in the soil need to be recycled.



Note: +, increase; −, decrease; ±, increase or decrease; ※, salt is evenly distributed in the soil; §, it has a negative effect on soil structure.

Fig. 3 Effects of washing salinity by irrigation on soil quality

6 Analysis of influencing factors of soil quality with time

From 1986 to 2020, the mean SOM at the soil depth of 0 – 20 cm in Hetao Irrigation District in autumn 1986 was 10.9 g/kg[45], and the mean SOM before spring planting from 2005 to 2008 was 13.9 g/kg[46]. The mean SOM in autumn 2011 was 10.9 g/kg[47], the mean SOM in autumn 2019 was 11.70[11], and the SOM measured in autumn 2020 was 11.31 g/kg. Therefore, the mean SOM content in the soil at the depth of 20 cm is 10.9 to 13.9 g/kg. Therefore, the SOM in Hetao Irrigation District remained basically stable and increased slightly in recent years. The main reasons are as follows: (i) The Hetao Irrigation District mainly uses the water of the Yellow River for irrigation, which is rich in sediment and can increase SOM. (ii) The cumulated irrigated soil formed by the natural diversions of the Yellow River in the past few hundred years has laid a solid foundation for the maintenance of SOM[39]. (iii) SOM content can be maintained by fertilizing measures such as returning straw to field and applying organic fertilizer. SOM was positively correlated with soil fertility[47]. Therefore, genearally, the changes of soil fertility and soil quality in Hetao Irrigation District are stable with time.

The average pH of 0 – 20 cm soil layer in Hetao Irrigation District was 8.00[45] in autumn 1986, 8.06[48] before spring planting in 2010, 8.15[49] in autumn 2011, 8.14[11] in autumn 2019, and 8.07 in autumn 2020. The range of soil pH at the depth of

0 – 20 cm was 8.00 – 8.15. Therefore, in the past 35 years, the average soil pH in this area was basically stable, but had a slightly increasing trend. The reason is that fertilization and SOM mineralization can increase soil pH with time, and irrigation and arid climate are also factors affecting soil pH. Large amount of irrigation can reduce soil pH[36–44]. However, after irrigation, the dry climate will lead to an increase in the salt content of the topsoil, resulting in the accumulation of carbonate and bicarbonate of Na, K, Ca and Mg, which in turn increases the pH[40]. However, this increasing trend of pH may not increase significantly due to the increase of SOM and washing salinity by irrigation annually. Nevertheless, enough attention must be paid to the increasing trend of soil pH.

From 1978 to 2014, the area of salinized lands in Hetao Irrigation District showed a downward trend, mainly due to the downward trend of groundwater level[50]. This shows that the average salinity in the tillage layer of agricultural soil in Hetao Irrigation District decreased over time.

The questionnaire survey of this study shows that only 5.86%, 11.72% and 16.39% of the growers think that their yield, soil fertility and soil quality have decreased in the past 20 years (Table 1). This means that on the whole, the soil quality in Hetao Irrigation District has no significant change or has a tendency to improve, that is, it is stable over time. A questionnaire survey on the effect of irrigation on cultivated land quality in the past 20 years showed that 23.53% of growers thought it was disadvantageous, while others thought it was favorable (13.03%), had no effect (15.97%) or could not be judged (47.48%), that is, about 76% of growers believed that irrigation had no significant negative effect on soil quality. 30.80% of the growers thought that fertilization was disadvantageous to the soil quality in the past 20 years, while others thought it was beneficial (7.59%), had no effect (13.92%) or could not be judged (47.68%), that is, about 70% of the growers believed that fertilization had no significant negative effect on soil quality (Table 1).

Table 1 Questionnaire survey results of soil quality in Hetao Irrigation District (2019)

Questions	Alternative answers	Respondents//%
Question 1: What are the changes in crop yields in the last 20 years?	a. Increased	2.09
	b. Decreased	5.86
	c. No obvious change	92.05
Question 2: What are the changes in soil fertility in the last 20 years?	a. Increased	6.28
	b. Decreased	11.72
	c. No obvious change	82.01
Question 3: What are the changes in soil quality in the last 20 years?	a. Improved	6.01
	b. Reduced	16.39
	c. No obvious change	77.60

Note: 239 agricultural producers were chosen as respondents in Hetao Irrigation District.

Over the past 35 years, precipitation has been stable (because the annual precipitation is very low, it has little effect on crops, mainly by irrigation), the temperature has shown an upward trend (Fig. 4)[51], and the groundwater table has shown a downward trend[50]. Three environmental factors interact with fertilization and washing salinity by irrigation (including flood irrigation, land leveling and plastic film mulching), and jointly affect soil quality for a long time. As a result, soil quality can remain stable for a long time (Fig. 5).

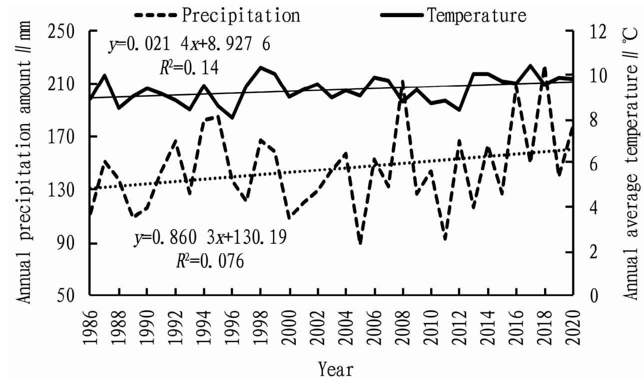


Fig. 4 Changing trend of annual average temperature and annual precipitation over time in Hetao Irrigation District (1986 – 2020)

7 Application analysis of the empirical framework

Based on the previous analysis, in the empirical framework of Hetao Irrigation District, it is difficult to adjust the amount of irrigation and fertilizer to balance soil salt leaching and nutrient leaching (growers adopt the simplest method, that is, direct irrigation with a large amount of water and fertilization with a considerable amount of fertilizer); soil salinity is the most difficult to control (salinity varies greatly with water movement); it is common to adjust SOM content (returning straw to field and applying organic fertilizer, *etc.*); soil pH is seldom adjusted (to be exact, it has not attracted enough attention); land leveling and plastic film mulching have been matured and popularized. Therefore, in the application of empirical framework, the adjustment of irrigation water amount and fertilization is the key; the adjustment of soil organic matter and pH is the basis; land leveling and plastic film mulching are necessary conditions for maintaining soil quality; soil salinity is a direct variable that affects soil quality.

The irrigation framework can be applied in two ways: (i) To understand and evaluate the soil quality under the condition of washing salinity by irrigation. The method is to first investigate the changes of irrigation water amount and fertilizer application rate, SOM, pH and salinity with time, and then understand and evaluate the changing trend of soil quality and find out the specific problems in the soil according to the changing trend of SOM content, pH and salinity with time. (ii) To maintain soil quality by adjusting the quantity, mode and direction of various factors. The method is to find out the problems existing in soil quality according to the investigation results of soil quality, find out the unbalanced factors accordingly, and adjust these factors (SOM, pH, irrigation rate or fertilization rate) in time. For example, for the current adjustment in Hetao Irrigation District, the general principle should be "increase SOM, decrease soil pH, reduce irrigation water and fertilizer and achieve a balance between them". The empirical framework can be applied to the above two aspects for a long time. It is not only a logical method in theory, but also a method to find and analyze practical soil problems, and provide ideas and methodology for solving problems.

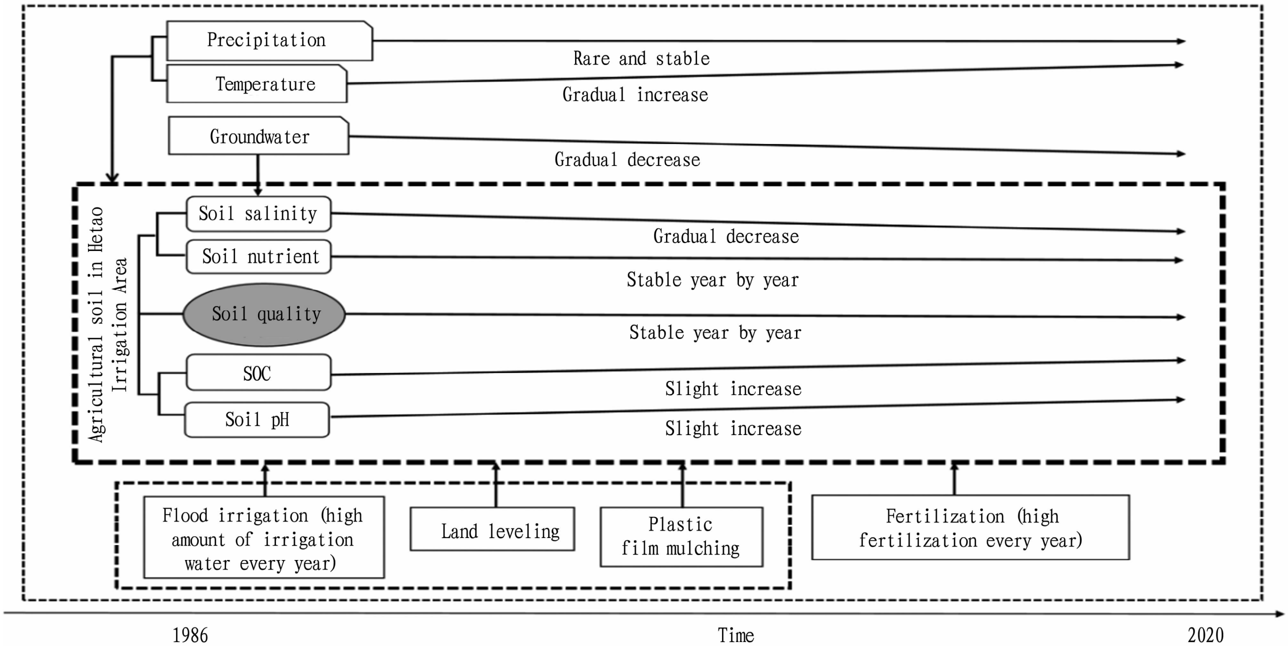


Fig. 5 Changing trend of agricultural soil quality, SOC, pH, salinity, nutrients and environmental factors over time in Hetao Irrigation District

8 Conclusions

The empirical framework proposed in this study can be used as a theoretical norm for evaluating soil quality under the condition of washing salinity by irrigation. According to the empirical framework, under the long-term operation of washing salinity by irrigation, the soil quality in Hetao Irrigation District showed a stable trend with time. But there are also two problems: (i) excessive ratess of irrigation rate and fertilization leads to serious nutrient leaching and pollution of natural water system; (ii) soil pH tends to increase. These two problems (including three factors: irrigation rate, fertilization, soil pH) are not out of balance with the other four factors, so the soil quality in Hetao Irrigation District showed a stable trend in the past. However, if the two problems can not be resolved, they will lead to the imbalance of various factors, and the soil quality will be seriously reduced. Therefore, it is suggested that future research and implementation should focus on how to adjust these three factors to maintain the long-term stability of soil quality. The framework also provides a reference for other regions.

References

[1] ORDOS. Inner Mongolia irrigation structure included in ICID register. Ordos New Media Center, China Daily. (2019-11-13) [2021-6-15]. http://subsites. Chinadaily. Com. Cn/ordosen/en/2019-09/04/c _ 405397. html. (in Chinese).

[2] Nachshon U. Cropland soil salinization and associated hydrology: trends, processes and examples[J]. Water, 2018, 10(8): 1030.

[3] SHI H, TAKEO A, KINZO N, *et al.* Simulation of leaching requirement for Hetao Irrigation Area considering salt redistribution after irrigation[J]. Transactions of the Chinese Society of Agricultural Engineering, 2002, 5: 67 – 72. (in Chinese).

[4] HOU GJ, GAO HM, WANG SC, *et al.* An introduction to agricultural soils in China[M]. Beijing, China: Agricultural Press, 1982. (in Chinese).

[5] LIANG JC, LI RP, SHI HB, *et al.* Effect of mulching on transport and distribution of nutrients in saline soil in Hetao Irrigation Area[J]. Journal of Agricultural Machinery, 2016, 47(2): 113 – 121. (in Chinese).

[6] YANG XH, XIA YH, WEI X, *et al.* Influence of traditional irrigation methods on farmland water environment in Hetao Irrigation Area and its control measures[J]. Modern Agricultural Technology. 2017, 1: 171, 177. (in Chinese).

[7] WANG YH, GAO XL, BAI LJ, *et al.* Study on the construction of ecological security barrier in Northern Inner Mongolia[J]. Environment and Development, 2019, 31(9): 202 – 205. (in Chinese).

[8] LGAM. Framework. The Local Government & Municipal (LGAM) Knowledge Base, The Knowledge Bases Australia. [R/OL]. (2008-10-1) [2021-7-12]. http://www. Lgam. Info/framework. Html.

[9] WANG LP, LIU TX, DING YH, *et al.* Analysis on the characteristics and trend of climate change in Hetao Irrigation Area in recent 50 years [J]. Journal of Beijing Normal University (Natural Science Edition), 2016, 52(3): 402 – 407. (in Chinese).

[10] GENG Q, WU P, ZHAO X, *et al.* A framework of indicator system for zoning of agricultural water and land resources utilization: A case study of Bayannur, Inner Mongolia[J]. Ecological Indicators, 2014, 40: 43 – 50.

[11] LAI LM, MEI L, YANG Y. Analysis on characteristics and development of agricultural soil in Hetao Irrigation Area of Inner Mongolia[J]. Jiangsu Agricultural Sciences, 2022, 50(02): 213 – 218. (in Chinese).

[12] WALKLEY A, BLACK IA. An examination of the degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method[J]. Soil Science, 1934, 37(1): 29 – 38.

[13] MCLEAN EO. Soil pH and lime requirement. Methods of soil analysis: part 2 chemical and microbiological properties[M]. Madison, Wisconsin, USA: American Society of Agronomy, Soil Science Society of America, 1982, 199 – 224.

[14] LY/T 1239-1999 Determination of pH value of forest soil[S]. Forestry Industry Standard of the People's Republic of China, 1999. (in Chinese).

[15] WANG LP, CHEN YX, ZENG GF, *et al.* Irrigation and drainage and salinization control in Hetao Irrigation Area, Inner Mongolia[M]. Beijing: Water Conservancy and Electric Power Press, 1993: 315. (in Chinese).

[16] LI WB. Study on recommended fertilization of wheat and maize in Hetao Irrigation Area of Inner Mongolia[D]. Beijing: Chinese Academy of Agricultural Sciences, 2011: 80–81. (in Chinese).

[17] BÜNEMANN EK, BONGIORNO G, BAI Z, *et al.* Soil quality: A critical review[J]. Soil Biology and Biochemistry, 2018, 120: 105–125.

[18] CHEN ED. A brief history of water conservancy in Hetao Irrigation Area [M]. Beijing: Water Conservancy and Electric Power Press, 1988. (in Chinese).

[19] MCCAULEY A, JONES C. Soil and water management module 4: water and solute transport in soils. A self-study course from the MSU extension service continuing education series, Minnsota State University (MSU), USA. (2019-7-13)[2021-7-10]. http://landresources. Montana. Edu/swm/. Html.

[20] HUANG ZH. Summary of academic symposium on prevention and control of saline-alkali soil in Mongolia and Ningxia[J]. Ningxia Agriculture and Forestry Science and Technology, 1963, 11: 28–29. (in Chinese).

[21] XU RH. Discussion on control measures of secondary saline-alkali land in Inner Mongolia[J]. China Water Conservancy, 1962, 9: 22–28. (in Chinese).

[22] BAI DC. Experimental report on plastic film mulching cultivation in Hetao Irrigation Area[J]. Inner Mongolia Agricultural Science and Technology, 1983, 4: 8–12. (in Chinese).

[23] LIU YC. Analysis on autumn irrigation function and autumn irrigation water saving potential in Hetao Irrigation Area of Inner Mongolia[J]. Inner Mongolia Water Conservancy, 2017, 5: 51–52. (in Chinese).

[24] National Bureau of Statistics. China Statistical Yearbook 2019[M]. Beijing: China Statistics Press, 2019. (in Chinese).

[25] BONTEN L, KROES JG, GROENENDIJK P, *et al.* Modeling diffusive Cd and Zn contaminant emissions from soils to surface waters[J]. Journal of Contaminant Hydrology, 2012, 138: 113–122.

[26] GROENENBERG JE, RÖMKENS PFAM, COMANS RNJ, *et al.* Transfer functions for solid - solution partitioning of cadmium, copper, nickel, lead and zinc in soils: derivation of relationships for free metal ion activities and validation with independent data[J]. European Journal of Soil Science, 2010, 61(1): 58–73.

[27] GROENENBERG JE. Evaluation of models for metal partitioning and speciation in soils and their use in risk assessment[D]. Wageningen University, Wageningen, Netherlands, 2011. (2011-2-18)[2020-2-13]. https://library. Wur. Nl/webquery/wurpubs/fulltext/162091. Pdf.

[28] MCBRIDE M, SAUVE S, HENDERSHOT W. Solubility control of Cu, Zn, Cd and Pb in contaminated soils[J]. European Journal of Soil Science, 1997, 48(2): 337–346.

[29] LI BG, GONG YS, ZUO Q, *et al.* Dynamic model of farmland soil water and its application[M]. Beijing: Science Press, 2000. (in Chinese).

[30] BRAY RH. Ionic competition in base-exchange reactions[J]. Journal of the American Chemical Society, 1942, 64: 954–963.

[31] HILL MW, HOPKINS BG, JOLLE VD, *et al.* Phosphorus mobility through soil increased with organic acid-bonded phosphorus fertilizer (Carbond® P)[J]. Journal of Plant Nutrition, 2015, 38(9): 1416–1426.

[32] LOWRANCE R. Nitrogen outputs from a field-size agricultural watershed [J]. Journal of Environmental Quality, 1992, 21(4): 602–607.

[33] CARRILLO-GONZALEZ R. Mechanisms and pathways of trace element mobility in soils[J]. Advances in Agronomy, 2006, 91: 111–178.

[34] FENG ZZ, WANG XK, FENG ZW. Soil N and salinity leaching after the autumn irrigation and its impact on groundwater in Hetao Irrigation Area, China[J]. Agricultural Water Management, 2005, 71(2): 131–143.

[35] NEIDHARDT H, NORRA S, TANG X, *et al.* Impact of irrigation with high arsenic burdened groundwater on the soil-plant system: results from a case study in the Inner Mongolia, China[J]. Environmental Pollution, 2012, 163(4): 8–13.

[36] GUAN XY, GAO ZY, WANG SL, *et al.* Effect of autumn irrigation quota on soil salt leaching in Hetao Irrigation Area[C]. National Symposium on Agricultural Soil and Water Engineering, 2010, 470–477. (in Chinese).

[37] Nanjing Institute of Soil, Chinese Academy of Sciences. Chinese Soil [M]. Beijing, China: Science Press, 1978. (in Chinese).

[38] Soil Taxonomy Research Group, Nanjing Institute of Soil Research, Chinese Academy of Sciences, China Soil Taxonomy Research Cooperation Group. Chinese soil taxonomy: the first scheme[M]. Beijing: Science Press, 1991. (in Chinese).

[39] PAN MH, LI Y, SUMNER ME. Handbook of soil sciences: properties and processes, second edition[M]. Boca Raton: CRC Press, 2011.

[40] LIU CX. Screening of saline-alkali tolerant microorganisms and their role in the formation of saline-alkali soil aggregates[D]. Nanjing: Nanjing Agricultural University, 2009. (in Chinese).

[41] KING GM, HENRY K. Impacts of experimental flooding on microbial communities and methane fluxes in an urban meadow, Baton Rouge, Louisiana[J]. Frontiers in Ecology and Evolution, 2019, 7: 288.

[42] UNGER IM, KENNEDY AC, MUZIKA RM. Flooding effects on soil microbial communities[J]. Applied Soil Ecology, 2009, 42(1): 1–8.

[43] RENGASAMY P, TAVAKKOLI E, MCDONALD GK. Exchangeable cations and clay dispersion: net dispersive charge, a new concept for dispersive soil[J]. European Journal of Soil Science, 2016, 67(5): 659–665.

[44] RIGI MR, FARAHBAKHSH M, REZAEI K. Adsorption and desorption behavior of herbicide metribuzin in different soils of Iran[J]. Journal of Agricultural Science & Technology, 2015, 17(3): 777–787.

[45] Soil Survey Office of Bayannur League. Bayannur soil in Inner Mongolia Autonomous Region: the second soil survey report of Inner Mongolia Autonomous Region[M]. Bayannur League Soil Survey Office, 1987. (in Chinese).

[46] LI WB. Study on recommended fertilization of wheat and maize in Hetao Irrigation Area of Inner Mongolia[D]. Beijing: Chinese Academy of Agricultural Sciences, 2011. (in Chinese).

[47] ZHANG N, ZHANG DL, QU ZY, *et al.* Spatial variability of organic matter in Hetao Irrigation Area of Inner Mongolia at different scales[J]. Journal of Ecology, 2016, 35(3): 630–640. (in Chinese).

[48] LIU X, WEI ZS, WANG CS, *et al.* Spatial analysis of soil salinization in Hetao Irrigation Area based on ArcGIS[J]. People's Yellow River, 2011, 33(12): 88–91. (in Chinese).

[49] LI X, JIAO Y, DAI G, *et al.* Soil bacterial community diversity of different saline-alkali degrees in Hetao Irrigation Area of Inner Mongolia [J]. Chinese Environmental Science, 2016 36(1): 249–260. (in Chinese).

[50] HU Q. Effect of irrigation water on organic carbon and water and salt transport in saline-alkali soil[D]. Shandong Tai'an: Shandong Agricultural University, 2019. (in Chinese).

[51] WHEAT A. Meteorological data. Wheat germ-agricultural meteorology big data system V1.4.5, Wheat Germ Big Data Information (Ningbo) Co., Ltd. (2021-12-22)[2022-3-20]. Http://www. wheata. cn. (in Chinese).