HAL
open science

Reinforced soil salinization with distance along the river: A case study of the Yellow River Basin

Xiquan Wang, Hongyuan Zhang, Zhizhong Zhang, Chenping Zhang, Kai Zhang, Huancheng Pang, Stephen M Bell, Yuyi Li, Ji Chen, R Thompson

To cite this version:

Xiquan Wang, Hongyuan Zhang, Zhizhong Zhang, Chenping Zhang, Kai Zhang, et al.. Reinforced soil salinization with distance along the river: A case study of the Yellow River Basin. Agricultural Water Management, 2023, 279, pp.108184. 10.1016/j.agwat.2023.108184 . hal-03967512

HAL Id: hal-03967512

https://hal.science/hal-03967512v1

Submitted on 1 Feb 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Agricultural Water Management 279 (2023) 108184

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Reinforced soil salinization with distance along the river: A case study of the Yellow River Basin

Xiquan Wang [a], Hongyuan Zhang [a], Zhizhong Zhang [b], Chenping Zhang [b], Kai Zhang [c], Huancheng Pang [a], Stephen M. Bell [d], Yuyi Li [a,*], Ji Chen [e,f,g]

[a] Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, China
[b] Bayannur Modern Agriculture and Animal Husbandry Development Center, Bayannur 015000, China
[c] College of Tobacco, Henan Agricultural University, Zhengzhou 450002, China
[d] Laboratoire des Sciences du Climat et de l'Environnement, LSCE-IPSL (CEA-CNRS-UVSQ), Université Paris-Saclay, 91191 Gif-sur-Yvette, France
[e] Department of Agroecology, Aarhus University, Tjele 8830, Denmark
[f] Aarhus University Centre for Circular Bioeconomy, Aarhus University, Tjele 8830, Denmark
[g] iCLIMATE Interdisciplinary Centre for Climate Change, Aarhus University, Roskilde 4000, Denmark

ARTICLE INFO

Handling Editor Dr R. Thompson

Keywords:
Soil salinization
Cation exchange capacity
Exchangeable sodium percentage
Soil pH
Structural equation model

ABSTRACT

Clarifying the relationship between salt-affected soils and their adjacent river systems is critical to address the challenges posed by soil salinization on agricultural production. Among the various biophysical and land management factors linked to soil salinization, few studies have investigated the importance of the distance along the river. Based on the Hetao Irrigation District of the Yellow River Basin, we collected 5314 soil samples and analyzed 17 soil parameters to explore the relationship between salt-affected soils and their distance along the river. Soil salinization was reinforced by the distance along the river, as a trade-off between soil ion accumulation and nutrient regulation. Soil total water-soluble salt content increased by 16.4 mg kg^{-1} every kilometer, likely due to ions leaching from the soils upstream and partially accumulating in the soils downstream, especially for Cl^-, SO_4^{2-}, and Na^+. Greater input and less solubility of Ca^{2+} based soil amendments, phosphorus fertilizers, and organic materials on the less salt-affected soils upstream may explain the declines in soil Ca^{2+}, available phosphorus, and soil organic matter with distance along the river. With every kilometer along the river, soil exchangeable sodium and cation exchange capacity increased by 8.89×10^{-4} and 1.26×10^{-2} cmol kg^{-1}, respectively, which led to an increase in soil exchangeable sodium percentage by 9.59×10^{-5}. The increase in soil exchangeable sodium along the river was mainly due to Na^+ accumulation, while soil cation exchange capacity was regulated by soil organic matter and total nitrogen. Soil pH increased by 1.21×10^{-3} per kilometer along the river, associated with the decrease of soil organic matter. Future saline soil amelioration and reutilization initiatives at regional scales may be improved by accounting for the changes in soil physicochemical properties resulting from the distance along the river.

1. Introduction

Globally, soil salinization has been recognized as a pressing issue that threatens agricultural production, ecosystem health, and food security (Hopmans et al., 2021). Approximately one billion hectares of arid and semi-arid areas remain barren due to salinity or water scarcity, and nearly 20% of irrigated land is affected by secondary salinization (Sahab et al., 2021). China, for instance, has ~34 million hectares of saline soil, 36% of which can be potentially used for agricultural production after amelioration (Wang et al., 2017). Soil salinization is not just a function of the properties of the soil itself, but also the water-related conditions of the surrounding land (Hayat et al., 2019). Hence salt-affected soils frequently occur in alluvial plains, intensively irrigated districts, and river valleys, such as the Indo-Gangetic Basin in India, the Indus Basin in Pakistan, and the Yellow River Basin in China. The level of soil salinity in these regions is closely related to the spatial distribution of their river systems (Shahid et al., 2018). Therefore, to promote amelioration of saline soils and their subsequent reutilization in salt-affected regions, the spatial relationships between local river systems and salt-affected soils must first be understood.

* Corresponding author.
E-mail address: liyuyi@caas.cn (Y. Li).

https://doi.org/10.1016/j.agwat.2023.108184
Received 12 September 2022; Received in revised form 12 January 2023; Accepted 20 January 2023
Available online 1 February 2023
0378-3774/© 2023 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

The distance along the river (DAR) is a crucial parameter for characterizing the relationship between river systems and their adjacent soils. It is defined as the curve length from the entrance point of the river into the study area to the projection point of the specific sampling site, as illustrated in Fig. 1 for the Yellow River. It may also be an important factor influencing soil salinization throughout the stream network (Kaushal et al., 2017). Generally, the groundwater table becomes shallower with increasing DAR, leading to an upward movement and accumulation of salt in surface soils (Mao et al., 2020). Indeed, human-dominated land and water use accelerates weathering and increases anthropogenic salts and available and total nutrients (Jin et al., 2021). And yet it is the physical processes, such as salt transport pathways, irrigation, and drainage practices, that modulate the relationship between DAR and soil salinization. A previous study demonstrated that the accumulation of ions and water-extractable organic matter in streams increase from upstream to downstream (Zhang et al., 2021), but whether it contributed greatly to soil salinization in the irrigated agriculutral district remains to be determined.

Clarifying the nature of this relationship will provide much needed scientific support for sustainable soil and water use, saline soil amelioration, and soil health maintenance in salt-affected regions. Although several studies have focused on the drivers of primary and secondary salinities (Daliakopoulos et al., 2016; Hayat et al., 2019; Hopmans et al., 2021), few have isolated the role of DAR in relation to soil salinization. Severe soil salinization is characterized by high values for total water-soluble salt content, pH, and exchangeable sodium percentage (ESP), which is determined by the ratio of exchangeable sodium to the cation exchange capacity (CEC) (Sahab et al., 2021). Both soil total water-soluble salt and pH are usually affected by the soil ions, where major cations of saline soil are sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}), and major anions are chloride (Cl^-), sulphate (SO_4^{2-}), bicarbonate (HCO_3^-), and carbonate (CO_3^{2-}) (Qadir et al., 2000). In addition, soil exchangeable sodium and CEC are mainly influenced by soil ions and soil nutrients (Hopmans et al., 2021), and soil nutrients have been correlated with soil organic matter (SOM), total nitrogen (TN), alkaline hydrolyzed nitrogen, available phosphorus, and exchangeable potassium.

Here, we have explored the relationship between DAR and the extent of soil salinization in the Hetao Irrigation District, China, by sampling and analyzing 5314 soil samples. The main objective of this work is to define the relationship between DAR and soil cations (Na^+, K^+, Ca^{2+}, and Mg^{2+}), anions (Cl^-, SO_4^{2-}, HCO_3^-, and CO_3^{2-}), nutrients (SOM, TN, alkaline hydrolyzed nitrogen, available phosphorus, and exchangeable potassium), and salinization indexes (total water-soluble salt, soil pH, exchangeable sodium, CEC, and ESP). We will determine whether DAR relates to soil salinization, and, if so, the nature and intensity of this relationship (i.e., direct or indirect). We hypothesize that soil salinization is reinforced by DAR, directly and indirectly related to soil ions and nutrients.

2. Materials and methods

2.1. Study area

The Hetao Irrigation District (40°19′~41°18′N, 106°20′~109°19′E) is located in the northern section of the Yellow River, the second longest river in China. It is an alluvial flood plain and represents a typical salt-affected region of the river system. The average elevation is 1007–1050 m (Nie et al., 2021). It is tilted from southwest to northeast with a 0.2‰ slope, and bordered by the Langshan Mountain to the north and the Yellow River to the south (Fig. 1). It is one of the largest irrigation districts and most important agricultural production regions in China, with 5.7×10^5 ha of irrigated land and 1.12×10^6 ha of total area. The salt concentration of the irrigation water taken from the Yellow River is ~0.6 g L^{-1} (Chang et al., 2019; Zhai et al., 2021), which was higher downstream than upstream. The average annual rainfall ranges from 130 to 200 mm, characterizing its arid to semi-arid continental climate (Li et al., 2020a). This region suffers from water shortages due to the large discrepancy between rainfall and evaporation (Zhang et al., 2020b), and so irrigation primarily coming from the Yellow River is essential for crop production. In addition, soil salinization is another limiting factor for agricultural development in this region, with 45% of its arable land susceptible to soil salinization (Li et al., 2020b). The soils are formed by lake and alluvial sediments deposits, which led to finer soil textures following directional patterns. In other words, soil textures are sandy loam to silt loam in the southern and western parts, while they

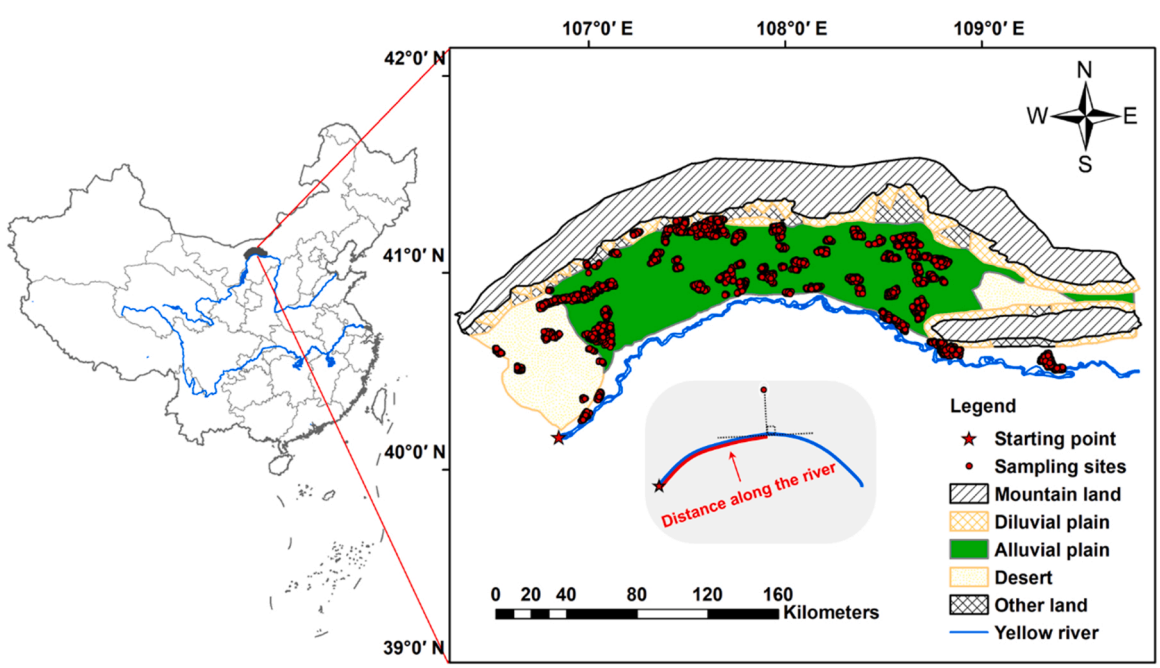


Fig. 1. Location of the Hetao Irrigation District study area and sampling sites. The distance along the river (DAR) is defined as the curve length from the entrance point of Yellow River into the study area to the projection point of the sampling site.

are silt to clay in the northern and eastern parts (Ren et al., 2016). More detailed information can be found in Guo et al. (2008).

2.2. Soil sampling and measurement

Soil samples were collected from 7.2 × 10^4 ha of arable land before irrigation in November and December 2017 using a grid sampling strategy (Fig. 1). First, the borders of 5399 sampling sites with an area of 13.3 ± 3.3 ha per site were outlined. Next, a subsampling site of 3.3 ha was selected randomly from each sampling site. And finally, ten representative soil subsamples were collected from the subsampling site to produce one composite sample (Fig. S1). All sampling positions were located using a global positioning system device. Overall, a total of 5399 composite samples were collected from the 0–20 cm soil depth by an electric soil auger in the field, of which 5314 samples were ultimately measured and 85 samples rejected due to unclear labelling or poor

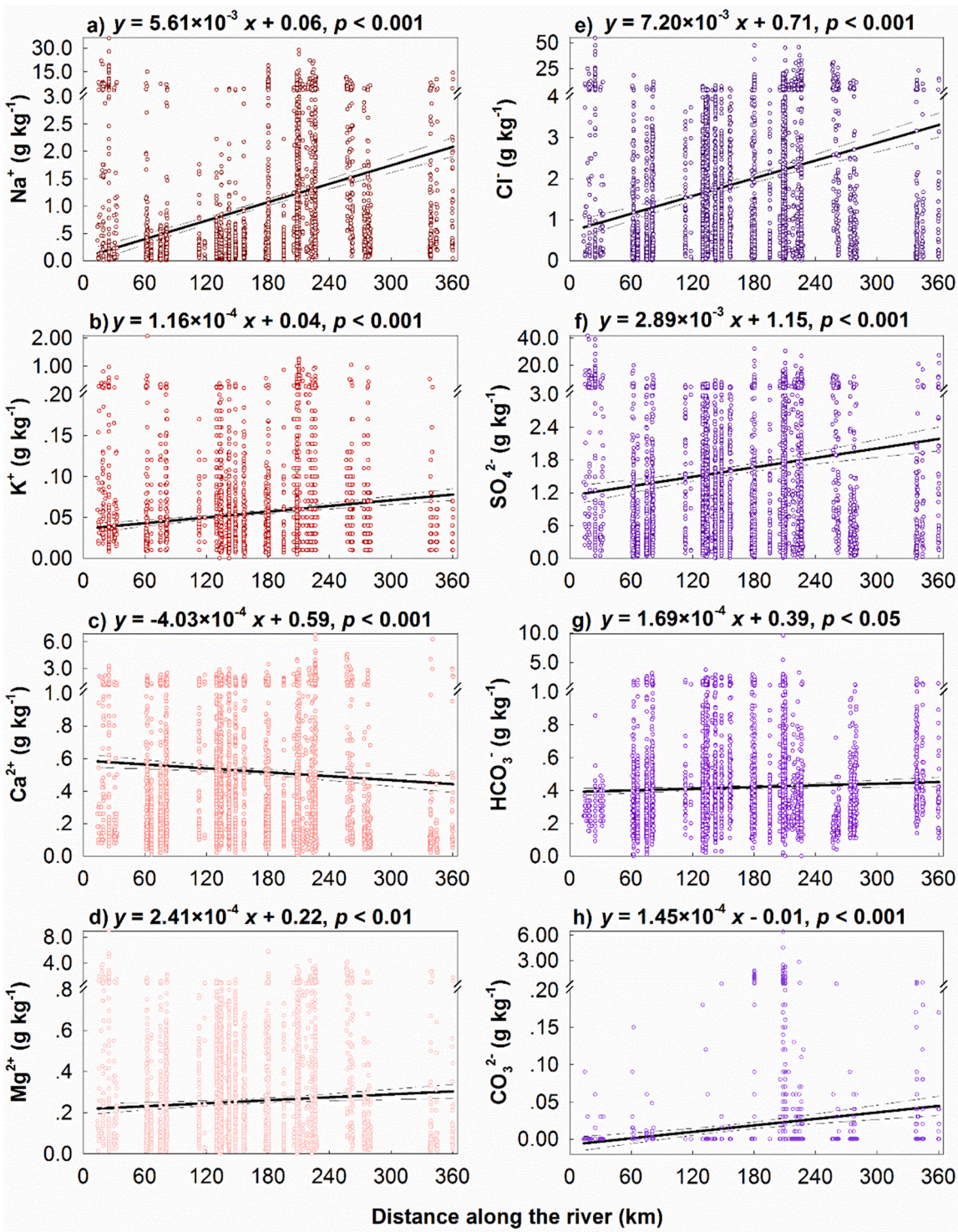


Fig. 2. Relationships between water-extractable ions and the distance along the river (DAR). There are four types of cations, a) Na^+, b) K^+, c) Ca^{2+}, and d) Mg^{2+}, as well as four types of anions, e) Cl^-, f) SO_4^{2-}, g) HCO_3^-, and h) CO_3^{2-}. The solid and dashed lines indicate the linear regression lines and 95% confidence intervals (n = 5314), respectively.

preservation. Only active arable lands were sampled, and the regions that were not sampled were mostly barren due to salinity or water scarcity. In other words, similar land use type, cropping system, irrigation regime, and so on, were ensured at a regional scale.

A total of 17 soil parameters were analyzed. Four types of cations (Na^+, K^+, Ca^{2+}, and Mg^{2+}) were determined using an Atomic Absorption Spectrophotometer by inductively coupled plasma mass spectrometry (ICP-MS). Anions Cl^-, HCO_3^-, and CO_3^{2-} were detected by titrimetric method, and SO_4^{2-} was analyzed by the barium sulfate turbidity method (Bao, 2000). SOM and TN were measured by the $K_2Cr_2O_7$ oxidation-reduction titration and Kjeldahl digestion methods (Bao, 2000), respectively. Alkaline hydrolyzed nitrogen was assayed using the alkaline hydrolysis diffusion method. Available phosphorus and exchangeable potassium were extracted with $NaHCO_3$ (0.5 mol/L) and NH_4OAc (1 mol/L), and determined using a Continuous Flow Analyzer (Skalar+Analytical, Breda, Netherlands) and flame photometry (BWB Technologies, Newbury, UK), respectively. The total water-soluble salt was measured using the residual drying method, and its threshold values for non, slightly, moderately, and highly saline soil are 2, 4, 6, and 10 g kg^{-1} in the Hetao Irrigation District, respectively (Table S1). The soil pH was assessed with a pH meter in a 1:2.5 soil-to-water suspension, with similar readings and following a linear relationship with the 1:5 soil-to-water suspension international standard (Huang et al., 2021). The exchangeable sodium was extracted with 1 M NH_4OAc (deionized water) and detected using an Atomic Absorption Spectrophotometer (AA-7000, Shimadzu Inc., Japan). The CEC was measured by the sodium acetate extraction method. The ESP was determined based on the ratio of exchangeable sodium (Exch-Na) to CEC, both expressed in ($cmol_c$ kg^{-1}) (Richards, 1954), according to Eq. 1:

$$\text{ESP}\ (\%) = \text{Exch-Na} / \text{CEC} \times 100 \tag{1}$$

2.3. Statistical analysis and structural equation modeling

All datasets were tested for normality and homogeneity before analysis. A nonparametric test (Kruskal–Wallis) was used when either data normality (Shapiro–Wilk test), symmetry (coefficient of symmetry between −1.96 and 1.96) or the equality of error variances (Levene's test) was not confirmed per dataset. DAR was calculated using the ArcGIS 10.4 platform (Fig. 1). The total length of DAR considered in this study was 360.6 km, and a similar extent of variation was assumed

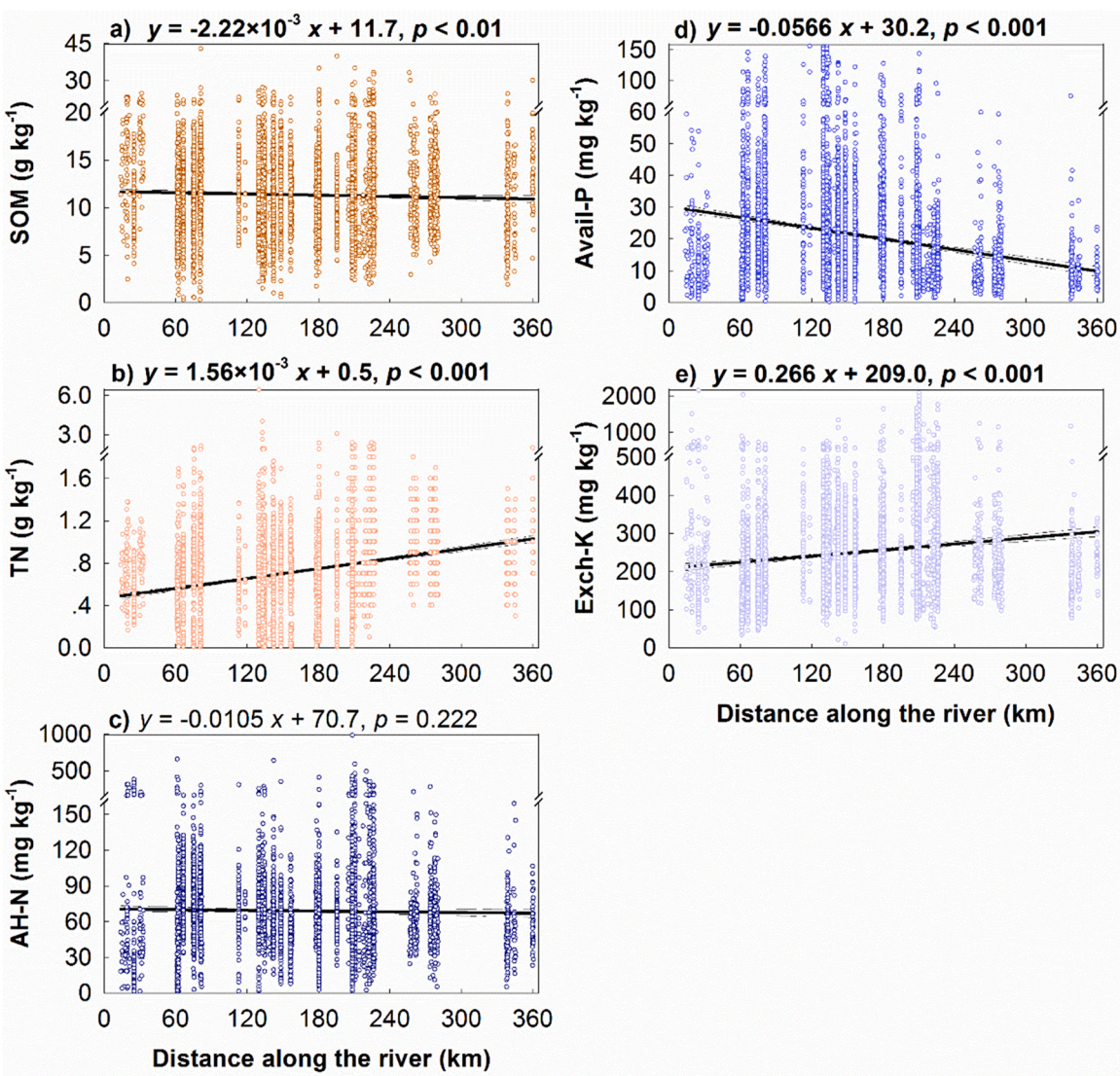


Fig. 3. Relationships between soil fertility parameters and the distance along the river (DAR). There are two types of soil total nutrients, a) soil organic matter (SOM) and b) total nitrogen (TN), as well as three types of soil available nutrients, c) alkaline hydrolyzed nitrogen (AH-N), d) available phosphorus (Avail-P), and, e) exchangeable potassium (Exch-K). The solid and dashed lines indicate the linear regression lines and 95% confidence intervals ($n = 5314$), respectively.

lateral to the river based on the grid sampling approach and high quantity of soil samples taken. The relationships between DAR and soil parameters were tested by linear regressions (Figs. 2–4), and their Pearson's correlation coefficients were calculated using SPSS version 21.0 software (IBM SPSS Software Inc., Armonk, NY, USA). All regressions and correlations were considered at an error probability of $p < 0.05$. Figures were plotted with SigmaPlot 14.0 software (Systat Software Inc., San Jose, CA, USA).

Redundancy analysis (RDA) was conducted to explore the potential soil parameters affecting soil salinization using CANOCO 5.0 (Microcomputer Power, Ithaca, NY, USA) (Fig. 5). In order to test the hypothesis that soil salinization was reinforced by DAR and associated with soil ions and nutrients, structural equation modeling (SEM) was performed to evaluate the direct and indirect relationships of DAR on the soil salinization indexes with exchangeable sodium, CEC, ESP, total water-soluble salt, and pH (Fig. 6a and S2). Based on the results of the correlation analysis, RDA analysis, and prior theoretical knowledge, other hypotheses were made for the SEM as follows: (a) DAR had indirect relationships on soil salinization through cations (Na^+, K^+, Ca^{2+}, and Mg^{2+}) and anions (Cl^-, SO_4^{2-}, HCO_3^-, and CO_3^{2-}), due to salt leaching and accumulation (Mao et al., 2020); (b) DAR had indirect relationships on soil salinization led by nutrient regulation, including total nutrients (SOM and TN) and available nutrients (alkaline hydrolyzed nitrogen, available phosphorus, and exchangeable potassium) (Hopmans et al., 2021); (c) DAR had direct relationships on soil salinization, resulting from other factors linked to DAR, such as terrain, landform, soil formation, climate conditions, and vegetation distribution (Daliakopoulos et al., 2016). Standardized total effect (STE), the sum of the direct and indirect effects of DAR on soil parameters, was calculated from the SEM (Fig. 6b). A direct effect does not pass through any intermediate variables whereas an indirect effect must pass through an intermediate variable. Bootstrapping was conducted to test the probability that path coefficients differed from zero, as a few of the variables were not normally distributed (Fan et al., 2016). The root-mean squared error of approximation (RMSEA) and goodness-of-fit index (GFI) were used to estimate model fit. All the SEM analyses were conducted with AMOS version 24.0 software (IBM SPSS Software Inc., Armonk, NY, USA).

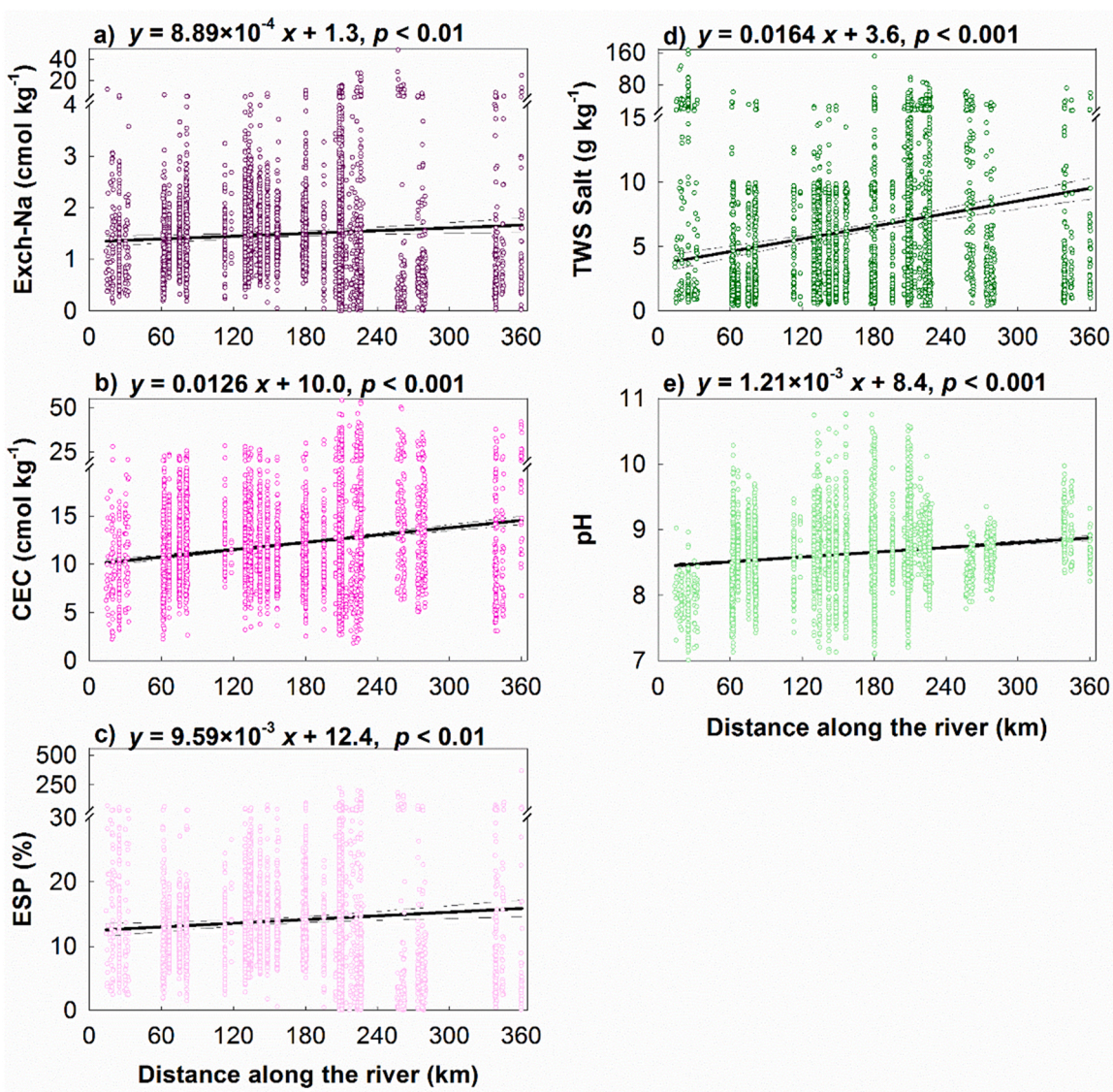
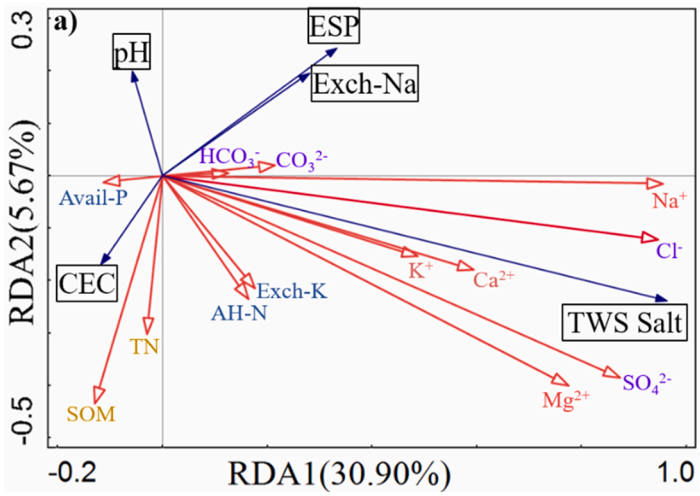


Fig. 4. Relationships between soil salinization indexes and the distance along the river (DAR). There are five types of soil salinization indexes, a) exchangeable sodium (Exch-Na), b) cation exchange capacity (CEC), c) exchangeable sodium percentage (ESP), d) total water-soluble salt (TWS salt), and e) pH. The solid and dashed lines indicate the linear regression lines and 95% confidence intervals ($n = 5314$), respectively.



b)

Environmental factors	Contribution (%)	*p* value
Na^+	74.1	**0.002**
SO_4^{2-}	8.6	**0.002**
SOM	5.9	**0.002**
Ca^{2+}	4.3	**0.002**
Mg^{2+}	1.9	**0.022**
CO_3^{2-}	1.8	**0.014**
Cl^-	1.4	**0.040**
TN	0.7	0.150
Exch-K	0.5	0.212
K^+	0.4	0.216
Avail-P	0.2	0.402
HCO_3^-	0.1	0.528
AH-N	<0.1	unknown

Fig. 5. a) Redundancy analysis (RDA) showing variations in soil salinization indexes relating to environmental factors, and b) the contributions of each environmental factor to soil salinization indexes. The angles between soil salinization indexes and environmental factors reflect their correlations, and the acute or obtuse angles represent positive or negative correlations, respectively. The explained variations of the first and second axes are given in brackets. Abbreviations: SOM, soil organic matter; TN, total nitrogen; AH-N, alkaline hydrolyzed nitrogen; Avail-P, available phosphorus; Exch-K, exchangeable potassium; Exch-Na, exchangeable sodium; CEC, cation exchange capacity, ESP, exchangeable sodium percentage; TWS salt, total water-soluble salt.

3. Results

3.1. Cation and anion relationships with DAR

Positive correlations were identified between DAR and water-extractable ions, except for Ca^{2+} ($p < 0.05$, Fig. 2). With an increase in DAR by 1 km, linear regressions indicated that Cl^-, Na^+, SO_4^{2-}, Mg^{2+}, HCO_3^-, CO_3^{2-}, and K^+ increased by 7.20, 5.61, 2.89, 0.24, 0.17, 0.15, and 0.12 mg kg^{-1}, while Ca^{2+} decreased by 0.40 mg kg^{-1}. Notably, higher increments were detected for Cl^-, Na^+, and SO_4^{2-}, being more than ten times that of Mg^{2+}, HCO_3^-, CO_3^{2-}, and K^+.

3.2. Total and available nutrient relationships with DAR

Opposing responses of SOM and TN to DAR were found (Fig. 3a and b). For every increase in DAR by 1 km, SOM decreased by 2.22 mg kg^{-1}, while TN increased by 1.56 mg kg^{-1}. No relationship was detected between DAR and alkaline hydrolyzed nitrogen (Fig. 3c). Available phosphorus decreased by 0.057 mg kg^{-1}, while exchangeable potassium increased by 0.266 mg kg^{-1} with 1 km increase in DAR (Fig. 3d and e).

3.3. Soil salinization relationship with DAR

With an increase in DAR by 1 km, exchangeable sodium and CEC increased by 8.89×10^{-4} and 1.26×10^{-2} cmol kg^{-1}, respectively (Fig. 4a and b). Therefore, the ratio of exchangeable sodium to CEC (i.e., ESP) increased by 9.59×10^{-5} per km in DAR (Fig. 4c). Total soil water-soluble salt and soil pH increased by 16.4 mg kg^{-1} and 1.21×10^{-3} for every km in DAR, respectively (Fig. 4d and e). Overall, soil salinization was always evaluated by ESP, total soil water-soluble salt, and soil pH, it was reinforced with DAR.

3.4. Direct and indirect relationships of DAR on soil salinization

Redundancy analysis showed that Na^+, SO_4^{2-}, SOM, Ca^{2+}, Mg^{2+}, CO_3^{2-}, and Cl^- were the key driving factors for the soil salinization indexes (Fig. 5a). They contributed 74.1%, 8.6%, 5.9%, 4.3%, 1.9%, 1.8%, and 1.4% of the variance in soil salinization indexes, i.e., exchangeable sodium, CEC, ESP, total water-soluble salt, and pH in this study (Fig. 5b, $p < 0.05$).

Multiple direct and indirect associations were found between DAR and soil salinization indexes (Fig. 6a and S2). DAR was positively correlated with cations (Na^+, K^+, Ca^{2+}, and Mg^{2+}), anions (Cl^-, SO_4^{2-}, HCO_3^-, and CO_3^{2-}), and total nutrients (SOM and TN), while it was negatively associated with available nutrients (alkaline hydrolyzed nitrogen, available phosphorus, and exchangeable potassium) ($p < 0.001$). A high path coefficient was found from DAR to soil pH (coefficient = 0.34, $p < 0.001$). DAR mainly affected CEC (STE = 0.172), total water-soluble salt (STE = 0.139), and soil pH (STE = 0.166), rather than exchangeable sodium (STE = 0.037) and ESP (STE = −0.010) (Fig. 6b). Overall, the SEM explained 14% of the differences in total water-soluble salt, 26% for CEC, 32% for pH, 35% for exchangeable sodium, and 85% for ESP (Fig. 6a).

4. Discussion

4.1. Cation and anion relationships with DAR

The fact that the concentrations of most water-extractable ions showed an increasing trend with DAR could be the result of irrigation and drainage in the arable lands, with these ions being dissolved from soils upstream and subsequently transported along the river to be accumulated in soils downstream (Paudyal et al., 2016). Conversely, water-extractable Ca^{2+} is known to be converted into insoluble salts (such as $CaCO_3$), and release soluble cations (such as Na^+). Ca^{2+} based soil amendments, such as commercial calcium sulfate and flue gas desulfurization gypsum, have been regularly applied during saline land amelioration in this region (Wang et al., 2017). Notably, the lands upstream generally had lower salt contents than downstream, implying a positive feedback loop where land managers preferentially select these less-saline lands to ameliorate for cultivation over more-saline lands downstream (Li et al., 2020b). These processes could explain the decreases in soil Ca^{2+} content and the ratio of Ca^{2+} to Mg^{2+} (Fig S3), and the increase in soil Na^+ content upstream to downstream.

This region is notably distributed with sulfate-chloride and chloride-sulfate saline soils, as indicated by the much higher contents of Cl^- (1.83 ± 3.68 g kg^{-1}, means ± standard deviations), SO_4^{2-} (1.60 ± 2.70 g kg^{-1}), and Na^+ (0.93 ± 2.17 g kg^{-1}) compared to the other ions (Fig. 2). The fact that the rates of increase for Cl^-, Na^+, and SO_4^{2-} were more than ten times the rates of Mg^{2+}, HCO_3^-, CO_3^{2-}, and K^+ calls for special attention to be put on these three ions in soils with greater DAR (Zhou et al., 2021).

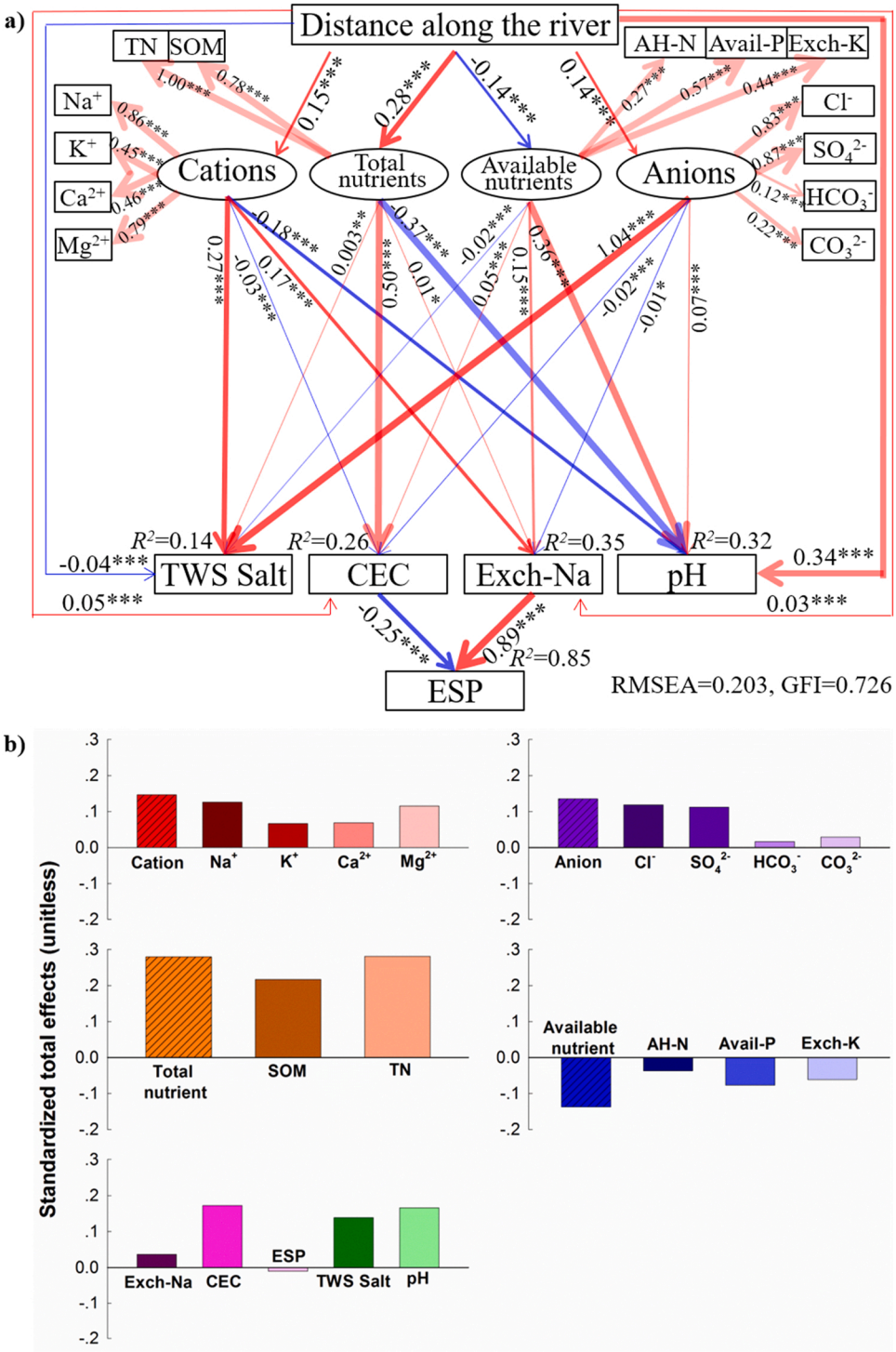


Fig. 6. a) Structural equation model (SEM) for the direct and indirect relationships of the distance along the river (DAR) on soil salinization indexes, and b) Standardized total effects (STE) from the SEM, the sum of the direct and indirect effects of the distance along the river (DAR) on soil parameters. Red and blue arrows indicate positive and negative relationships, respectively. Arrow width is proportional to the strength of the relationship. Numbers near the arrow lines are indicative of the correlations. The proportion of explained variance (R^2) appears alongside soil salinization indexes in the model. Significance levels of each predictor are $^{*}p < 0.05$, $^{**}p < 0.01$, and $^{***}p < 0.001$. RMSEA, root-mean squared error of approximation; GFI, the goodness-of-fit index for the model. Abbreviations: SOM, soil organic matter; TN, total nitrogen; AH-N, alkaline hydrolyzed nitrogen; Avail-P, available phosphorus; Exch-K, exchangeable potassium; Exch-Na, exchangeable sodium; CEC, cation exchange capacity, ESP, exchangeable sodium percentage; TWS salt, total water-soluble salt.

4.2. Total and available nutrient relationships with DAR

The accumulation of water-extractable organic matter is known to increase from upstream to downstream in river systems (Dong et al., 2020; Stutter and Cains, 2017; Ye et al., 2019; Zhang et al., 2021), leading to this study's hypothesis that the SOM content would increase in soils upstream to downstream. However, the response of SOM to DAR was more influenced by carbon inputs from organic materials (e.g., crop residues) than those from irrigation water. The retention of organic materials in the fields is indeed one of the main strategies for saline soil amelioration in this region, which directly increases SOM contents (Huo et al., 2017). As discussed before, land managers preferentially select these less-saline lands upstream to ameliorate for cultivation over more-saline lands downstream (Li et al., 2020b). Crop performance and distribution also contributed to the variation of SOM content with DAR. Crops grew better in upstream areas compared to downstream areas, partly due to a higher ratio of Ca^{2+} to Mg^{2+} (Karimov et al., 2009). This ratio decreased remarkably with DAR (Fig S3), and played a negative role in regulating crop growth. In addition, the percentage of wheat and maize planting area decreased, while that of sunflower and saline-tolerant forage increased with DAR, associated with soil salinity content in upstream and downstream areas (Gao et al., 2021). The

residues of wheat and maize were partly returned to the soil, while the residues of sunflower and forage were usually removed from the farmland in this region. Therefore, SOM decreased with DAR, due to both increases in below- and aboveground organic material inputs in the land upstream than downstream. Conversely, TN increased with DAR due to higher chemical N fertilizer input in the downstream area. Lower productivity in the downstream areas usually resulted in farmers applying more N fertilizer to boost crop growth. More N application but less crop absorption led to more N accumulation in the soils downstream than soils upstream (Zhang et al., 2016). Therefore, a relatively lower ratio of SOM to TN was detected in the soil downstream compared to upstream (Fig. 3a and b). Overall, these results would suggest that more organic material inputs and less chemical N fertilizer inputs are a possible recommendation for this region, especially for the soils downstream.

This study found no significant linear correlation between alkaline hydrolyzed N and DAR. Only surface soils (0–20 cm) were collected after crop harvest in this study. In other words, potential factors like soil sampling depth, sampling period, seepage losses, and study area may weaken or alter the relationship of DAR on soil alkaline hydrolyzed N content. The soils in this region were poor in available phosphorus (21.4 $\pm$ 19.7 mg kg^{-1}, means $\pm$ standard deviations) (Fig. 3d). Therefore, phosphorus fertilizer has been typically applied annually in this region (e.g., 124.5 kg P_2O_5 ha^{-1} for maize) (Zhang et al., 2013). Phosphorus is easily fixed in soils through adsorption and chemical reaction (An et al., 2013). As mentioned before, less-saline lands upstream were earlier cultivated than more-saline lands downstream, which led to more phosphorus accumulation in the lands upstream. These factors help explain why the available phosphorus content decreased with DAR. In contrast, the soil in this region is rich in exchangeable potassium (250 $\pm$ 154 mg kg^{-1}) (Fig. 3e), promoting dissolution from the soils upstream, transportation along the river, and accumulation in the soils downstream. These processes are intensified as a result of irrigation and drainage in the saline lands. Therefore, the exchangeable potassium content increased with DAR. These results would suggest the need for more phosphorus application and less potassium fertilizers in downstream areas.

4.3. Soil salinization relationship with DAR

The CEC was mainly associated with the total nutrients (including TN and SOM in this study) (Kang et al., 2021), supported by the comparatively higher path coefficients (Fig. 5a). Even though the CEC was closely related with SOM (Beldin et al., 2007; Oorts et al., 2003), the CEC was more associated with TN (Fig S2c). These results indicate that the CEC of the saline soil with low SOM content (11.4 $\pm$ 4.4 g kg^{-1}, means $\pm$ standard deviations) depended more on mineral surfaces (indexed with TN) than organic surfaces (indexed with SOM) (Zhang et al., 2020a), and the CEC increase with DAR is mainly associated with the increases in soil TN. Field practices aimed at increasing SOM and/or TN therefore have the potential to also increase soil CEC. This supports the hypothesis that N fertilization promotes plant growth under salt stress conditions through reducing ion accumulation (Pang et al., 2005), demonstrated here due to the simultaneous increase in soil CEC and TN. This also explains why such high amounts of N fertilizer are commonly applied in this region.

The exchangeable sodium was mainly associated with cations, especially Na^+ (Sidi et al., 2015), with high path coefficients between exchangeable sodium and cations / Na^+ (Fig. 5a and S2a). Therefore, the increase of exchangeable sodium with DAR was likely due to Na^+ accumulation from the soils upstream to downstream. This result also indicates that bad drainage systems may increase ESP for the soils downstream. The ratio of exchangeable sodium to CEC (i.e., ESP) was more determined by exchangeable sodium compared to CEC, confirmed by the higher path coefficient from exchangeable sodium to ESP than that from CEC to ESP (Fig. 5a). These results indicate that the increase of ESP with DAR was mainly caused by the greater contribution of Na^+ to total cations in the soils downstream than that upstream. Field management strategies aiming to decreasing soil Na^+ content, such as underground pipe drainage (Zhou et al., 2021), therefore has the potential to decrease ESP in this region, especially with increasing DAR.

Soil total water-soluble salt was mainly influenced by anions and cations (Fig. 5a), especially for Cl^-, SO_4^{2-}, and Na^+ (Fig S2a and b), and most ions increased with DAR. Furthermore, saline land amelioration in this region usually combines with irrigation and drainage, which reduce the natural salt contents upstream and further encouraging preferential cultivation. Therefore, total water-soluble salt likely increased due to ions leaching from the soils upstream and accumulating in the soils downstream. A high path coefficient was found from DAR to soil pH, which was attributed to other factors associated with DAR influencing soil pH, such as terrain, landform, climate conditions, and vegetation distribution (Hopmans et al., 2021). Soil pH was negatively correlated with total nutrients (Fig. 5a). Specifically, soil pH was mainly affected by SOM (Fig S2c), indicating that field management practices for increasing SOM also have the potential to decrease soil pH. These results suggest that soil pH increased due to the decrease in SOM with DAR. Notably, soil pH was also positively associated with available nutrients (Fig. 5a), especially available phosphorus (Fig S2d). Some studies have demonstrated that saline soil amelioration and utilization increased soil pH (Li et al., 2015; Sun et al., 2013, 2012), simultaneously with the increases of available nutrient contents due to fertilization and irrigation. Overall, DAR is an important factor for soil salinization as it determines the dynamics of several key soil parameters for sustainable agricultural production in salt-affected regions.

4.4. Uncertainties and implications

The increase of soil salinity content with DAR can be attributed to the progressively slower flow of the river system, the higher salt concentration of the irrigation water, and the shallower groundwater table. Therefore, there will be less leaching and more upward movement and accumulation of salt in surface soils downstream than upstream (Mao et al., 2020). It is important to note that the studied soil is predominantly loess in the Hetao Irrigation District, where soil salts are more likely dissolved and run off during waterlogged conditions. Overall, the DAR is a fundamental parameter linked to soil salinization in the Yellow River basin (Fig. 7), but further research is needed to test whether this concept applies for other river systems.

The increase of soil salinity with DAR may be overestimated due to more salt leaching in soil upstream areas than downstream areas. For example, saline lands upstream have longer utilization history than those downstream, and the salinity in the surface soils is decreased through salt leaching during saline soil utilization (Chang et al., 2019). In addition, the percentage of wheat and maize planting area decreases, and that of sunflower and forage area increases with DAR (Gao et al., 2021). It has been reported that greater salt leaching is associated with more irrigation per unit of wheat and maize area, compared to sunflower and forage area (Li et al., 2020a). Therefore, the longer time period of saline soil utilization and more fresh water consumption per unit of area in upstream areas compared to downstream areas will likely cause an overestimation of the increase of soil salinity with DAR. Other uncertainties may result from the soil sampling depth and sampling period in this study, as secondary salinization is often coupled with saline soil utilization in the irrigated regions, and salt accumulation in surface soils typically occurs after crop harvest in this region (Zhang et al., 2020b). Overall, the relationship between DAR and soil salinization is closely integrated to intrinsic soil characteristics and anthropogenic activities, such as soil fertility and salinity, crop performance and distribution, as well as field management. It is noteworthy that more studies on the relationship of soil salinity and DAR are needed, which considering various new aspects of saline soil utilization history, cropping systems, and soil sampling strategies (e.g., different depths).

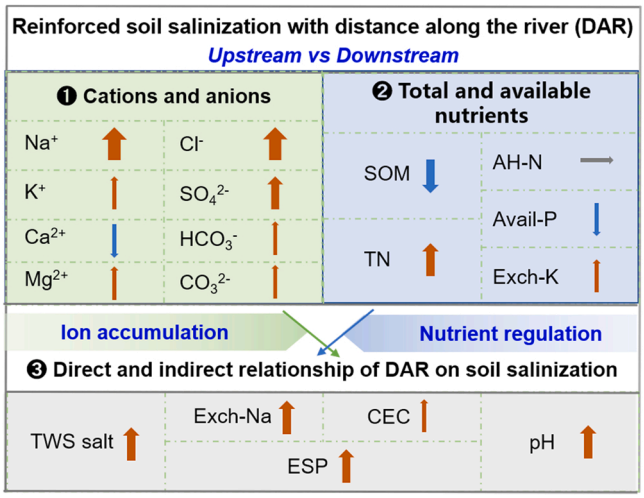


Fig. 7. Graphical abstract illustrating reinforced soil salinization with distance along the river (DAR) by ion accumulation and nutrient regulation. Orange, gray, and blue arrows indicate the parameters are increased, maintained, and decreased with DAR, respectively. Arrow width is proportional to the strength of the relationship. Abbreviations: SOM, soil organic matter; TN, total nitrogen; AH-N, alkaline hydrolyzed nitrogen; Avail-P, available phosphorus; Exch-K, exchangeable potassium; Exch-Na, exchangeable sodium; CEC, cation exchange capacity, ESP, exchangeable sodium percentage; TWS salt, total water-soluble salt.

5. Conclusion

To the best of our knowledge, this is the first study to investigate the relationship between DAR and soil salinization in the Yellow River basin, which is one of the main irrigated agricultural regions in the world facing severe salt stress. DAR was positively correlated with soil Na^+, K^+, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-, and CO_3^{2-}, TN, and exchangeable potassium, but it was negatively associated with Ca^{2+}, SOM, and available phosphorus. No significant relationship was detected between DAR and alkaline hydrolyzed nitrogen. The increase of exchangeable sodium with DAR was largely due to Na^+ accumulation from upstream to downstream, while for the cation exchange capacity it was mainly a trade-off between TN and SOM. Therefore, soil exchangeable sodium, cation exchange capacity, and exchangeable sodium percentage were increased with DAR. Soil total water-soluble salt content increased with DAR, likely due to ions leaching from the soils upstream and partially accumulating in soils downstream through irrigation and drainage, especially for Cl^-, SO_4^{2-}, and Na^+. Soil pH increased with DAR, associated with the decrease in SOM. Overall, the degree of soil salinization increased with DAR. This work suggests that DAR is a fundamental parameter linked to soil salinization in the Yellow River basin, but whether this concept holds for other river systems remains uncertain and requires further investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This study was supported by the National project (NK2022180406, NK2022180105), the National Natural Science Foundation of China (No. 31871584, 32101852), the China Postdoctoral Science Foundation (2022M710165), the Agricultural Science and Technology Innovation Program (ASTIP No. CAAS-ZDRW202201), 'Open the list' in charge of the science and technology project of Ordos (JBGS-2021-001), and Inner Mongolia Autonomous Region Research Project: Rejuvenating the Inner Mongolia with science and technology (2021EEDSCXSFQZD011).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2023.108184.

References

An, D., Yang, L., Wang, G., Lan, R., Wang, T., Jin, Y., 2013. Mechanisms of phosphorus fixation in soils and efficient utilization of phosphate fertilizer. Chem. Ind. Eng. Proc. 32, 1967–1973 (in Chinese with English abstract). ⟨https://hgxb.cip.com.cn/CN/Y2013/V32/I08/1967⟩.

Bao, S., 2000. Soil agro-chemistrical analysis. Agricultural Press, Beijing: China.

Beldin, S.I., Caldwell, B.A., Sollins, P., Sulzman, E.W., Lajtha, K., Crow, S.E., 2007. Cation exchange capacity of density fractions from paired conifer/grassland soils. Biol. Fert. Soils 43, 837–841. https://doi.org/10.1007/s00374-006-0161-y.

Chang, X., Gao, Z., Wang, S., Chen, H., 2019. Modelling long-term soil salinity dynamics using SaltMod in Hetao Irrigation District, China. Comput. Electron. Agr. 156, 447–458. https://doi.org/10.1016/j.compag.2018.12.005.

Daliakopoulos, I.N., Tsanis, I.K., Koutroulis, A., Kourgialas, N.N., Varouchakis, A.E., Karatzas, G.P., Ritsema, C.J., 2016. The threat of soil salinity: a European scale review. Sci. Total Environ. 573, 727–739. https://doi.org/10.1016/j.scitotenv.2016.08.177.

Dong, Y., Li, Y., Kong, F., Zhang, J., Xi, M., 2020. Source, structural characteristics and ecological indication of dissolved organic matter extracted from sediments in the primary tributaries of the Dagu River. Ecol. Indic. 109, 105776 https://doi.org/10.1016/j.ecolind.2019.105776.

Fan, Y., Chen, J., Shirkey, G., John, R., Wu, S.R., Park, H., Shao, C., 2016. Applications of structural equation modeling (SEM) in ecological studies: an updated review. Ecol. Process 5, 19. https://doi.org/10.1186/s13717-016-0063-3.

Gao, Y., Qiao, R., Ji, S., Bai, X., Wang, L., Chang, X., 2021. Changes and driving factors of crops planting structure in Hetao Irrigation Region in Inner Mongolia. J. Desert Res. 41, 110–117 (in Chinese with English abstract). ⟨http://www.desert.ac.cn/article/2021/1000-694X/1000-694X-2021-41-3-110.shtml⟩.

Guo, H., Yang, S., Tang, X., Li, Y., Shen, Z., 2008. Groundwater geochemistry and its implications for arsenic mobilization in shallow aquifers of the Hetao Basin, Inner Mongolia. Sci. Total Environ. 393, 131–144. https://doi.org/10.1016/j.scitotenv.2007.12.025.

Hayat, K., Bundschuh, J., Jan, F., Menhas, S., Hayat, S., Haq, F., Ali, S.M., Chaudhary, H. J., Abid, U., Zhang, D., Zhou, Y.F., Zhou, P., 2019. Combating soil salinity with combining saline agriculture and phytomanagement with salt-accumulating plants. Crit. Rev. Environ. Sci. Tech. 50, 1085–1115. https://doi.org/10.1080/10643389.2019.1646087.

Hopmans, J.W., Qureshi, A.S., Kisekka, I., Munns, R., Grattan, S.R., Rengasamy, P., 2021. Critical knowledge gaps and research priorities in global soil salinity. Adv. Agron. 1–191. https://doi.org/10.1016/bs.agron.2021.03.001.

Huang, X., Chen, G., Hong, J., Du, L., Cheng, W., Wang, S., Luo, X., Zhang, G., Jiang, L., Zhang, L., 2021. Comparing pH determination in cultivated land soil (in Chinese with English abstract). Hubei Agric. Sci. 60, 106–109. https://doi.org/10.14088/j.cnki.issn0439-8114.2021.19.022.

Huo, L., Pang, H., Zhao, Y., Wang, J., Lu, C., Li, Y., 2017. Buried straw layer plus plastic mulching improves soil organic carbon fractions in an arid saline soil from Northwest China. Soil Til. Res. 165, 286–293. https://doi.org/10.1016/j.still.2016.09.006.

Jin, L., Whitehead, P.G., Bussi, G., Hirpa, F., Taye, M.T., Abebe, Y., Charlesb, K., 2021. Natural and anthropogenic sources of salinity in the Awash River and Lake Beseka (Ethiopia): modelling impacts of climate change and lake-river interactions. J. Hydrol. -Reg. Stud. 36, 100865 https://doi.org/10.1016/j.ejrh.2021.100865.

Kang, T., Zhou, C., Wei, Z.Q., 2021. Regional distribution characteristics and influencing factors of soil cation exchange capacity in Jiangxi. Chin. Agric. Sci. Bull. 37, 66–71 (in Chinese with English abstract). https://www.casb.org.cn/CN/10.11924.

Karimov, A., Qadir, M., Noble, A., Vyshpolsky, F., Anzelm, K., 2009. Development of magnesium-dominant soils under irrigated agriculture in Southern Kazakhstan. Pedosphere 19, 331–343. https://doi.org/10.1016/S1002-0160(09)60124-7.

Kaushal, S.S., Duan, S., Doody, T.R., Haq, S., Smith, R.M., Newcomer Johnson, T.A., 2017. Human-accelerated weathering increases salinization, major ions, and alkalinization in fresh water across land use. Appl. Geochem. 83, 121–135. https://doi.org/10.1016/j.apgeochem.2017.02.006.

Li, X., Kang, Y., Wan, S., Chen, X., Chu, L., 2015. Reclamation of very heavy coastal saline soil using drip-irrigation with saline water on salt-sensitive plants. Soil Til. Res. 146, 159–173. https://doi.org/10.1016/j.still.2014.10.005.

Li, X., Zhang, C., Huo, Z., Adeloye, A.J., 2020a. A sustainable irrigation water management framework coupling water-salt processes simulation and uncertain optimization in an arid area. Agric. Water Manag. 231, 105994 https://doi.org/10.1016/j.agwat.2019.105994.

Li, Y., Pang, H., Zhang, Z., Liu, S., Zhang, C., Wei, Y., 2020b. Characteristics and countermeasures of improvement zoning of saline-alkali soil in Hetao Plain of Inner Mongolia. Chin. J. Agric. Resour. Reg. Plan. 41, 115–121 (in Chinese with English abstract). http://www.cjarrp.com/zgnyzyyqh/ch/reader/view_abstract.aspx?file_no=20200514&flag=1.

Mao, W., Zhu, Y., Wu, J., Ye, M., Yang, J., 2020. Modelling the salt accumulation and leaching processes in arid agricultural areas with a new mass balance model. J. Hydrol. 591, 125329 https://doi.org/10.1016/j.jhydrol.2020.125329.

Nie, W., Dong, S., Li, Y., Ma, X., 2021. Optimization of the border size on the irrigation district scale – example of the Hetao irrigation district. Agr. Water Manag. 248, 106768 https://doi.org/10.1016/j.agwat.2021.106768.

Oorts, K., Vanlauwe, B., Merckx, R., 2003. Cation exchange capacities of soil organic matter fractions in a Ferric Lixisol with different organic matter inputs. Agr. Ecosyst. Environ. 100, 161–171. https://doi.org/10.1016/S0167-8809(03)00190-7.

Pang, H., Yang, J., Xie, X., 2005. Effects of N fertilization on the growth and in vivo Cl^- and Na^+ accumulation in winter wheat under NaCl stress. J. Plant Nutr. Fertil. 11, 654–664 (in Chinese with English abstract).

Paudyal, R., Kang, S., Sharma, C.M., Tripathee, L., Sillanpää, M., 2016. Variations of the physicochemical parameters and metal levels and their risk assessment in Urbanized Bagmati River, Kathmandu, Nepal. J. Chem. -NY 2016, 1–13. https://doi.org/10.1155/2016/6025905.

Qadir, M., Ghafoor, A., Murtaza, G., 2000. Amelioration strategies for saline soils: a review. Land Degrad. Dev. 11, 501–521 https://doi.org/ 10.1002/1099-145X(200011/12)11:6<501::AID-LDR405>3.0.CO;2-S.

Ren, D., Xu, X., Hao, Y., Huang, G., 2016. Modeling and assessing field irrigation water use in a canal system of Hetao, upper Yellow River basin: application to maize, sunflower and watermelon. J. Hydrol. 532, 122–139. https://doi.org/10.1016/j.jhydrol.2015.11.040.

Richards, L.A., 1954. Diagnosis and improvement of saline and alkali soils. Agriculture Handbook, No. 60. US Department of Agriculture, Washington DC.

Sahab, S., Suhani, I., Srivastava, V., Chauhan, P.S., Singh, R.P., Prasad, V., 2021. Potential risk assessment of soil salinity to agroecosystem sustainability: current status and management strategies. Sci. Total Environ. 764, 144164 https://doi.org/10.1016/j.scitotenv.2020.144164.

Shahid, S.A., Zaman, M., Heng, L., 2018. Soil salinity: historical perspectives and a world overview of the problem. Guideline for salinity assessment, mitigation and adaptation using nuclear and related techniques, pp. 43–53. https://doi.org/10.1007/978-3-319-96190-3_2.

Sidi, N., Aris, A.Z., Talib, S.N., Johan, S., Yusoff, T.S.T.M., Ismail, M.Z., 2015. Influential factors on the cation exchange capacity in sediment of Merambong Shoal, Johor. Procedia Environ. Sci. 30, 186–189. https://doi.org/10.1016/j.proenv.2015.10.033.

Stutter, M.I., Cains, J., 2017. Changes in aquatic microbial responses to C-substrates with stream water and sediment quality related to land use pressures. Chemosphere 184, 548–558. https://doi.org/10.1016/j.chemosphere.2017.06.009.

Sun, J., Kang, Y., Wan, S., Hu, W., Jiang, S., Zhang, T., 2012. Soil salinity management with drip irrigation and its effects on soil hydraulic properties in north China coastal saline soils. Agr. Water Manag. 115, 10–19. https://doi.org/10.1016/j.agwat.2012.08.006.

Sun, J., Kang, Y., Wan, S., 2013. Effects of an imbedded gravel–sand layer on reclamation of coastal saline soils under drip irrigation and on plant growth. Agric. Water Manag. 123, 12–19. https://doi.org/10.1016/j.agwat.2013.03.004.

Wang, S., Chen, Q., Li, Y., Zhuo, Y., Xu, L., 2017. Research on saline-alkali soil amelioration with FGD gypsum. Resour. Conserv. Recycl. 121, 82–92. https://doi.org/10.1016/j.resconrec.2016.04.005.

Ye, Q., Zhang, Z., Liu, Y., Wang, Y., Zhang, S., He, C., Shi, Q., Zeng, H.X., Wang, J., 2019. Spectroscopic and molecular-level characteristics of dissolved organic matter in a highly polluted urban river in South China. ACS Earth Space Chem. 3, 2033–2044. https://doi.org/10.1021/acsearthspacechem.9b00151.

Zhai, Z., Shi, W., Guo, J., Liu, L., 2021. Study on comprehensive control measures of soil salinity in Jiefangzha irrigation area of the Hetao irrigation district based on SaltMod model. J. Soil Water Conserv 35, 314–318 (in Chinese with English abstract). ⟨https://trqs.chinajournal.net.cn/WKB3/WebPublication/paperDigest.aspx?paperID=03a685c4-2611-4a03-9e17-2ed1ecad6c5e⟩.

Zhang, C., Zhi, J., Hang, G., Yao, Y., Bu, D., 2020a. Distribution characteristics and influencing factors of cation exchange capacity of different types of saline soil in cotton planting region of upper reach of Tarim river. Xinjiang Agric. Sci. 57, 1057–1070 (in Chinese with English abstract). ⟨http://www.xjnykx.com/CN/10.6048/j.issn.1001-4330.2020.06.009⟩.

Zhang, H., Pang, H., Zhao, Y., Lu, C., Liu, N., Zhang, X., Li, Y.Y., 2020b. Water and salt exchange flux and mechanism in a dry saline soil amended with buried straw of varying thicknesses. Geoderma 365, 114213. https://doi.org/10.1016/j.geoderma.2020.114213.

Zhang, J., Zhao, P., Tuo, D., Duan, Y., Li, H., Jin, C., et al., 2013. Effects of different phosphorus application amounts on yield of maize and soil phosphorus content in Hetao Irrigation District of Inner Mongolia (in Chinese with English abstract). J. Anhui Agric. Sci. 41, 10997–11000. https://doi.org/10.3969/j.issn.0517-6611.2013.27.036.

Zhang, J., Zhao, P., Pan, Z., Duan, Y., Li, H., Wang, B., et al., 2016. Determination of input threshold of nitrogen fertilizer based on environment-friendly agriculture and maize yield. Trans. Chin. Soc. Agric. Eng. 32, 136–143 (in Chinese with English abstract). ⟨http://www.tcsae.org/nygcxb/article/abstract/20161220?st=search⟩.

Zhang, P., Cao, C., Wang, Y., Yu, K., Liu, C., He, C., et al., 2021. Chemodiversity of water-extractable organic matter in sediment columns of a polluted urban river in South China. Sci. Total Environ. 777, 146127 https://doi.org/10.1016/j.scitotenv.2021.146127.

Zhou, L., Li, R., Miao, Q., Dou, X., Tian, F., Yu, D., et al., 2021. Effects of underground drainage pipe spacing on salt and alkali characteristics and fertility of heavy saline soil in Hetao irrigation area. Soils 53, 602–609 (in Chinese with English abstract). ⟨http://soils.issas.ac.cn/tr/article/abstract/tr202006010213?st=search⟩.