Article

Loading Capacity of Sewage Sludge for Forestry Application in Chinese Provincial Capital Cities

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Abstract: The application of sewage sludge (SS) in forestry is considered a viable option. However, the long-term application of SS potentially leads to metal accumulation, posing an environmental risk. Understanding the loading capacity of SS for forestry application is therefore of great significance. We used data from published studies and statistical bulletins across 31 provincial capital cities (PCCs) in China to calculate the loading capacity (LC) of SS for forestry application for each PCC. The results are as follows: (1) the mean value of the priority control threshold was $33 \text{ t} \cdot \text{ha}^{-1} \cdot \text{y}^{-1}$ in 31 PCCs, while the variations ranged from 7 to $91 \text{ t} \cdot \text{ha}^{-1} \cdot \text{y}^{-1}$ among different PCCs. The priority control thresholds ($S_{\min}$) of 1/2 PCCs were higher than $30 \text{ t} \cdot \text{ha}^{-1} \cdot \text{y}^{-1}$ (CJ-T 362-2011). The $S_{\min}$ values of Lanzhou, Tianjin, Hohhot, Shanghai, and Yinchuan were above $55 \text{ t} \cdot \text{ha}^{-1} \cdot \text{y}^{-1}$, but $S_{\min}$ values of Kunming and Changsha were below $10 \text{ t} \cdot \text{ha}^{-1} \cdot \text{y}^{-1}$. (2) Cd was the priority control metal in most of the PCCs (27/31), with the exception of Shanghai and Guangzhou (Cu), Beijing (Hg), and Tianjin (Zn). (3) The total loading capacity was 507 million $\text{t} \cdot \text{y}^{-1}$, which was 125 times higher than the total quantity of the dry SS ($404 \times 10^4 \text{ t}$) for the 31 PCCs. Our results have important practical significance for the use of urban sludge forest land in China and suggest that SS disposal policies need to be tailored to specific regions. We provide a scientific basis to guide the development of national and provincial forestry policies.

Keywords: sewage sludge; forestry application; loading capacity; priority control metal

1. Introduction

Sewage sludge (SS) is a residue of domestic and industrial wastewater treatment [1–3], and global sewage production exceeded 300 billion $\text{t} \cdot \text{y}^{-1}$ in 2010 [4,5]. Although improvements in urban sewage treatment capacity have resulted in enhanced water quality, the amount of sewage sludge has significantly increased. By the end of 2017, the capacity of sewage treatment plants in China was 157 million $\text{t} \cdot \text{d}^{-1}$, with municipal domestic sewage treatment accounting for 42.6 billion m^3 ; the amount of dry sludge produced was 9.51 million t [6]. The disposal and treatment of SS are major challenges in sewage management [1], and sustainable sludge handling needs to meet the requirements of efficient resource recycling without the distribution of harmful substances.

Sewage sludge contains large amounts of organic carbon as well as nitrogen, phosphorus, potassium, and various trace elements necessary for plant growth, fertility, thereby potentially improving soil structure and increasing plant growth [7–10]. Municipal sewage sludge, given that it meets the quality criteria for agricultural use, stimulates crop yield [11]. In a previous study, in the underlying soil horizons after the application of $3 \text{ t} \cdot \text{ha}^{-1} \cdot \text{y}^{-1}$ of SS, the trace metal contents remained stable [12]. The application of sludge at a rate of $3 \text{ t} \cdot \text{ha}^{-1} \cdot \text{y}^{-1}$ did not significantly increase

the bioavailability of As, Cu, Zn, Hg, Pb, Cd, and Cr, as demonstrated for mushroom cultivation [13]. In another study, dried urban sewage sludge residues were applied to a sugar maple (*Acer saccharum* Marsh.) and yellow birch (*Betula alleghaniensis* Britton) forest in Quebec at a dose of $38.6 \text{ t ha}^{-1} \cdot \text{y}^{-1}$, and Zn, Cd, Cu, and Pb concentrations were below the detection limits [14]. These studies have shown that the leaching of major and trace elements into the soil is generally low at low SS quantities [11–14], most likely because a high percentage of elements may be retained in the humus layer by metal complexation to the surface of organic matter [15–18]. In a study in Sweden, long-term application of sewage sludge to farmland did not result in significant changes in the soil bacterial resistome [19]. However, such an approach can result in the accumulation of metals, potentially entering the food chain and threatening human health [20,21]. Farmers are generally not inclined to use SS because of its negative reputation and unpleasant odors [22]. However, given the fact that most wastewater treatment plants are in cities and that transportation is expensive, the application in forests (zero or minimal transportation cost) may represent a viable alternative of sludge disposal in China, which also would avoid direct contact with animals and humans [23,24]. So far, sewage sludge has been mainly applied to forest surfaces, while sludge compost has been used as a tree seedling container media [17], mainly for tree species such as poplar, paulownia, Chinese pine, black locust, Chinese pagoda tree, and Chinese arborvitae [25]. Based on a previous study, SS in Shenyang is suitable for application to forests and grasslands or nurseries, where food chain contamination with cadmium is not a concern [26]. A study on the influences of sewage sludge on the degradation of hexazinone and the formation of its major metabolites has improved our understanding of the pollution risk when applying SS to forest soil [27]. Sewage sludge-based *Bacillus thuringiensis* production, followed by its use in forest and agro-crops for pest control, is an acceptable disposal practice [28].

When evaluating the applicability of SS, metal concentrations are still an important index [1]. According to the Soil Pollution Survey of China in 2014, metal concentrations in forests exceeded the standard levels by 10%, with Cd and As being the main contaminants [29]. The metals Zn, Cu, and Ni are considered the main metals limiting the application of SS in England [30], and in a study on grasslands which had received sludge for more than 10 years at a dose of $39 \text{ t ha}^{-1} \cdot \text{y}^{-1}$, the soil concentrations of Hg and Cd were significantly increased [31]. With the development of efficient transportation and heating techniques, Cd and Hg are the elements most likely limiting the application of SS because of their inertness, migration, high biomagnification, and strong toxicity [32–34]. In an earlier study, the application of $6 \text{ t ha}^{-1} \cdot \text{y}^{-1}$ of SS with low trace element concentrations modified the transfer of Cd, Hg, and Pb to mushrooms in some sites [18].

In 2000, China started to make efforts to decrease its metal emissions by the implementation of stricter regulations [1]. In this sense, understanding the loading capacity of SS for forestry application is of great significance in terms of resource reuse [35,36]. In China, the threshold level of SS used in forests is $30 \text{ t ha}^{-1} \cdot \text{y}^{-1}$, and continuous application should not exceed 15 years according to the Standard CJ/T 362-2011 [37]. Nevertheless, the natural conditions and the area of urbanization in China differ largely. The lack of specific thresholds restricts the application of SS in forestry, making it necessary to establish threshold values for each city, based on the concentrations of metals in SS, as well as the soil dynamic environmental capacity [38]. In this context, the objectives of this study were to (1) screen and identify the priority control metal of SS for forestry application and to (2) determine and design its maximum loading capacities, with the overall aim to propose suggestions for each provincial capital city (PCC). This will be helpful to determine the potential of urban sludge for forestry application, eventually providing a theoretical basis for national and provincial forestry policies.

2. Methods

2.1. Data Preparation

We analyzed the metal concentrations in SS in 31 PCCs in mainland China, using the bibliometric method to screen 1082 valid data from 129 references (Figure 1) from international studies published

between 2006 and 2018, including the Chinese National Knowledge Infrastructure, the Science Direct database, and some official reports (see Tables S1 and S2). The data screening principles were as follows: first, the metal testing protocols of the selected studies were associated with strict quality assurance and control, containing parallel samples, blank samples, and standard materials, and the recovery rate needed to be conformed to the determination standard. Second, in case the data were normally distributed, the average metal content was represented using the arithmetic mean; if the data conformed to a logarithmic normal distribution, the geometric average was used. Data on the baseline values of soil metals were obtained from our previous research [29]; area of forestry and quantity of dry SS treated data were obtained from the Statistical Yearbook on Urban Construction 2017 [39]. Spatial distribution maps were produced with the GIS software ArcGIS 10.

Figure 1. Amounts and distribution of data for each provincial capital city in China from 2006 to 2018.

2.2. Calculating the Loading Capacity of SS for Forestry Application

The soil environmental capacity for metals is the maximum amount that the soil can load in certain regions and periods, and to know this capacity is crucial to control the amount of metals brought in via SS application. As an ecosystem, soil can decrease the concentrations of pollutants and their accumulation [40]. Thus, we adopted the soil dynamic environmental capacity (Q_n) when SS is used in long-term application programs in forestry. The Q_n is defined by the following equation [41,42]:

$$Q_n = 2.25 \times 10^6 \times (S_i - C_i K^n) (1 - K) / [K(1 - K^n)] \times 10^{-6},$$

where Q_n is the soil dynamic environmental capacity, $\text{kg} \cdot \text{ha}^{-1} \cdot \text{y}^{-1}$; 2.25×10^6 is the average mass of surface soil (0–20 cm) per hectare, ($\text{kg} \cdot \text{ha}^{-1}$); i represents the certain metal of the eight metal elements; S_i is the risk screening value for soil contamination of metal i , ($\text{mg} \cdot \text{kg}^{-1}$), adopting the other criteria for forestry soil in GB 15618-2018 (Table 1) [43]; C_i is the baseline value of soil metal i , ($\text{mg} \cdot \text{kg}^{-1}$); K is the

residual rate of the soil metal, which is associated with the absorption of plants, soil loss, and leaching and generally amounts to 0.90 [44]; n is the time (here, 15 years); and 10^{-6} is the unit scaling factor.

Table 1. Risk screening values for soil and limits for sewage sludge (SS).

Metal	Risk Screening Values for Soil				Unit: mg·kg ⁻¹	
					Limits for SS	
	pH ≤ 5.5	5.5 < pH ≤ 6.5	6.5 < pH ≤ 7.5	pH > 7.5	<6.5	≥6.5
As	40	40	30	25	75	75
Cd	0.3	0.3	0.3	0.6	5	20
Cr	150	150	200	250	600	1000
Cu	50	50	100	100	800	1,00
Hg	1.3	1.8	2.4	3.4	5	15
Ni	60	70	100	190	100	200
Pb	70	90	120	170	300	1000
Zn	200	200	250	300	2000	4000

Note: Risk screening values for soil and limits for SS data were derived from GB 15618-2018 and GB/T 23486-2009, respectively.

The loading capacity of SS for forestry application in PCC was calculated by the following equations:

$$S_n = Q_n/W_{si} \times 10^3$$

$$T = S_{min} \times AF \times 10^{-6}$$

where S_n is the i threshold of the metal of SS for forestry application, t·ha⁻¹·y⁻¹; W_{si} is the i concentration of SS (meeting the requirements GB/T 23486-2009 [45] in Table 1), mg·kg⁻¹; T is the loading capacity of SS for forestry application, million t·y⁻¹; S_{min} is the priority control threshold (minimum value of eight S_{ns}); AF is the area of forestry in PCC, (ha); and 10^3 and 10^{-6} are the unit scaling factors.

3. Results

3.1. Spatial Distribution of Metals in SS

All PCCs' SS met the requirements established in the GB/T 23486-2009 (Figure 2).

The As concentrations ranged between 9.27 and 48.33 mg·kg⁻¹, with a mean value of 19.05 mg·kg⁻¹. They exceeded 30 mg·kg⁻¹ in Hangzhou, Beijing, Shanghai, Guangzhou, and Xi'an. In five southwestern PCCs, the As concentrations of SS ranged between 20 and 30 mg·kg⁻¹, while in about one-third of the PCCs, they ranged from 10 to 20 mg·kg⁻¹. In contrast, in Nanjing and Chongqing, the levels were below 10 mg·kg⁻¹.

The Cd concentrations showed a range of 1.70 to 7.13 mg·kg⁻¹, with an average value of 3.84 mg·kg⁻¹. Most of the PCCs with lower Cd levels were located in industrial zones of such as Beijing, Shanghai, Tianjin, Guangzhou, Harbin, Changchun, Zhengzhou, and Chengdu. The Cd concentrations in Xi'an, Shijiazhuang, Kunming, and Hangzhou ranged from 6.0 to 7.5 mg·kg⁻¹; PCCs with Cd concentrations from 4.5 to 6 mg·kg⁻¹ and 3 to 4.5 mg·kg⁻¹ accounted for one-third of all PCCs.

Regarding the Cr concentrations, we observed a range of 77.03 to 481.86 mg·kg⁻¹, with an average value of 172.26 mg·kg⁻¹; the highest level was found for Tianjin. Sewage sludge from Hangzhou, Xi'an, and Shanghai had Cr levels of 369.28, 343.62, and 307.20 mg·kg⁻¹, respectively. In four PCCs, the levels ranged from 200 to 300 mg·kg⁻¹, although Cr concentrations mainly varied from 100 to 200 mg·kg⁻¹. In Nanchang, Shenyang, Beijing, Harbin, and Nanjing, the Cr levels were below 100 mg·kg⁻¹.

Figure 2. Spatial distribution of metal concentrations of sewage sludge for 31 provincial capital cities.

The minimum and maximum Cu concentrations were 99.21 and $751.6 \text{ mg}\cdot\text{kg}^{-1}$, respectively, with a mean value of $258.47 \text{ mg}\cdot\text{kg}^{-1}$. In most PCCs, the Cu concentrations of SS were below $500 \text{ mg}\cdot\text{kg}^{-1}$. In Wuhan, Haikou, Tianjin, and Shanghai, the levels ranged from 300 to $500 \text{ mg}\cdot\text{kg}^{-1}$; the minimum value was found for Lanzhou.

The Hg concentrations ranged between 1.13 and $12.42 \text{ mg}\cdot\text{kg}^{-1}$, with a mean value of $3.06 \text{ mg}\cdot\text{kg}^{-1}$. In contrast to the Cd distribution, the PCCs with the highest concentrations were located in highly industrialized areas such as Beijing, Tianjin, Shijiazhuang, Harbin, and Changchun. In 23 PCCs, the Hg concentrations of SS were below $3 \text{ mg}\cdot\text{kg}^{-1}$.

For the Ni concentrations, we observed a range from 22.54 to $111.01 \text{ mg}\cdot\text{kg}^{-1}$, with an average value of $53.43 \text{ mg}\cdot\text{kg}^{-1}$. In most PCCs, the Ni concentrations of SS were below $100 \text{ mg}\cdot\text{kg}^{-1}$, with the exception of Hangzhou. In Tianjin, the Ni level of SS was $87.17 \text{ mg}\cdot\text{kg}^{-1}$. The PCCs with concentrations ranging from 60 to $80 \text{ mg}\cdot\text{kg}^{-1}$ and from 40 to $60 \text{ mg}\cdot\text{kg}^{-1}$ accounted for one-third of all PCCs.

In the northwestern and northeastern areas, Ni concentrations in SS were more than 20 and less than 40 mg·kg⁻¹.

The Pb concentrations varied between 34.27 and 241.80 mg·kg⁻¹; the mean value was 92.35 mg·kg⁻¹. The highest level was observed for Tianjin, followed by Shenyang. In seven PCCs, the Pb levels of SS ranged from 100 to 200 mg·kg⁻¹, while in two-thirds of the PCCs, the levels were between 50 and 100 mg·kg⁻¹. For Chengdu and Lanzhou, we observed levels below 50 mg·kg⁻¹.

The minimum and maximum Zn concentrations were 376.80 and 2024.53 mg·kg⁻¹, respectively, with a mean value of 870.15 mg·kg⁻¹. Similar to the Hg distribution, the PCCs with the highest concentrations were located in industrial areas such as Tianjin, Hangzhou, Shijiazhuang, Wuhan, and Shanghai. In eight PCCs, the Zn levels of SS ranged from 800 to 1200 mg·kg⁻¹, while in 17 PCCs, the range was 400 to 800 mg·kg⁻¹. For Shenyang, the lowest Zn concentration of about 400 mg·kg⁻¹ was observed.

3.2. Threshold of SS for Forestry Application, S_n

As shown in Figure 3, the S_n s values of eight metals differed within the same PCC, while those of certain metals differed among 31 PCCs. By screening the smallest three S_n s values for each PCC, we found that two of them appeared for Cd and Zn, while the other ones appeared for Cu, except for As in Xi'an and Hg in Beijing, Shijiazhuang, and Hohhot. Based on the S_n s values, the priority control metals were Cd (27 cities), Cu (Shanghai and Guangzhou), Hg (Beijing), and Zn (Tianjin).

The S_n s values of As varied from 116 t·ha⁻¹·y⁻¹ in Xi'an to 1292 t·ha⁻¹·y⁻¹ in Chongqing. In 11 PCCs, the values exceeded 592 t·ha⁻¹·y⁻¹, while in Shenyang, Wuhan, and Fuzhou, the values exceeded 1000 t·ha⁻¹·y⁻¹. In Hangzhou, the S_n value was below 200 t·ha⁻¹·y⁻¹.

The S_n s of Cd ranged between 7 and 91 t·ha⁻¹·y⁻¹, with 50% of the S_n s values being above the average of 35 t·ha⁻¹·y⁻¹. In Lanzhou and Shanghai, the S_n s values were above 70 t·ha⁻¹·y⁻¹, while in Changsha and Kunming, they were below 10 t·ha⁻¹·y⁻¹.

The S_n s of Cr ranged from 152 to 958 t·ha⁻¹·y⁻¹, and 50% of the S_n s values were above the average of 397 t·ha⁻¹·y⁻¹. In Hohhot (628 t·ha⁻¹·y⁻¹) and Nanjing (958 t·ha⁻¹·y⁻¹), the values were above 600 t·ha⁻¹·y⁻¹, while they were below 200 t·ha⁻¹·y⁻¹ in Tianjin, Hangzhou, Changsha, Wuhan, Xi'an, Guangzhou, and Fuzhou.

The minimum S_n of Cu was 18 t·ha⁻¹·y⁻¹ in Guangzhou, while the maximum level was 301 t·ha⁻¹·y⁻¹ in Lanzhou; one-third of the S_n s values were above the average of 104 t·ha⁻¹·y⁻¹. Nanjing's S_n value was 263 t·ha⁻¹·y⁻¹, while those of the other cities were above 40 t·ha⁻¹·y⁻¹ and below 200 t·ha⁻¹·y⁻¹.

For Hg, the S_n s values varied from 42 t·ha⁻¹·y⁻¹ in Beijing to 759 t·ha⁻¹·y⁻¹ in Guiyang, with one-third of the values being higher than the average 305 t·ha⁻¹·y⁻¹. The S_n s values in Shanghai and Lanzhou had Hg levels of 604 and 5221 t·ha⁻¹·y⁻¹, respectively, while the levels were above 400 t·ha⁻¹·y⁻¹ in Urumqi, Ji'nan, and Lhasa. Only Beijing's S_n value was below 100 t·ha⁻¹·y⁻¹.

The S_n s values of Ni ranged between 216 and 2582 t·ha⁻¹·y⁻¹, with an average of 728 t·ha⁻¹·y⁻¹. The values were above 1000 t·ha⁻¹·y⁻¹ in Hohhot (1035 t·ha⁻¹·y⁻¹), Shijiazhuang (1044 t·ha⁻¹·y⁻¹), Lhasa (1449 t·ha⁻¹·y⁻¹), Yinchuan (1711 t·ha⁻¹·y⁻¹), Urumqi (1747 t·ha⁻¹·y⁻¹), and Lanzhou (2582 t·ha⁻¹·y⁻¹) and below 300 t·ha⁻¹·y⁻¹ in Chengdu, Hangzhou, and Guangzhou.

The S_n s levels of Pb ranged from 143 to 1522 t·ha⁻¹·y⁻¹ (average 439 t·ha⁻¹·y⁻¹) and were above 600 t·ha⁻¹·y⁻¹ in Hohhot (613 t·ha⁻¹·y⁻¹), Zhengzhou (672 t·ha⁻¹·y⁻¹), Shanghai (718 t·ha⁻¹·y⁻¹), Nanjing (881 t·ha⁻¹·y⁻¹), and Lanzhou (1522 t·ha⁻¹·y⁻¹). In Guangzhou, Changsha, Shenyang, and Fuzhou, the S_n s values were between 140 and 200 t·ha⁻¹·y⁻¹.

The minimum and maximum S_n s levels of Zn were 36 t·ha⁻¹·y⁻¹ in Wuhan and 216 t·ha⁻¹·y⁻¹ in Lanzhou, respectively, with an average of 95 t·ha⁻¹·y⁻¹. The remaining S_n s levels ranged between 50 and 100 t·ha⁻¹·y⁻¹.

PCC	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn
Beijing	278	51	516	70	42	357	387	54
Changchun	810	38	437	72	118	525	296	82
Changsha	398	7	163	59	231	367	159	92
Chengdu	753	43	356	96	181	216	485	68
Chongqing	1292	22	432	128	201	300	318	119
Fuzhou	1114	24	199	52	243	348	193	80
Guangzhou	388	35	182	18	245	273	143	73
Guiyang	235	26	527	132	759	943	348	84
Haikou	936	19	336	46	234	381	248	51
Hangzhou	184	14	161	50	360	271	316	50
Harbin	883	37	540	101	156	748	519	80
Hefei	890	23	352	50	369	414	347	52
Hohhot	486	57	628	155	142	1035	613	124
Ji'nan	634	48	458	109	480	841	592	112
Kunming	410	9	339	48	232	489	352	106
Lanzhou	500	91	506	301	522	2582	1522	216
Lhasa	471	37	525	145	485	1449	504	99
Nanchang	983	23	445	60	352	390	257	87
Nanjing	802	36	958	263	345	946	881	155
Nanning	572	14	411	56	236	359	314	88
Shanghai	235	91	237	57	604	752	718	68
Shenyang	1012	13	494	55	284	596	158	148
Shijiazhuang	521	25	568	150	141	1044	459	56
Taiyuan	318	20	336	178	381	390	408	107
Tianjin	422	69	152	63	122	668	213	62
Urumqi	482	37	481	119	437	1747	412	83
Wuhan	1061	22	164	44	360	380	316	36
Xi'an	116	11	169	141	180	439	382	76
Xining	380	36	363	193	345	981	528	156
Yinchuan	436	55	535	112	288	1711	552	178
Zhengzhou	355	43	350	108	377	627	672	112
Anverage	592	35	397	104	305	728	439	95

Figure 3. Threshold levels of the different metals for sewage sludge application to forests in 31 provincial capital cities. Unit: $\text{t}\cdot\text{ha}^{-1}\cdot\text{y}^{-1}$, Note: Values in red represent thresholds for priority control metal, S_{min} .

3.3. Loading Capacity of SS for Forestry Application

The S_{min} s varied from 7 to 91 $\text{t}\cdot\text{ha}^{-1}\cdot\text{y}^{-1}$, with an average of 33 $\text{t}\cdot\text{ha}^{-1}\cdot\text{y}^{-1}$ in 31 PCCs, distributed between 10 and 50 $\text{t}\cdot\text{ha}^{-1}\cdot\text{y}^{-1}$ and accounting for 80% (Table 2). Among them, the S_{min} s of 50% of the PCCs were higher than 30 $\text{t}\cdot\text{ha}^{-1}\cdot\text{y}^{-1}$ (CJ-T 362-2011). The S_{min} of Lanzhou was 91 $\text{t}\cdot\text{ha}^{-1}\cdot\text{y}^{-1}$, followed by those of Tianjin (62 $\text{t}\cdot\text{ha}^{-1}\cdot\text{y}^{-1}$) and Hohhot, Shanghai, and Yinchuan, with values of 57, 57, and 55 $\text{t}\cdot\text{ha}^{-1}\cdot\text{y}^{-1}$, respectively. There were five and six PCCs with S_{min} values from 40 to 50 $\text{t}\cdot\text{ha}^{-1}\cdot\text{y}^{-1}$ and 30 to 40 $\text{t}\cdot\text{ha}^{-1}\cdot\text{y}^{-1}$, respectively. In seven PCCs, the values ranged from 20 to 30 $\text{t}\cdot\text{ha}^{-1}\cdot\text{y}^{-1}$, including Shijiazhuang, Chongqing, and Wuhan. In Taiyuan, Haikou, Guangzhou,

Nanning, Hangzhou, Shenyang, and Xi'an, the S_{min} values were below $20 \text{ t}\cdot\text{ha}^{-1}\cdot\text{y}^{-1}$, while those of Kunming and Changsha were 9 and $7 \text{ t}\cdot\text{ha}^{-1}\cdot\text{y}^{-1}$, respectively.

Table 2. Loading capacities of sewage sludge in 31 provincial capital cities.

PCC	$S_{min} (\text{t}\cdot\text{ha}^{-1}\cdot\text{y}^{-1})$	Forest Area (10^4 ha)	Loading Capacity (Million $\text{t}\cdot\text{y}^{-1}$)
Harbin	37	244	90.2
Chongqing	22	374	83.4
Beijing	42	76.8	32.5
Hohhot	57	43.2	24.8
Changchun	38	63.1	24.0
Chengdu	43	55.0	23.8
Lasa	37	57.6	21.5
Lanzhou	91	20.9	19.1
Fuzhou	24	72.4	17.5
Hangzhou	14	113	15.6
Nanning	14	106	15.3
Ji'nan	48	28.2	13.6
Shijiazhuang	25	51.6	13.0
Zhengzhou	43	23.7	10.2
Guiyang	26	39.3	10.1
Kunming	9	103	9.1
Xining	36	24.5	8.9
Yinchuan	55	14.4	8.0
Hefei	23	33.1	7.7
Urumqi	37	20.9	7.7
Tianjin	62	11.1	6.9
Guangzhou	18	31.5	5.8
Xi'an	11	48.5	5.5
Wuhan	22	24.0	5.3
Shenyang	13	39.9	5.1
Changsha	7	64.8	4.6
Shanghai	41	10.3	4.2
Nanchang	23	16.9	3.9
Nanjing	36	10.3	3.7
Taiyuan	20	16.1	3.2
Haikou	19	8.8	1.6

Note: Forest area data were derived from publicly available information.

The forest areas in the 31 PCCs varied from 8.76×10^4 (Haikou) to 374×10^4 ha (Chongqing), with an average of 59.6×10^4 ha. Most AFs in the PCCs were between 10×10^4 and 80×10^4 ha. Harbin had the second largest forest area of 244×10^4 ha. In three PCCs, namely Kunming, Nanning, and Hangzhou, the forest area was above 100×10^4 ha. In Beijing, Fuzhou, Changsha, Changchun, Lhasa, Chengdu, and Shijiazhuang, the forest area ranged from 50×10^4 to 80×10^4 ha. Half of the forest areas were between 20×10^4 and 50×10^4 ha, while in Haikou, this area accounted for less than 10×10^4 ha.

The loading capacities varied from 1.6 million $\text{t}\cdot\text{y}^{-1}$ (Haikou) to 90.2 million $\text{t}\cdot\text{y}^{-1}$ (Harbin), with an average of 16.4 million $\text{t}\cdot\text{y}^{-1}$ in 31 PCCs; the total loading capacity reached 507 million $\text{t}\cdot\text{y}^{-1}$. Chongqing had the second largest loading capacity, equaling 83.4 million $\text{t}\cdot\text{y}^{-1}$. Beijing's loading capacity was slightly above 30 million $\text{t}\cdot\text{y}^{-1}$. In Hohhot, Changchun, Chengdu, and Lhasa, loading capacities were between 20 and 30 million $\text{t}\cdot\text{y}^{-1}$, while in the following eight PCCs, the loading capacities were over 10 million $\text{t}\cdot\text{y}^{-1}$: Lanzhou, Fuzhou, Hangzhou, Nanning, Jinan, Shijiazhuang, Zhengzhou, and Guiyang. The PCCs with loading capacities below 10 million $\text{t}\cdot\text{y}^{-1}$ accounted for 50%. Tianjin's, Shanghai's, and Guangzhou's loading capacities were 6.9, 5.9, and 5.8 million $\text{t}\cdot\text{y}^{-1}$, respectively. Loading capacities were also lower than 5 million $\text{t}\cdot\text{y}^{-1}$ in Changsha, Nanchang, Nanjing, and Taiyuan.

4. Discussion

The application of sewage sludge in forestry is common in several countries around the world [46]. In so-called “sludge landscaping”, treated sludge is applied to cultivated soil, as a soil amendment, and to urban or suburban woodland as organic fertilizer (including municipal green belts, woodlands, grasslands, parks, seedling bases, highway isolation zones, stadiums, etc.), promoting tree growth and improving the ornamental quality of flowers. In the US, municipal sludge is widely used in gardening and applied to parks, grasslands, and ornamental woodlands. China has also started to apply sewage sludge in landscaping, and sewage sludge treatment and disposal in Beijing, Shanghai, and Guangzhou have received increased attention [47]. So far, several studies have dealt with the responses of the soil–forestry systems to the application of sewage sludge. For example, in a greenhouse pot experiment, a mix of sewage sludge and garden waste compost changed the form of metals in the soil [48]. Wang et al. [49] analyzed the effects of applying excess sludge of the Shenyang North Sewage Treatment Plant to grassland and showed that the organic matter content in the soil increased by 12.79–80.80%, the biomass of the grassland increased, and the color of the grass became more intense. Field experiments along the Haitun Expressway have shown that sludge and garbage compost can be used as additives for slope greening [50].

There are, however, only a few reports on the threshold values of metals in SS for forestry application. According to previously established guidelines, the amount of sewage sludge should not exceed $30 \text{ t} \cdot \text{ha}^{-1} \cdot \text{y}^{-1}$, and continuous application should be limited to 15 years (CJ/T 362-2011) [38]. In our study, the average S_{min} of SS for forestry application was $32.14 \text{ t} \cdot \text{ha}^{-1} \cdot \text{y}^{-1}$. However, we observed considerable regional differences among different PCCs. Generally, the S_{min} values in the southern PCCs were lower than those in the northern ones, mainly because the risk screening values for soil contamination of Cd are lowest ($0.3 \text{ mg} \cdot \text{kg}^{-1}$) in acidic soil. They also have higher Cd contents in soil and SS, in addition to the smallest risk screening values, resulting in levels for Changsha and Kunming below $10 \text{ t} \cdot \text{ha}^{-1} \cdot \text{y}^{-1}$. In Guiyang, the Cd levels in soil and SS were closer to those for Changsha; however, the S_{min} value was $25.76 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{y}^{-1}$ due to the risk screening values of alkaline soil. The Cd contents in soil and SS were low and the risk screening value was high; all three factors lead to the highest S_{min} level in Lanzhou. Risk screening values for soil contamination are determined by acid-base properties. To increase the S_{min} , we can start by improving the contents of metals in the soil and reducing the metals in SS.

To evaluate the loading capacity, we sorted out the quantity of treated dry SS (Q) of each PCC in 2017 (Figure 4). The larger the multiple between loading capacity and Q , the greater the potential of SS for forestry application in this city. The Q s varied from 0.20×10^4 to $31.43 \times 10^4 \text{ t}$, except for Beijing ($137.25 \times 10^4 \text{ t}$), and the total Q was up to $404.40 \times 10^4 \text{ t}$. The total loading capacity reached $505.71 \text{ million t} \cdot \text{y}^{-1}$, being 125 times as high as the total Q , suggesting a great potential of SS for forestry application. Lhasa' loading capacity was $21.50 \times 10^4 \text{ million t} \cdot \text{y}^{-1}$, and Q was $0.20 \times 10^4 \text{ t}$, suggesting that the former was far superior to the latter. The loading capacity in Harbin was up to 1000 times higher than its Q . There were four PCCs with a loading capacity more than 500 times higher as their Q s, namely Xining (933.67 times), Fuzhou (792.71 times), Changchun (621.86 times), and Chongqing (575.41 times). The times varied from 100 to 500 in 12 PCCs, including Hohhot, Urumqi, Jinan, Chengdu, and Shijiazhuang. Loading capacities were between 80 to 100 times higher than Q s in Zhengzhou, Xi'an, and Wuhan, while the loading capacities of Tianjin and Hangzhou were about 60 times higher than their corresponding Q s. In Guangzhou, Haikou, Beijing, Changsha, and Shanghai, the times were 28.75, 24.01, 23.68, 20.40, and 14.54, respectively.

Figure 4. Differences between loading capacity and quantity of treated dry sewage sludge.

The loading capacity depended on two factors, S_{min} and AF . Determining these factors enables us to put forward more precise suggestions for each PCC. In Chongqing and Harbin, the high loading capacities were attributed to their largest forest areas. Beijing's loading capacity was the third largest because of its higher S_{min} and AF values. Loading capacities were similar in Hohhot, Changchun, and Chengdu (about 24 million $t \cdot y^{-1}$), but Hohhot's and Chengdu's capacities were a factor of their S_{min} , while Changchun's capacity was accounted for by its AF . Lhasa's loading capacity was above 20 million $t \cdot y^{-1}$, mainly because of its high S_{min} and AF values. The loading capacity in Lanzhou was 19.1 million $t \cdot y^{-1}$, although its S_{min} was the highest. Loading capacities over 15 million $t \cdot y^{-1}$ were attributed to high AF s in Fuzhou, Hangzhou, and Nanning. Tianjin and Yinchuan had the second and the fourth largest S_{min} , respectively, but their AF s were slightly over 10×10^4 ha, which resulted in loading capacities of 6.9 and 7.7 million $t \cdot y^{-1}$, respectively. By comparison, Shanghai's and Changsha's loading capacities were about 4 million $t \cdot y^{-1}$, caused by the S_{min} and AF values, respectively. Haikou had the smallest AF , resulting in the lowest loading capacity.

5. Conclusions

Sewage sludge contains large amounts of organic matter that can improve forest soil structure and increase soil fertility, promoting plant growth. However, excessive use of SS will cause pollution to forest land. In this sense, we calculated the thresholds for the application of sewage sludge in forestry in China for the first time, considering an adequate application dose for 31 provincial capital cities. The loading capacities differed significantly among the PCCs, making it necessary to formulate specific standards for each area. The S_{min} values varied from 7 to 91 $t \cdot ha^{-1} \cdot y^{-1}$, with an average of 33 $t \cdot ha^{-1} \cdot y^{-1}$ in 31 PCCs; in 50% of the PCCs, the values were higher than 30 $t \cdot ha^{-1} \cdot y^{-1}$ (CJ-T 362-2011). The priority control metals were Cu in Shanghai and Guangzhou, Hg in Beijing, Zn in Tianjin, and Cd in other cities; such information facilitates the development of management strategies for the safe application of sewage sludge in forestry. Sewage sludge shows considerable potential in forestry, based on the relatively high loading capacities, albeit with differences among the different PCCs. Based on this, it is inevitable that for each region, specific sludge disposal policies are formulated. The presented results provide basic data and technical guidance for forestry application.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2071-1050/12/18/7551/s1>, Table S1: The data resource of metal in Provincial capital city. Table S2: The descriptive statistics of baseline and background value in provincial capital city.

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