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The Effect of Fertilizers on Soil Total and Available Cadmium in China: A Meta-Analysis

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Abstract: The unreasonable use of fertilizers is a significant cause of cultivated soil cadmium (Cd) accumulation. Although there is research about the effect of fertilizers on soil cadmium (Cd) accumulation under different crops, soils, and cultivation durations locally and specifically, its relative and determinant factors are seldom comprehensively and comparatively researched and evaluated. We used meta-analysis to analyze the effects of fertilizers (mineral fertilizer N, P, K (NPK) with manure (NPKM), NPK with straw (NPKS), and the mineral fertilizer N (N), NK (NK)), crops, duration, climate, and soil texture on the Chinese soil total and available Cd change during 1987–2022. The results showed that the order of the increased soil total and available Cd change was NPKM (total: 62%–104%, available: 61%–143%) > NPKS (50%–86%, 48%–116%) > NPK (25%–50%, 35%–75%) > NK (5%–19%, 19%–33%) > N (2%–6%, 7%–31%). NPKM and NPKS significantly increased the total Cd under maize (104%, 86%) and available Cd under rice (136%, 116%). Cd changed the fastest with the NPKM cultivation duration for total Cd under maize (slope: 5.9) and available Cd under rice (6.6). The change of the soil total and available Cd had the higher value in the semiarid region, clay soils, lower pH, and long cultivations. The change of the soil total and available Cd were highest (398%, 375%) in the semiarid region for clay loam after 20–25 years of NPKM fertilization, when the pH decreased to the lowest (−1.9). According to the aggregated boosted tree analysis, the fertilizers and duration were the best explanatory variable (>53%) for the soil total and available Cd. In conclusion, the soil Cd could be mitigated through reducing the long–term manure, straw, and P fertilizer content with Cd, and field managements such as liming, wetting, and drying according to the crops, climate, and soil texture.

Keywords: Cd; fertilizers; crop rotations; climate; soil texture

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1. Introduction

Cadmium (Cd) is a prevalent heavy metal contaminant in agricultural soil [1]. Large concentrations of Cd in the soil can harm crop development, production, and quality, and they can enter the bodies of humans and other animals through food chain enrichment, endangering human health [1]. Because of its toxicity and persistence in soils, Cd has been classified as a priority inorganic soil pollutant globally [2]. Therefore, the investigation of the Cd concentration in soil holds immense importance.

The natural concentration of Cd in agricultural soil is determined by the parent material of the soil [3,4]; however, anthropogenic activities like fertilizers can have a significant impact on agricultural soil Cd concentrations [5]. Prior research suggested that manures and other fertilizers containing Cd could be major sources of Cd entering soil [6]. For instance, it has been shown that livestock manures supply 55% of all Cd imports into China's agricultural soils [7]. After 17 years of cultivation, Li and Wei (2009) discovered that the application of pig manure fertilizer raised the total Cd concentration in rice soil by 138%–162% and the available Cd concentration by 212–225% in southeast China as compared to the initial treatment [8]. Gao and Huang (2021) observed that the rice soil total Cd level treated with cattle manure significantly increased by 142% from 0.12 to 0.29 mg·kg^{-1} in Qiyang country of China after 38 years' cultivation [9]. After 27 years of agriculture, the pig manure treatment greatly increased the total Cd content in the paddy soil in Hangzhou, China, from 0.2 to 0.85 mg·kg^{-1}, which is much greater than the soil environmental quality risk management standard (0.3 mg·kg^{-1}) [10]. Zhao and Qiu (2018) found that all fertilization treatments (nitrogen, phosphorus, and potassium fertilizers (NPK), NPK plus straw (NPKS), and NPK plus manure (NPKM)) increased the soil available and total Cd by an average of 28% and 17% compared to CK (no-fertilizer control) under wheat in Zhengzhou of China after 20 years' cultivation [11].

Moreover, the water management, organic matter, pH, and texture of the soil all significantly affect the bioavailability of Cd. When fertilization had been applied, the degree of reactions and interactions occurring varies, leading to varying degrees of changes in the soil physicochemical properties [12], which, in turn, affects the morphological change and bioavailability of Cd in soil [13]. According to Yu and Gu (2022), applying organic fertilizer to acidic soil can more successfully increase the soil's capacity to adsorb Cd than it can in alkaline soil [14]. According to Eriksson (1990), adding NPK-fertilizers into loamy sand and clay soils, the extractable Cd was taken up to a greater extent from the sand than from the clay [15]. This suggests that different soil types and fertilizer had different reactions, but further systematic research is not available at this time. For paddy fields, water management is a crucial factor affecting Cd concentration [16,17]. Flooding raises the pH of lower-pH paddy soil from acidic to neutral, improves soil organic matter's capacity to adsorb and compound with Cd, and reduces Cd activity; on the other hand, under some flooded conditions, it is possible for $SO_4{}^{2-}$ to be reduced to S^{2-} due to the prevailing reduction conditions [18]. This reduction process can promote the formation of precipitates when combined with Cd^{2+}, further contributing to the reduction in Cd activity [19]; under drainage conditions, the soil redox potential (Eh) increases, and sulfides are oxidized, releasing Cd^{2+}. The Cd availability in the soil rises concurrently with a reduction in soil pH.

Food safety and environmental risk are threatened since the effects of fertilizer on the soil Cd under various soil qualities, cropping years, and climate conditions have not been compared and thoroughly studied. Therefore, in order to evaluate the impact of fertilization on the soil Cd in polluted soils, we collected data from 1708 paired observations and performed a meta-analysis utilizing those data. We took into account a number of factors in this study, such as the climate, crop rotation method, length of cultivation, and soil characteristics (e.g., texture, and pH). Our study set out to determine the following: (1) how different fertilizer applications affected soil Cd content; (2) how climate, crop rotation, cultivation time, and soil properties (texture, pH) affected soil Cd content; and (3) what fertilizer application strategies were most effective in reducing soil Cd pollution while maintaining agricultural sustainability and safeguarding public health.

2. Materials and Methods

2.1. Data Collection

On the China National Knowledge Infrastructure "http://www.cnki.net (accessed on 30 August 2023)", China Science and Technology Journal Database "https://qikan.cqvip.com (accessed on 30 August 2023)", WanFang Data "https://www.wanfangdata.com.cn (accessed on 30 August 2023)", Web of Sciences "http://isiknowledge.com (accessed on 30 August 2023)", ScienceDirect "https://www.sciencedirect.com (accessed on 30 August

2023)", Elsevier "https://www.elsevier.cn (accessed on 30 August 2023)", SpringerLink "https://link.springer.com (accessed on 30 August 2023)", and Google Scholar "https://scholar.google.com (accessed on 30 August 2023)", pertinent peer-reviewed scientific journal articles were gathered using search terms like "long–term fertilization" and "soil Cd concentration". Relevant peer-reviewed works from 1987 to 2022 that focused on the phrase "responses of soil Cd concentration and soil chemical properties" were chosen. These works included information on the mean annual temperature, precipitation, soil textures, pH, and the total and available Cd concentrations in the soil. The information encompassed wide changes in soil, farming, fertilization, and climate overall. In addition, we selected the articles based on the following criteria: (1) China as the primary study area; (2) a clear study location (locality name, latitude, and longitude); (3) available crop types (wheat, maize, wheat-maize, wheat-rice, and rice), soil texture, and climatic conditions (mean annual temperature, MAP); (4) clear fertilizer management measures (cultivation duration, and fertilizers); (5) with the following treatments serving as the basis for the study: (i) no fertilization (CK); (ii) fertilization N (N); (iii) fertilization NK (NK); (iv) fertilization NPK (NPK); (v) fertilization NPK with straw returning to soil (NPKS); and (vi) fertilization NPK plus manure (NPKM).

We fetched 342 pertinent articles with 1708 data points for meta-analysis based on the screening criteria mentioned above (Figure 1). The 83 fertilizing experimental stations located in China were categorized into three zones based on the humidity index (HI): arid (HI $\leq$ 25), semiarid (25 < HI < 50), and humid (HI $\geq$ 50) (Figure 2). The microwave digestion extraction method was used to extract soil total Cd [20–22], and the diethylenetriamine pentaacetic acid (DTPA) extraction method was used to extract soil available Cd [23–25]. The studies used atomic absorption spectrometry (AAS) and inductively coupled plasma mass spectrometry (ICP-MS) for the soil total and available Cd content.

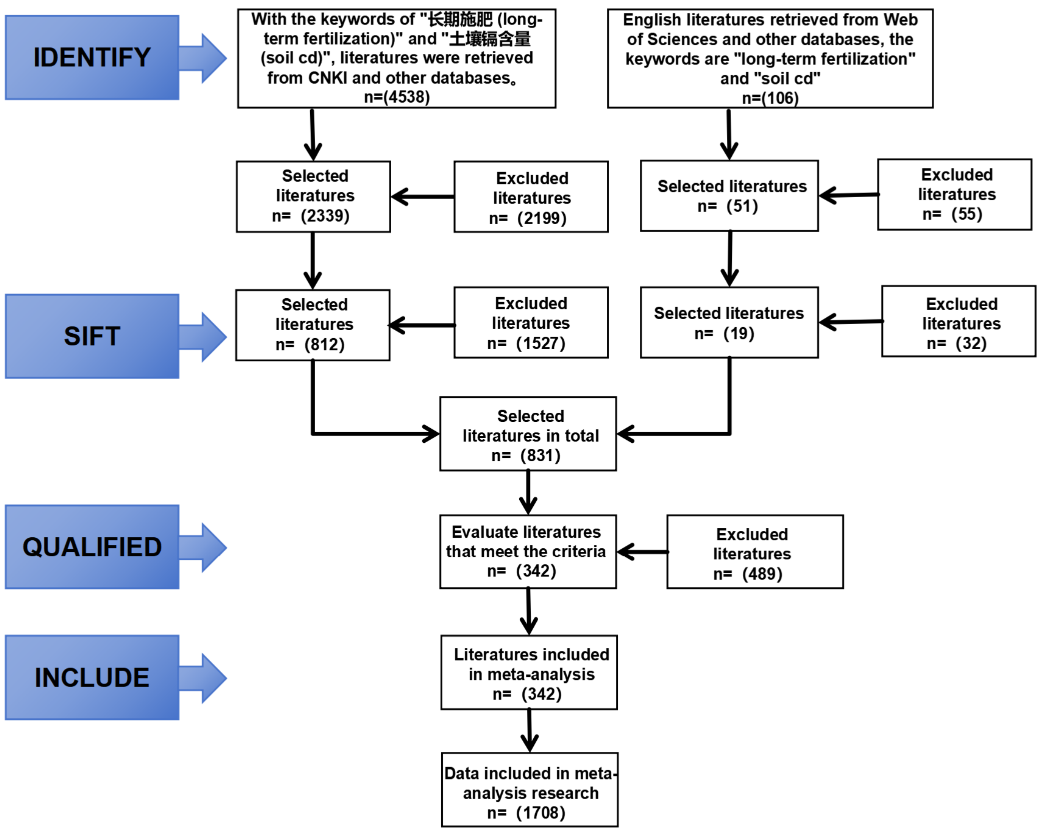

Figure 1. Literature screening process.

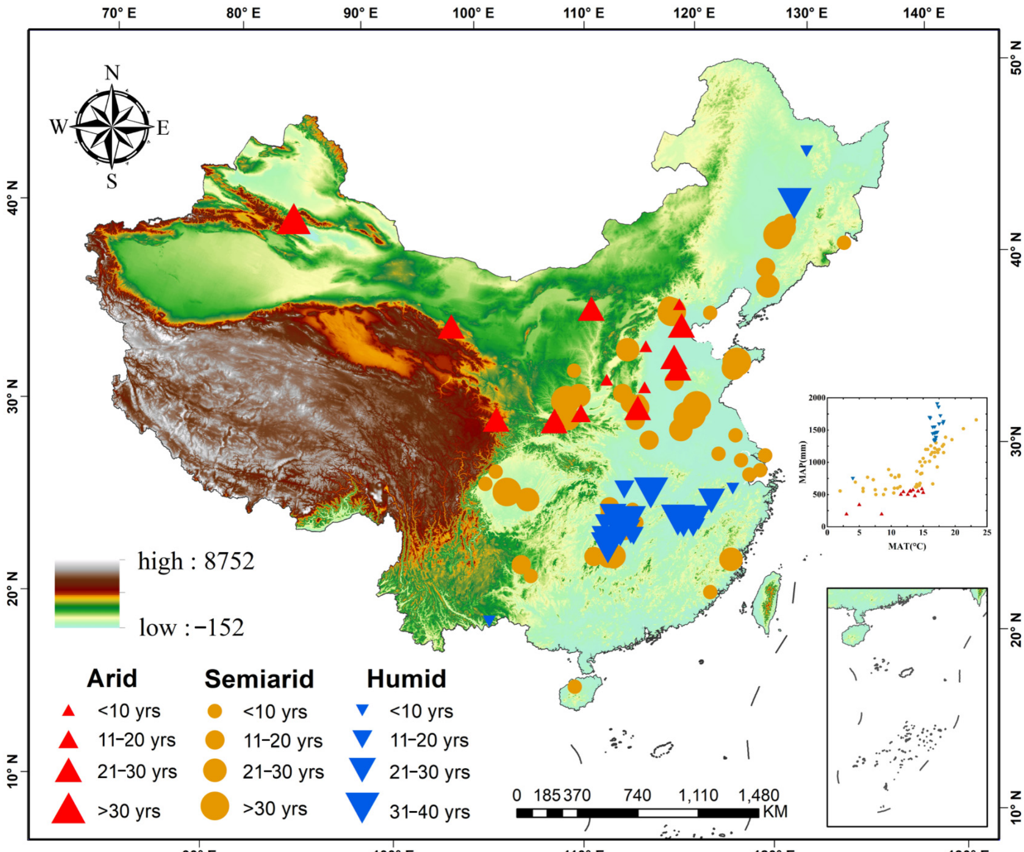

Figure 2. The 83 long–term fertilization experimental stations in China, displayed as specified by HI (HI = MAP/(MAT + 10) and cultivation duration (triangle: arid region, circle: semiarid region, and inverted triangle: humid region). The size of symbols corresponds to the cultivation duration. The digital elevation model (DEM) is a digital simulation of the terrain using limited terrain elevation data. MAT represents the mean annual temperature; MAP represents the mean annual precipitation. The map was sourced from website "http://bzdt.ch.mnr.gov.cn (accessed on 10 August 2023)" and modified.

2.2. Data Analysis Method

2.2.1. Meta-Analysis

A statistical method for combining and analyzing data from several research on a given subject is called meta-analysis. In a meta-analysis, an overall assessment of the effect size or association between variables was obtained by synthesizing the findings from various research. Meta-analysis can be used to more precisely assess the true impact size or relationship, as well as to examine and find trends, contradictions, and causes of variability in the results of prior studies. A meta-analysis's findings can yield important information for future study, policy creation, and clinical practice.

For the meta-analysis, we used the response ratio (RR) of the pooled count data as the impact size metric [26]. To improve the statistical performance, we perform a logarithmic transformation on RR. By linearizing the metric using the natural logarithm, the approximate normal distribution with a mean equal to the genuine response ratio is ensured. The calculation formula of RR and Ln(RR) are as follows [27]:

$$\mathrm{RR} = \mathrm{X_f}/\mathrm{X_c} \quad (1)$$

$$\mathrm{Ln(RR)} = \ln(\mathrm{X_f}/\mathrm{X_c}) = \ln \mathrm{X_f} - \ln \mathrm{X_c} \quad (2)$$

where X_c is the given soil Cd concentration value in the unfertilized control group, and X_f is the concentration value of Cd under the influence of fertilization.

The ln(RR) variance (Var) was calculated using Equation (3):

$$\mathrm{Var}(\ln \mathrm{RR}) = \frac{\mathrm{SD}_f^2}{n_f X_f^2} + \frac{\mathrm{SD}_c^2}{n_c X_c^2} \quad (3)$$

where n_f and n_c are the sample size of the fertilization and control groups, respectively. SD_f and SD_c are the SDs of the fertilization and control groups, respectively.

The calculation formula for Cd content increment is as below:

$$\mathrm{Increment} = X_f - X_c \quad (4)$$

Using the following equation, the average response ratio of the soil Cd content was converted into the percentage change in order to assess the effects directly on the soil Cd content:

$$\mathrm{Cd}\ \%\ \mathrm{Change} = (e^{\mathrm{Ln(RR)}} - 1) \times 100 \quad (5)$$

A positive effect of the fertilizer on the soil Cd content was indicated if the percentage change value was larger than zero. The fertilizer had a negative effect on the soil Cd content when the percentage change was less than 0.

2.2.2. Analysis of the Contribution of Explanatory Variables

Aggregated boosted tree (ABT) [28] analysis was used to rank the explanatory variables' contributions for various factors (HI, soil pH, cultivation duration, fertilizer regimes, crop types, and soil texture) in order to further analyze their significance to the effects on the responses of soil total and available Cd. ABT is an ensemble learning technique that improves predictive accuracy and generalization by combining multiple decision trees. ABT analysis was performed in Python 3.9 software, using "sklearn 1.3.2", "xgboost 2.0.3", and "pandas 2.0.3" packages in combination.

2.2.3. Statistical Analysis

Changes in soil total and available Cd content as a function of crop type, soil texture, cultivation time, and fertilizer type were examined using the linear regression method. The associations between the explanatory factors and the percentage change in the soil Cd content were examined using correlation analysis. The effects of soil texture, HI, cultivation time, and fertilizer types on the total amount of soil and available Cd content were tested using one-way ANOVA. Using SPSS 27.0 software, statistical tests were conducted. p values < 0.05 and <0.01 were considered extremely significant and significant, respectively.

3. Results

3.1. The Effects of Fertilization on Total and Available Cd% Change

The order of the increased soil total and available Cd change (%) under different fertilizers and crops was NPKM (total: 62%–104%; available: 61%–143%) > NPKS (50%–86%; 48%–116%) > NPK (25%–50%; 35%–75%) > NK (5%–19%; 19%–33%) > N (2%–6%; 7%–31%) (Figure 3). The organic fertilizer (NPKM, NPKS) significantly increased the change of total Cd% (104% and 86%) under maize and available Cd% (136% and 116%) under rice compared to mineral fertilizer. The NPKS treatment had the lower available Cd% (65%) change under wheat-maize compared to wheat-rice (114%) (Figure 3). The total and available Cd% change significantly increased under NPK compared to NK and N in all crop rotations, which had the highest total Cd% change under wheat-rice (50%) and available Cd% change under wheat (75%) (Figure 3).

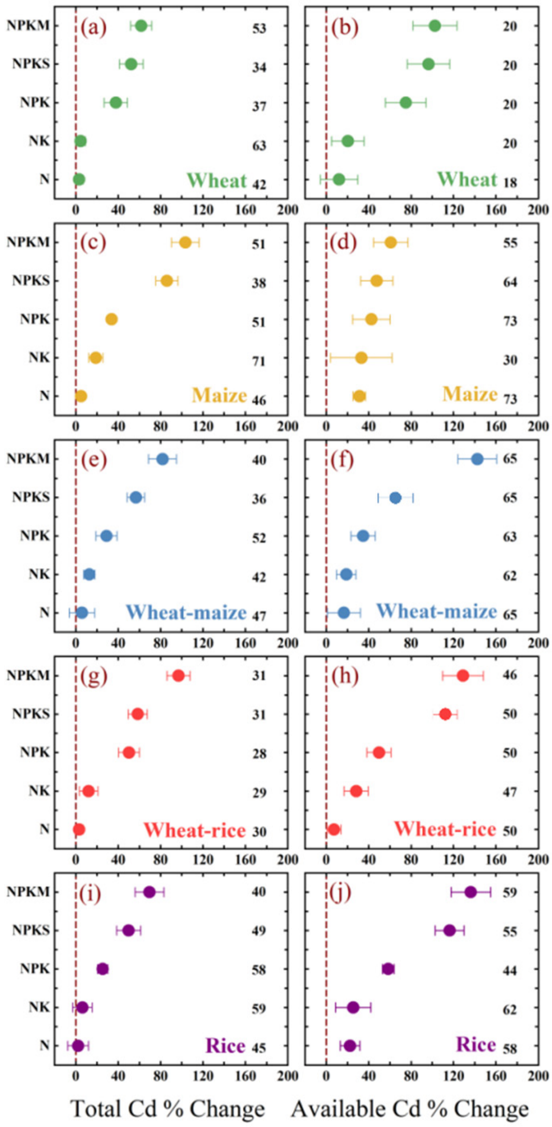

Figure 3. The effects of fertilizers (N, NK, NPK (phosphorus, potassium and nitrogen), NPKS (NPK with straw returning), and NPKM (NPK with manure)) on the soil Cd change (total Cd (**a**,**c**,**e**,**g**,**i**), available Cd (**b**,**d**,**f**,**h**,**j**)). Numbers of sampling data are in the rightmost column. % change was compared to the control. Points and whiskers are mean values with the standard error.

3.2. The Effects of the Fertilization Duration and Fertilizers on the Soil Total and Available Cd% Change

The total and available Cd exhibited a strong increasing trend after 35 years of NPK, NPKS, and NPKM fertilization with the increasing order (NPKM > NPKS > NPK > NK > N) under different crops (Figures 4 and 5). The biggest effect of the NPKM cultivation duration on the total Cd% change was under maize (correlational lineal slope: 5.9), and that on the available Cd% change was under rice (6.6). The biggest effect of the NPKS cultivation duration on the total Cd% change was under wheat-rice (4.0) and that on the available Cd% change was under rice (4.1). The NPK cultivation duration had the biggest effect on the total (2.2) and available (2.3) Cd% change under wheat-rice rotation. The N and NK cultivation duration had no big difference on the total and available Cd% change in all crop rotations (<2) (Figures 4 and 5).

3.3. The Effects of Climate on Soil Total and Available Cd% Change under Fertilizers

The change range of the soil total and available Cd% caused by mineral and organic fertilizers were highest in the semiarid region (−48% to 398% and −46% to 375%) compared to the arid (−16% to 236% and 18% to 33%) and humid region (−31% to 258% and −41% to 176%). The increases in the soil total and available Cd% change was the highest in the semiarid region when HI was between 35 and 45 in NPK (119 and 229%), NPKS (228 and 233%), and NPKM (398 and 375%), respectively (Figure 6).

3.4. The Effects of the Soil Texture, pH, and Cultivation Duration on Soil Cd% Change under Fertilizers

The soil pH changed much in clay loam (−1.9) compared to sandy loam (−0.5) and silty loam (−0.3). With the pH decreased most (−1.9) after 20–25 years of cultivation in clay loam, the highest total (398%) and available (375%) Cd% change reached the highest data. After 24 years of cultivation, the highest total Cd% changes was 305% in sandy loam and the highest available Cd% changes were 206% in silty loam (Figure 7).

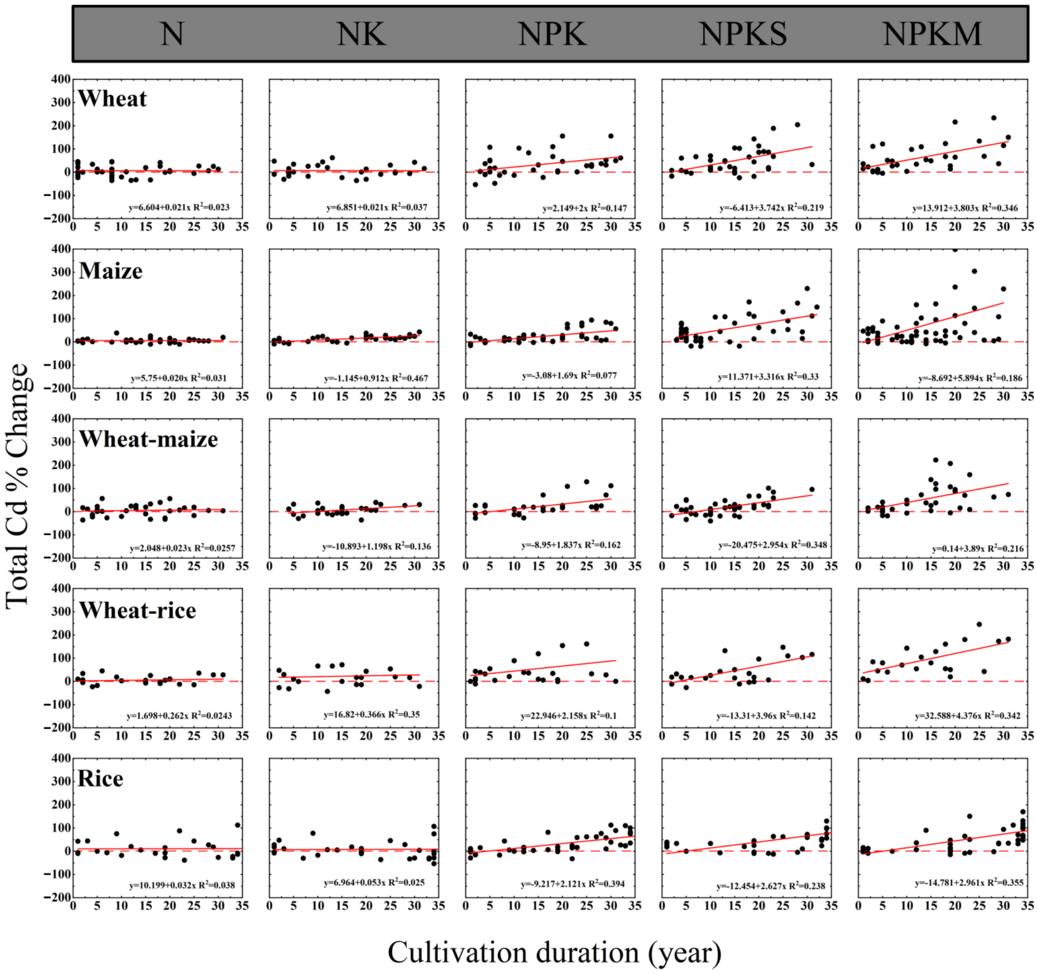

Figure 4. The effects of fertilizer types (N, NK, NPK (phosphorus, potassium and nitrogen), NPKS (NPK with straw returning), and NPKM (NPK with manure)) on the soil total Cd change with the cultivation duration. % change was compared to the control.

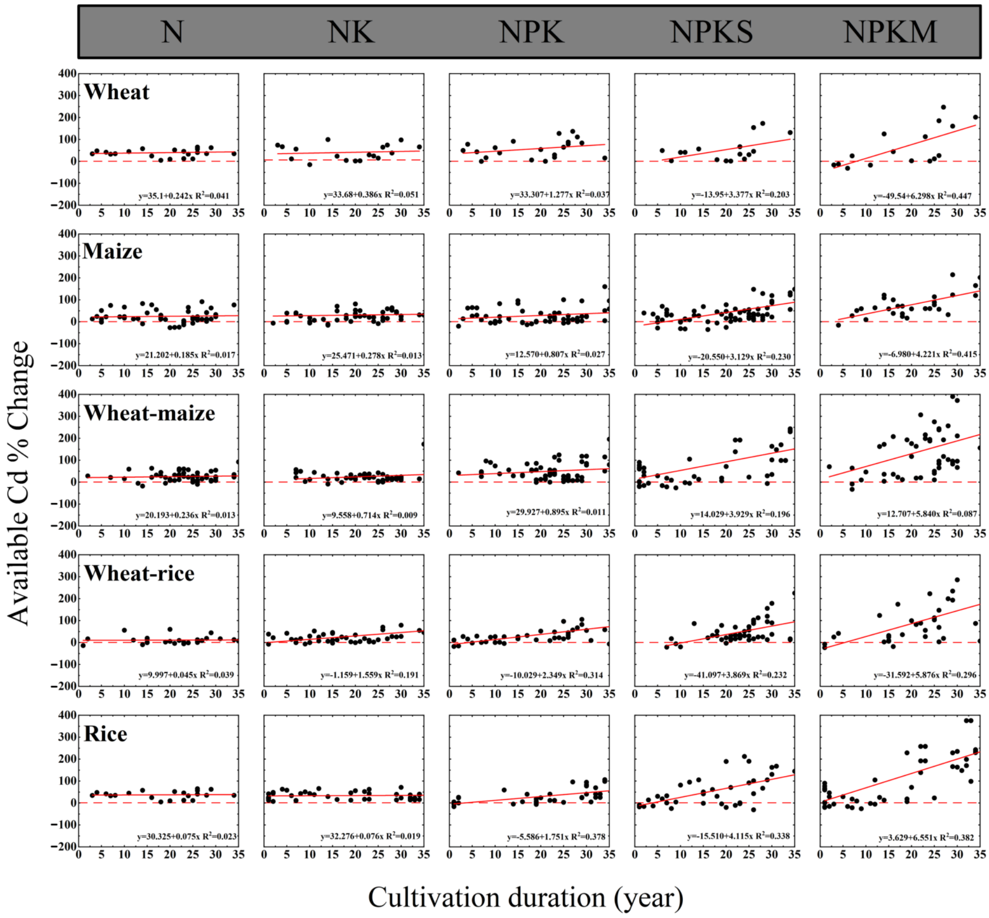

Figure 5. The effects of fertilizer types (N, NK, NPK (phosphorus, potassium and nitrogen), NPKS (NPK with straw returning), and NPKM (NPK with manure)) on the soil available Cd change with the cultivation duration. % change was compared to the control.

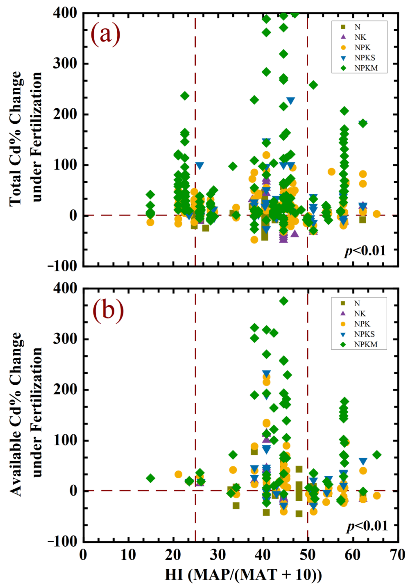

Figure 6. The scatter plot between the soil Cd% change (total Cd (**a**), available Cd (**b**)) and N, NK, NPK, NPKS, and NPKM depending on the HI (humidity index) (HI = MAP/(MAT + 10)). The horizontal dotted line indicates y = 25 or 50 and the vertical dotted line indicates x = 0. HI ≤ 25: arid region. 25 < HI < 50: semiarid region. HI ≥ 50: humid region. MAT: mean annual temperature, MAP: mean annual precipitation. Change was compared to the control.

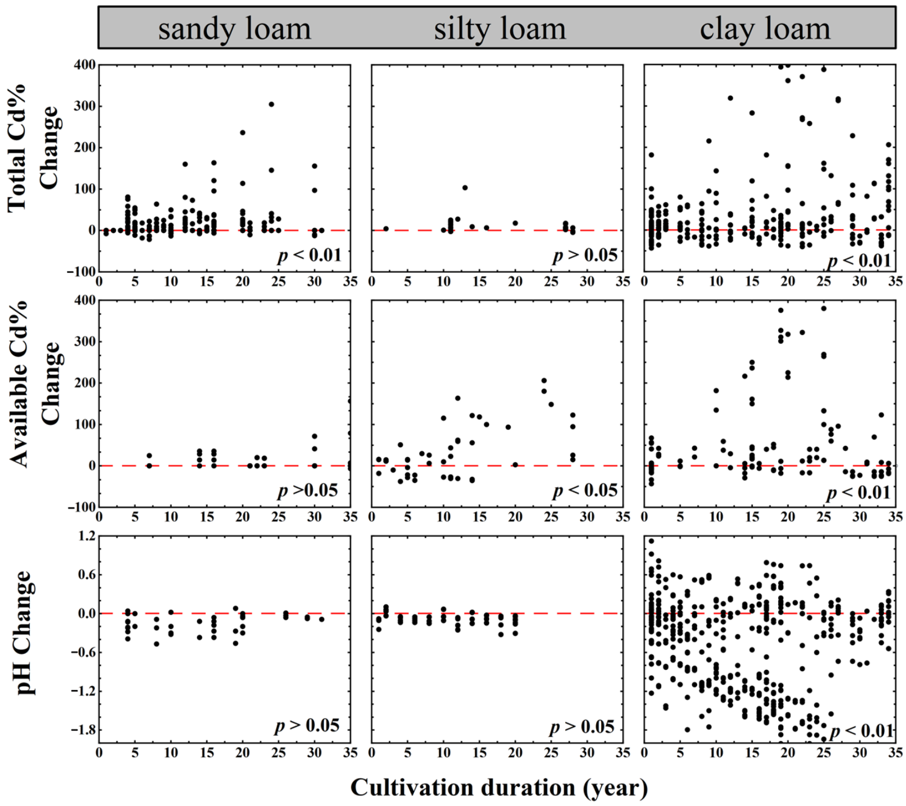

Figure 7. The effects of different soil textures (sandy loam, silty loam, and clay loam) on soil Cd. Change was compared to the control. The horizontal dotted line indicates y = 0.

4. Discussion

4.1. The Effects of Organic and Inorganic Fertilizers in Soil Total and Available Cd during Different Crop Cultivations

Organic fertilizer (NPKM, NPKS) significantly increased the total Cd and available Cd compared to mineral fertilizers (Figure 3) and this trend increased with the cultivation duration (Figures 4 and 5). Zhao and Yan (2014) also found similar results after applying organic fertilizer (NPKM, NPKS) to the soil [6]. That is caused from the multifaceted effects: (1) There is a rise in Cd in manure due to the widespread use of heavy metals as medications or food additives for cattle to protect against illnesses [7]. The straw returned to the soil along with the Cd it contained [29]. (2) The application of manure and straw returning still increased the soil organic matter (SOM) content [30]; the strong cation exchange ability of SOM enrichment frequently contributes to the buildup of Cd in the soil [31]. (3) Manure and crop straw can release organic acids into the soil during the microbial decomposition process [32,33]; as the amounts of organic acids increased, so did the percentage of Cd that was absorbed [34]. When compared to N and NK fertilizers, the inorganic NPK fertilizer increased the soil total and available Cd beneath all crops by a much greater amount. (Figure 3), which was consistent with earlier research [9,35]. That was mainly because of the Cd (0.06–1.10 mg·kg^{-1}) [36] content in phosphorus mineral fertilizer. Because the Cd content in manure (0.29–3.52 mg·kg^{-1}) [37] and straw (0.10–1.21 mg·kg^{-1}) [38] in Cd-contaminated locations were higher than the phosphorus mineral fertilizer, the order of total and available Cd followed the order under fertilizations: NPKM > NPKS > NPK.

Moreover, for monocropping, the organic fertilizer increased the soil total Cd to be the highest under maize and available Cd under rice (Figure 3). That was because maize grows in an oxidizing environment [39], while rice grows in a reducing environment [40]. The paddy field affected the increase in available Cd in soil because, under a reducing environment, Cd was more prone to transforming from the solid phase into the available form that could be easily absorbed by plant roots [41]; and Cd trends to mobilize in flooded paddy soil due to the reductive dissolution of the iron (oxyhydr) oxides to which Cd sorbs, resulting in an elevated available Cd accumulation in rice [42].

4.2. The Effects of Climate and Soil Properties (Texture, pH) on Soil Total and Available Cd under Different Fertilizer Regimes

The highest increases in the soil available Cd were observed in the semiarid and semi humid region (25 < HI < 50) compared to the arid and humid region. There is an increased solubility of soil Cd in the humid region, but a weakened solubility of soil Cd ions in the arid region [43]. The metal reactivity of soil in high HI was higher, resulting in the more complete movement of metals toward stable fractions; the metal mobility factor (MF) was more than 61.85% [44]. Simultaneously, soil oxides like manganese and iron oxide may participate in the process, generating cadmium-rich sediment and lowering the amount of Cd that is available in the soil [39].

The increase in the soil total Cd in the arid region was relatively low, which was related to the microenvironmental conditions of arid region soil and the particle size of soil components. The average SOC had the lower content in arid land (9.39 $g \cdot kg^{-1}$) compared to semiarid (13.35 $g \cdot kg^{-1}$) or humid land (16.22 $g \cdot kg^{-1}$) [45]. Rich organic matter can convert exchangeable metal parts into organic bound states in strongly bound forms [46], and, by combining its surface functional groups (carboxyl, hydroxyl, and phenolic) with Cd, the adsorption capacity of soil for Cd can be increased [47]. The soil component with the smallest particle size (such as clay) generally has the maximum adsorption capacity [48]. The clay content in arid region soil (0.76% to 0.94%) is lower than that in paddy soil (1.09% to 1.90%), which leads to a lower specific surface area and fewer adsorption sites, resulting in a weaker Cd adsorption capacity [49] (Figure 7). Moreover, the industry developed faster in the semiarid and humid region compared to the arid region [50], which results in the lower average Cd accumulation from human activities. The soil properties such as texture and pH had an effect on the total and available Cd (Figure 7, Table 1). The higher increases in the soil total and available Cd were observed in the clay loam region compared to sandy loam and silty loam with the order of clay loam > silty loam > sandy loam (Figure 7). Clay loam soil had fine particles, a relatively large surface area, and a stronger adsorption capacity [51]. Cd ions could bind to the particles of clay loam soil through mechanisms like electrostatic attraction and surface functional group adsorption [52]. In sandy loam soil, due to its high permeability, Cd was more prone to leaching downwards, resulting in a relatively smaller increase in both total and available Cd [53].

Table 1. The rank correlation coefficients of Spearman between the responses of soil Cd and the explanatory variables (pH, cultivation duration, and HI).

	Soil Cd		Explanatory Variables		
	Total Cd	**Available Cd**	**HI**	**Duration**	**pH**
Total Cd		0.53 ** 363	−0.14 ** 629	0.45 ** 608	−0.26 * 416
Available Cd			−0.23 ** 267	0.49 ** 625	−0.31 * 282
HI					−0.09 * 135
Duration					−0.16 ** 441
pH					

* = $p < 0.05$, ** = $p < 0.01$. First line stands for the correlation coefficient, second line stands for the significance, and third line stands for the sampling size. The hatched boxes indicate insignificant relations. Cells colored indicate the relation were positively (green) or negatively (orange) significant, respectively. MAT: mean annual temperature, MAP: mean annual precipitation. HI: humidity index (HI = MAP/(MAT + 10)).

4.3. The Suggestions and Reasonable Management for Cultivated Soil Cd Mitigation

Through the use of aggregated boosted tree analysis, we discovered that the longest period of agriculture was the most effective explanatory factor for the soil total Cd (32%), exhibiting a markedly upward trend as a function of cultivation years (Figures 4 and 8). The fertilizers had the best explanatory variable for soil available Cd (28%). Therefore, it was crucial to control the source of Cd by controlling the fertilizer input, and fertilization duration especially for the organic (manure and straw) and phosphorous fertilizer, particularly by carefully testing the Cd content of fertilizers before the application of or reduction of fertilizer [9] according to the plants' demand. The excessive content of heavy metals in feed is the main cause of Cd pollution in livestock manure [54]. The addition of metal elements in feed should be strictly controlled, and the metal inorganic salts in forages should be replaced with new, safe, and effective additives [54]. As a substitution, more new fertilizers, such as biochar [55], foliar-based fertilization [56], iron/manganese oxides, and so on, could be implemented, which had proven to be effective in reducing the bio-availability of Cd [57–59].

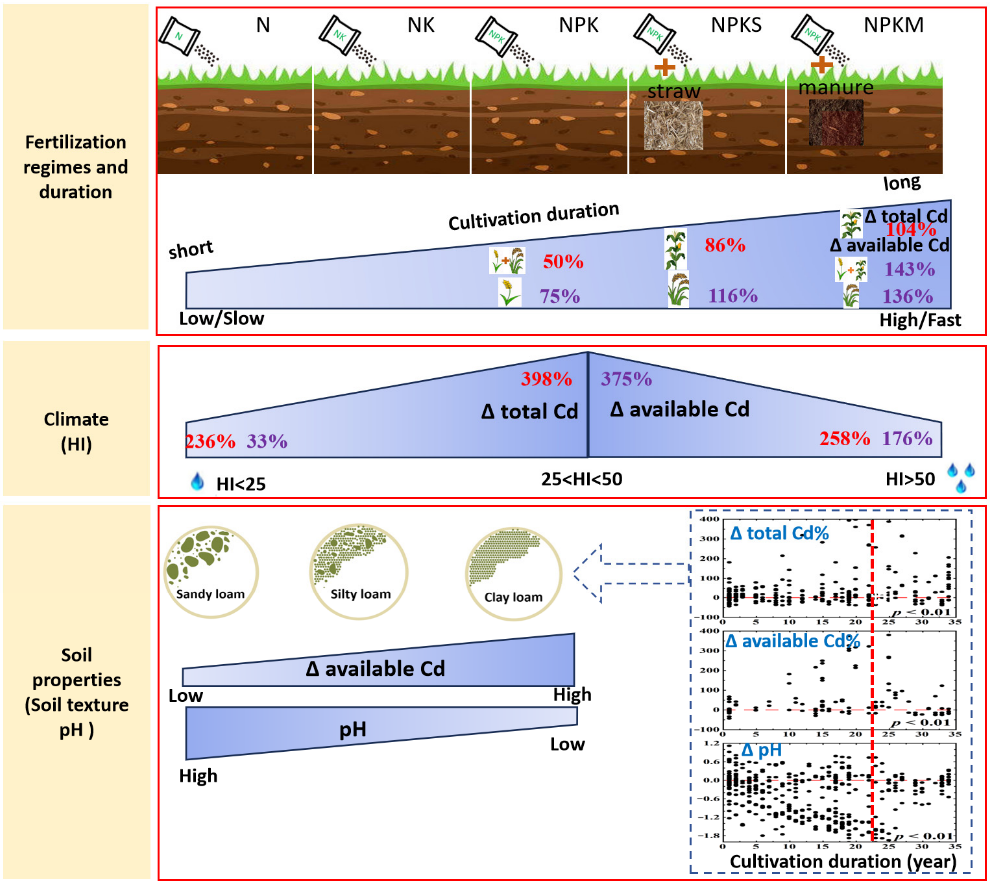

Figure 8. The effect of fertilization regimes, and duration, climate, soil properties on the soil total (number in purple), and available Cd (number in red).

Regular soil Cd remediation can maintain relatively low levels of Cd in the soil. Field management such as the wetting and drying in the rice cropping system could significantly reduce the Cd availability in soil [6]. Especially, pay attention to the plant growth stage; Cd levels in crop grains can be reduced by reducing the availability of Cd in the soil, especially during the critical growth stage of grain filling [60], which could ensure food security. The pH explained 16% and 14% of the soil total and available Cd, respectively (Table 2). As an illustration, lime was commonly used in Chinese farmland to address soil acidification and effectively manage the availability of Cd (Figure 8) [40,61].

Table 2. The responses of soil Cd (total and available Cd) according to ABT analysis.

Variation Explained (%)	Explanatory Variables					
	Fertilizer	Crop	HI	Duration	pH	Soil Texture
Total Cd	27	11	9	32	16	5
Available Cd	28	10	17	25	14	6

5. Conclusions

Through a meta-analysis of published 1708 data, we were able to determine how different fertilizer types, climate, crops, cultivation length, and soil texture affect soil total and available Cd. In contrast to other fertilizers, the use of organic fertilizers (NPKM and NPKS) across a 35-year period in our study resulted in a considerable and quick rise in the total and available Cd with the order NPKM > NPKS > NPK > NK > N. The highest effects on the increase in the soil total (104%) Cd under maize and available (143%) Cd under wheat-maize were attributed to the application of NPKM fertilizer. NPKS significantly increased the change of total Cd under maize (86%) and available Cd under rice (116%). The NPKS treatment had the higher available Cd change (114%) under wheat-rice compared to wheat-maize (65%). The NPK including mineral phosphorous demonstrated the highest increase in the total Cd under wheat-rice (50%) and available Cd under wheat (75%) compared to the other mineral fertilizers of NK and N. The Cd change was the highest with the NPKM cultivation duration for the total Cd under maize (correlational lineal slope: 5.9) and available Cd under rice (6.6), which was followed by NPKS on total Cd under wheat-rice (4.0) and available Cd under rice (4.1) during 35 years of cultivation. The soil total and available Cd increased the highest amount in the semiarid region (−48% to 398% and −46% to 375%) compared to the arid (−16% to 236% and 18% to 33%) and humid region (−31% to 258% and −41% to 176%). The continuous fertilization caused soil acidification with the pH reduced by 1.9 after 20 to 25 years, which led to the highest soil total Cd (398%) and available change (375%) for clay loam. The cultivation and the fertilizers were the best explanatory variable for the soil total Cd (32%, 27%) and soil available Cd (25%, 28%). Therefore, considering the crop rotations (upland crops were preferred) and climate conditions (especially for a semiarid climate), we should reduce the organic fertilizer amount with a local high Cd content (manure and straw) and P mineral fertilizer, substitute fertilizers without Cd (such as biochar, foliar-based fertilization, and so on), lime the acidified soils, and manage the drying and wetting especially in the pustulation period for reducing the bio-availability of Cd, mitigating soil Cd accumulation and food safety.

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