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Study:

Status Quo of Agricultural Soil Contamination in China from a European Perspective

By Lea Siebert

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List of Abbreviations

As	Arsenic
BTEX	Aromatic hydrocarbons
CHC	Chlorinated hydrocarbon
Cd	Cadmium
Cr	Chromium
Cu	Copper
DDD	Dichloro-diphenyl-dichloroethane
DDE	Dichloro-diphenyl-dichloroethylene
DDT	Dichloro-diphenyl-trichloroethane
GB 15618-1995	Chinese Soil Environmental Quality Standard 1995
GB 15618-2018	Chinese Soil Environmental Quality Standard 2018
HCH	Hexachlorocyclohexane
Hg	Mercury
LUCAS	Land Use/Cover Area frame statistical Survey Soil
MEP	Ministry of Environmental Protection
MLR	Ministry of Land and Resources
Ni	Nickel
P	Phosphate
PAE	Phthalic acid esters
PAH	Polycyclic aromatic hydrocarbon
Pb	Lead
PCB	Polychlorinated biphenyls
Zn	Zinc

1. Introduction

Healthy soils are the prerequisite for agricultural production and hence, they are the basis for food security. Furthermore, soil is a non-renewable resource which cannot be regenerated in a human lifetime (EEA2020). As a result, the topic of soil pollution is urgent and is gaining more and more attention. Besides market-related pressures to convert agricultural land into industrial, residential and other uses, soil is endangered by a number of factors, mainly erosion and soil contamination through various pollution pathways, first of all atmospheric depositions and agricultural inputs. Besides adverse impacts on the interlinked ecosystems, biodiversity and other environmental media, soil pollution has two major implications for human lives: health risks through the food chain and a reduction in yields as many pollutants are toxic for plants. Under consideration of these implications, soil contamination has the same result as soil erosion by wind or water, namely a reduction of arable land available for agricultural production.

For China, the efficient use of natural resources is an urgent matter as its agricultural area is comparatively small for sustaining the world's largest population. Consequently, food security has been on the top of political priorities for the last years and is also in the focus of the lately published 14^{th}-Five-Year Plan. The often quoted 120 million ha of agricultural land, which should be protected by drawing a "red line" to restrict urban sprawl are increasingly endangered as studies suggest that currently at least 19.4% of Chinese agricultural soils are contaminated (Zhao et al., 2015). This is by far not only a Chinese challenge, as also in Europe a considerable area of agricultural land is polluted.

In the following, the current status quo of contaminants in Chinese agricultural soils are analysed. In order to put these facts and numbers into context, they are compared to results from European and, partly German, soil surveys.

2. Soil Threats

Out of a total land size of 645 million ha, China currently has 135 million ha of agricultural land (forests and grassland not included) (SIO, 2019). In relation to its population size, this amounts to 0.09 ha per capita, whereas the ratio is 0.14 ha per capita in Germany and 0.22 ha in the European Union (Worldbank, 2018).

China's arable land resources are threatened by several factors. On one hand, **erosion** by wind or water can lead to the removal of the upper and most fertile soil layer, causing irreversible damages. Even though erosion also occurs naturally, with regard to agricultural soils its main cause are human land management decisions. On the other hand, soils are threatened through **pollution**, mostly related to anthropogenic emissions. Direct pollution results from agricultural soil usage and its related inputs, such as contaminated water, pesticides, herbicides, overuse of fertilizers and residues from mulch films. 66 million ha of farmland in China – almost 50% - are irrigated and hence, **irrigation water quality** is a crucial factor for soil pollution. The composition of **chemical and organic inputs** can lead to soil acidification and the accumulation of heavy metals. Indirect pollution results from **flooding** and **atmospheric deposition**. In their meta-analysis of pollution sources, Luo et al. (2009) found that atmospheric deposition and livestock manures were the main sources for pollution of agricultural land in China, whereas fertilizers, agrochemicals, irrigation water and sewage sludge were important input sources only for specific trace elements. With regard to atmospheric deposition, coal combustion plays an important role in China: in 2018, coal consumption amounted to 3.97 billion tons in total

(NBSPRC, 2020). This annual amount of coal contains approx. 51600 tons of Lead (Pb)[1], 38300 tons of Arsenic (As)[2], 1100 tons of Cadmium (Cd)[3] and 750 tons of Mercury (Hg)[4]. The sources of pollution mentioned above result in an accumulation of heavy metals and organic contaminants in the soil. In addition, excessive application of Nitrate-fertilisers leads to soil acidification, i.e. low pH-values. As a low pH-value in soils can increase the phytoavailability of trace elements, i.e. the uptake of heavy metals into the plant, the fertiliser-induced soil acidification might reinforce the adverse impacts of heavy metal contamination on both crop yields and human health through the food chain.

In Europe, heavy metals are accounting for 35% of soil pollution, followed by mineral oil (24%) and organic contaminants, such as aromatic hydrocarbons (BTEX), polycyclic aromatic hydrocarbons (PAHs) and chlorinated hydrocarbons (CHCs) which all contribute approx. 10%. The main sources of pollution are related to waste disposal, industrial and commercial activities, military uses, and oil and chemical storages and spills (Panagos et al., 2013a).

3. Contamination Status of Chinese Agricultural Soils

The assessment of soil quality at a national scale is a difficult endeavour. It is crucial to take into consideration firstly, how the data was collected and secondly, by which standards the collected data was classified and evaluated. For this purpose, 3.1 gives a short overview of data collection and assessment methods in China and in comparison with European approaches, before an overview on the contamination status of various pollutants is given in 3.2 and 3.3.

3.1 Excursion: Data Collection and Assessment Methods

Due to the size of China, comprehensive soil quality assessments which cover the whole country are very rare. Several meta-analysis were compiled based on smaller-scale field studies, e.g. focussing on heavy metals as done by Huang et al. (2019) (336 articles) or Zhang et al. (2015) (465 papers). The closest to a national-scale, representative assessment comes the survey conducted by the Ministry of Environmental Protection (MEP) and the Ministry of Land and Resources (MLR): between 2005 and 2013 topsoil samples were taken in a 8 x 8 km grid system covering 630 million ha (approx. 67% of the whole land area) and were analysed for 3 organic and 13 inorganic pollutants. According to the resulting "*Report on the national soil contamination survey (2005-2013)*", the thresholds[5] of at least one of the contaminants measured were exceeded in 19.4% of agricultural soils (MEP & MLR, 2014). As Zhao et al. (2015) illustrate, this could mean that 26 million ha of Chinese agricultural land are contaminated. An European equivalent to the Chinese survey is the "*Land Use/Cover Area frame statistical Survey Soil"* (LUCAS) which was conducted in 2009-2012 and 2015 and which assessed, among various other physico-chemical properties, the concentration of 11 heavy metals (Orgiazzi et al., 2017). The samples were taken in the topsoil (0-20 cm) with an average density of one sample every 199 km², which is equivalent to a 14 km x 14 km grid cell system (Panagos et al., 2013b). Based on LUCAS, 6.24% of European agricultural soil samples exceed the "lower guideline values" for heavy metal concentration, which means that 13.7 million ha are defined as contaminated with at least one

[1] For 13.0 mg Pb/kg coal (Fang et al. (2013), doi:10.1007/s10653-013-9581-4)
[2] For 9.65 mg As/kg coal (Kang et al. (2011), doi:10.1016/j.scitotenv.2011.10.026)
[3] For 0.28 mg Cd/kg coal (Shi et al. (2018), doi:10.3390/min8020048)
[4] For 0.19 mg Mg/kg coal (Zheng et al. (2007), doi:10.1016/j.scitotenv.2007.05.037)
[5] For the thresholds used in the survey see Table 1 GB 15618-1995 standard, black digits in red columns

heavy metal. However, taking the "threshold values" (Table 1, blue columns) as a baseline, 58.07% of the samples from agricultural soil have elevated heavy metal contents which suggests that in the EU an area of approx. 127.5 million ha could be polluted to a certain degree (Tóth et al., 2016).

The degree of contamination is defined by **thresholds** which are set as benchmarks necessary for comparing soil quality in different places. In the assessment of heavy metal content, local geochemical conditions such as a certain level of "natural background contamination" from non-anthropogenic sources and original soil pH values also have an impact on measured values and their implication for the soil status. For analysing the Chinese *National Soil Contamination Survey* (2005-2013) the Chinese Soil Environmental Quality Standard was used, which defines thresholds for eight heavy metals in three soil pH-value ranges (<6.5, 6.5-7.5,>7.5) as well as the organic pollutants Lindane and dichloro-diphenyl-trichloroethane (DDT) (GB 15618-1995) (Table 1, red columns). In 2018, thresholds for heavy metals were adjusted and further specified for acid soils below pH 5.5 and PAHs were added to the list of organic pollutants (partly displayed in Table 1 in red digits).

For the analysis of the European LUCAS soil survey, Tóth et al. (2016) used the standards from the Finnish legislation for contaminated soil as they "represent a good approximation in the mean values of different national systems in Europe" (Table 1, blue columns). In contrast, the German "precautionary values" distinguish between values for sand, silt and clay, respectively, and specify thresholds that differ considerably from the other two standards (Table 1, yellow columns) (BBodSchV, Annex II.4). Hence, it is clear, that the results of soil surveys and statements about contaminated land areas have to be considered with caution, as they are only comparable if they applied the same sampling methods and threshold standards.

Table 1: Comparison of different quality standard thresholds for heavy metals and organic pollutant in agricultural soils in mg per kg soil as used in China (red columns), Europe (blue columns) and Germany (yellow columns); applied for cadmium (Cd), arsenic (As), mercury (Hg), copper (Cu), lead (Pb), chromium (Cr), zinc (Zn) and nickel (Ni); and Lindane, dichloro-diphenyl-trichloroethane (DDT), Benzo(a)pyren and polycyclic aromatic hydrocarbons (PAH).

Metal/ organic pollutant [mg/kg]	**Chinese Soil Environmental Quality Standard (Class II)**				**European Soil contamination standards used for LUCAS (MEF, 2007)**		**Precautionary values according to German legislation (BBodSchV, Annex II.4)**		
	GB 15618-2018	**(GB 15618-1995) ***							
	pH ≤ 5.5 paddy field	**5.5 < pH ≤ 6.5**	**6.5 < pH ≤7.5**	**pH >7.5**	**Threshold value**	**Lower guideline value**	**sand**	**Silt/ loam**	**clay**
Cd	0.30	0.3	0.3	0.6	1	10	0.4	1	1.5
As	30	40	30	25	5	50	-	-	-
Hg	0.50	0.3	0.5	1.0	0.5	2	0.1	0.5	1
Cu	150	50	100	100	100	150	20	40	60
Pb	80	250	300	350	60	200	40	70	100
Cr	150	150	200	250	100	200	30	60	100
Zn	200	200	250	300	200	250	60	150	200
Ni	60	40	50	60	50	100	15	50	70
Lindane	0.1	0.5			-	-	-		
DDT	0.1	0.5			0.1	1	-		
Benzo[a] pyren	0.55	-			0.02	0.2	0.3 (humus <=8%) 1 (humus >8%)		

PAH	-	-	15	30	3 (humus <=8%) 10 (humus >8%)

*Applicable thresholds for respective contaminant in dry farm land

3.2 Heavy Metals

According to the *Report on the National Soil Contamination Survey*, analysing all soil samples (including non-arable land) suggests that 82.4% of the pollution is related to inorganic contaminants. Furthermore, the survey found that cadmium (Cd) and nickel (Ni) were the most common heavy metals, as respective thresholds were exceeded in 7% (Cd) and 4.8% (Ni) of all samples (Fig.1). Elevated levels of other heavy metals were also measured in a certain proportion of the samples: arsenic (2,7%), copper (2.1%), mercury (1.6%), lead (1.5%), chromium (1.1%) and zinc (0,9%). Unfortunately, this data refers to all soil samples which have been collected from all kinds of land uses, whereas no large-scale data was published specifically for agricultural soils. According to a meta-analysis with the same soil standard, 10.18% of agricultural land is affected by heavy metal pollution (Zhang et al. 2015).

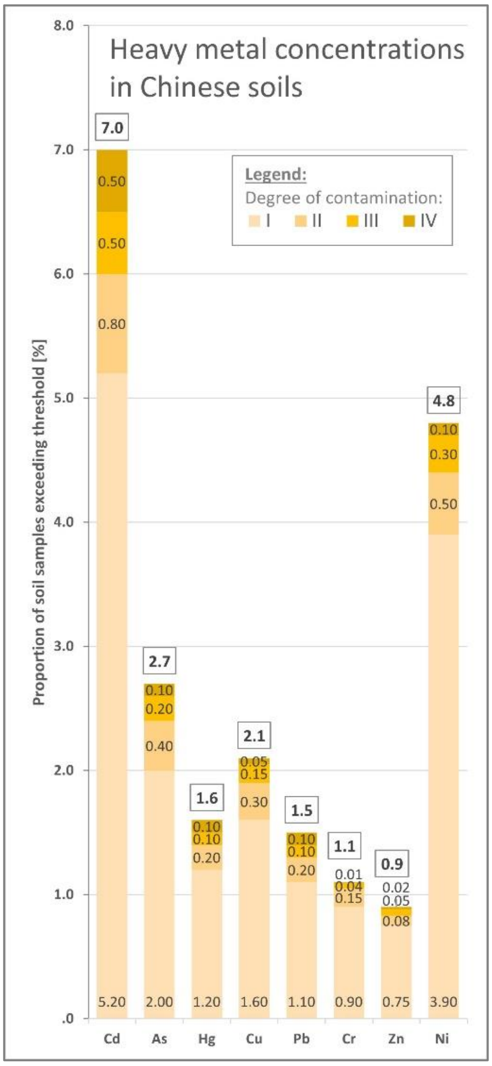

Figure 1: Proportion [%] of Chinese soil samples which exceed the heavy metal threshold for cadmium (Cd), mercury (Hg), arsenic (As), copper (Cu), lead (Pb), chromium (Cr), zinc (Zn) and nickel (Ni) with total numbers above each column. The stacked column sections display the degree of contamination: I= 1-2 times, II= 2-3 times, III= 3-5 times, IV= more than 5 times of threshold value. (Data from MEP & MLR, 2014, National Soil Contamination Survey, own graph).

With regard to **geographical distribution** of pollution, it was found that especially southern China is affected, which is related to chemical production plants, and mining and smelting activities (Zhang et al., 2015; Fig.2). However, in association with coarse particulate matter (PM 2.5-10), some metals, such as Pb, Zn, Cd and Ni, can be distributed in a radius <10km of the point source, whereas gaseous phase metals even might pollute regions in 200-2000 km distance (Zhang et al., 2019). Water can also transport contaminants over long distances and cause soil pollution in irrigated fields. The high pollution values for Tianjin in the North are mainly related to sewage irrigation in farmland soil (Zhang et al., 2015). Especially paddy rice field cultivation is affected by irrigation water quality, leading to Cd inputs of potentially up to 400 g per ha and year (Zhao et al., 2015). In addition to the geographical distribution of pollution sources, local soil characteristics, such as soil texture and soil pH, play an important role in the heavy metal intake rates of plants. In southern China many soils are very acidic which facilitates the phytoavailability of metals such as Cd (Zhao et al., 2015). Clay contents also increase the accumulation of many

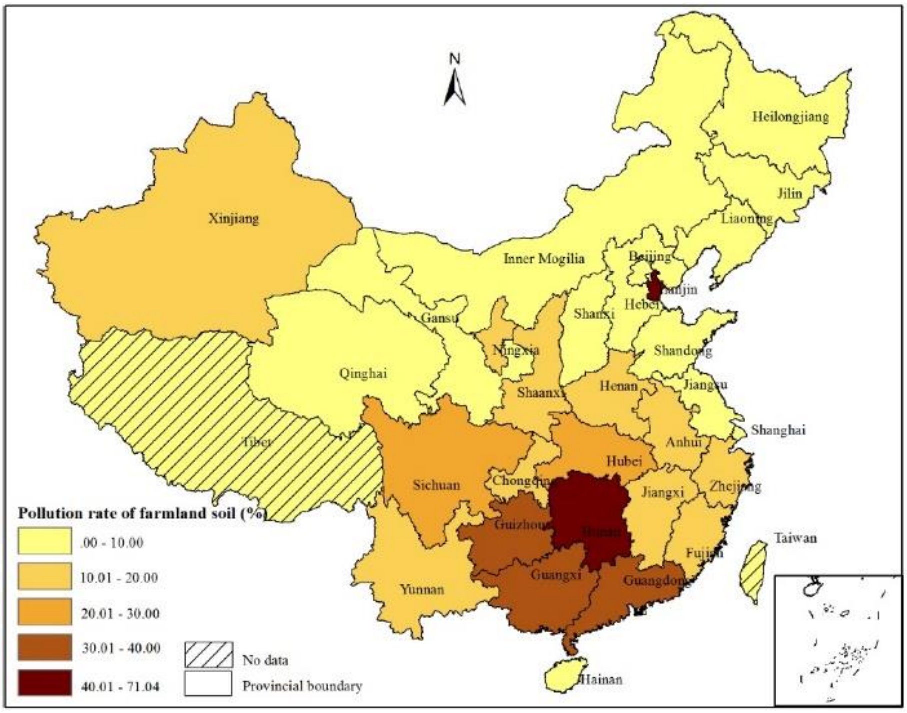

Figure 2: Heavy metal pollution of farmland by province (Zhang et al., 2015)

contaminants in the soil. Sandy soils, however, especially in regions with high precipitation rates, facilitate the leaching of contaminants which decreases the risk of plant uptake, but leads to a higher risk of groundwater pollution.

Cadmium (Cd)

According to the *National Soil Contamination Survey*, Cd is the most common pollutant in Chinese soils (Fig.1). 7% of Chinese soil samples exceed the threshold of 0.3-0.6 mg/kg, out of which 1.8% of samples exceed the threshold by 2-5 times. In Europe the threshold for Cd contamination is 1 mg/kg which was exceeded by 5.5% of samples collected across Europe (Tóth et al., 2016). However, taking Chinese thresholds as a benchmark, it can be assumed that European pollution values would be higher. As China's natural background levels are very low, Cd pollution is clearly related to human activities and mainly enters soil as fertiliser application and atmospheric deposition. In their analysis of trace element inputs into Chinese agricultural soils, Luo et al. (2009) found that 55% of soil Cd is related to livestock manure inputs, especially pig manure, and 35% results from atmospheric deposition. In Europe, phosphate (P) in inorganic fertilisers is a relevant source of Cd pollution, depending on the phosphate rock origin (Tóth et al. 2016). However, Cd concentrations in Chinese P-fertilizers are relatively low and hence, this source would only be relevant if fertiliser imports were increasing. In China, mining and smelting activities as well as the production of nickel-cadmium batteries and in general large-scale coal combustion contribute to Cd pollution. Cd emissions from industrial activities enter soil and plants either via airborne emissions or via contaminated irrigation water. The plant Cd uptake is correlated with plant species, soil pH and farming system. Zhao et al. (2015) estimate that Cd inputs in double-rice cropping systems can amount to 400 g/ha per year.

Cd in soils is easily taken up and accumulated by plants without affecting plant growths (Wang et al., 2019). In this respect, Cd pollution has not necessarily an impact on the quantity of food, but it even rather affects food quality as Cd is classified as a human carcinogen and food should not exceed 0.2 mg Cd per kg. In southern China, several adverse factors come together as *Indica* rice cultivars are traditionally grown in flooded paddy fields on acid soil. As a result, several analyses of locally produced grain found Cd concentrations from 0.33 to 0.69 mg/kg with several samples exceeding 1 mg/kg, posing a severe risk to human health, especially to those who consume the southern China average amount of 310 g rice per day (Wang et al., 2019).

Arsenic (As)

According to the Chinese national soil contamination survey, the thresholds of 25-40 mg/kg are exceeded by 2.7% of soil samples. In Europe, the proportion of samples exceeding action levels of *As* contamination is also below 5%. Tarvainen et al. (2013) in their assessment of *As* levels in agricultural soils throughout Europe found large differences between northern – on average 3 mg/kg – and southern soils – on average 10 mg/kg – Europe. However, these differences seem to be directly linked to geology and anomalies of high values coinciding with ore deposits or mineral belts. *As* mainly enters Chinese agricultural soils through atmospheric deposition. It is one of the hazardous trace elements in coal and released during combustion. Concentrations in Chinese coal vary from 0 to 35037 mg/kg with an arithmetic mean of 9.65 mg/kg. However, *As* emissions also depend on the treatment of raw coals before combustion and emission reduction systems in the power plant. The *As* concentration in fly ash is much higher than in the original coal and *As* soil contamination can occur in 80 km distance to a power plant (Kang et al., 2011). Another direct source for *As* pollution in agricultural soils in China are phosphate fertilizers and their production sites (Gong et al., 2020) as well as animal manure which is used as organic fertilizer (Luo et al., 2009). It is reported that *As* is still used as feed additive with the aim of disease control and weight improvement for swine and poultry in China and hence, *As* concentrations in pig and chicken manure are much higher than in other animal manure.

Due to its chemical properties, *As* is fixed in rather acid soils and more solutable and hence, more plant-available, in alkaline soils. In an environment of high pH values, *As* is more mobile and can be absorbed by plants and affect germination, growth and yields and lead to water stress and slowed-down photosynthesis due to interference with metabolic processes. In this regard, phytoavailability of *As* works contrary to the plant uptake of other heavy metals and hence, efforts to increase pH values to prevent e.g. Cd contamination can lead to an increase of As accumulation in plants.

Mercury (Hg)

In China, 1.6% of soil samples have Hg values above 0.3-1 mg/kg as thresholds are depending on the respective soil pH. In Europe, the general threshold of 0.5 mg/kg is exceeded in 0.8% of LUCAS soil samples (Panagos et al., 2021). The main input pathway of Hg in China is atmospheric deposition resulting from non-ferrous metal smelting, coal combustion and industrial production processes, such as battery and fluorescent lamp and cement production (Luo et al., 2009). Also in Europe, present and past mining activities are the main source of Hg contamination. Furthermore, coal combustion plays an important part. Although China's gold mining industry is small, it accounts for 37 % of the country's Hg emissions (Liu et al., 2021). With regard to the cropping system, Hg values are highest in rice and vegetable fields which supports the theory that polluted irrigation water is also a relevant input pathway.

High Hg values in the soil have adverse impacts on seed germination, plant morbidity and microbial activitiy. Furthermore, the food chain is a relevant exposure channel for humans (Liu et al., 2021). Especially rice can accumulate Hg and pose a risk to human health as it has been shown for the rural population in China's mining areas (Zhao et al., 2015).

Copper (Cu)

In China, 2.1% of soil samples exceed the Cu thresholds of 50 mg/kg in soils with a pH below 6.5 and 100 mg/kg for soils with higher pH values. A meta-analysis of Chinese studies from 1985-2016 found that 21% of soil samples from agricultural land exceeded the 50 Cu mg/kg threshold (Qin et al., 2021). These assessments are comparable to the European LUCAS survey, which found that 1.1% of soil samples exceeded 100 mg/kg. However, out of European samples of the land use type vineyards, 14.6% were above 100 mg/kg due to the traditionally extensive application of Cu fungicides in wine production. Soil samples from olive groves and fruit trees were also found to have elevated Cu contents (Ballabio et al., 2018). The application of Cu in fungicides such as Cu trichlorophenol, Cu-Zn mixtures and Cu sulfate are also a common source of Cu contamination in Chinese soils. Another source is the application of organic fertilisers: over ten years, Cu contents in chicken manure doubled, whereas contamination of pig manure increased tenfold (Luo et al., 2009). These increases are related to the addition of Cu to animal feeds to prevent diseases and improve growth performance, which is not regulated by standards or directives in China. The amounts of Cu in the soil are closely correlated with soil pH, precipitation and soil texture. In alkaline soils with high clay content and in areas with less rainfall, Cu is accumulated, wheras the chance of leaching into the groundwater increases with sand content and lower pH values in humid areas.

Within the range of 5-30 mg/kg, Cu is also one of the indispensable micronutrients for plant growth. Amounts of >100 mg/kg can lead to toxic effects in the plant and negatively affect growth, while excess Cu can be accumulated by plants in their tissue. Exposure to high-Cu-content food can cause liver diseases, neurological effects and Alzheimer-disease in humans (Ballabio et al., 2018).

Lead (Pb)

The main origin for Pb pollution in Chinese soils is atmospheric deposition, leading to a rate of 1.5% of soil samples which exceed the thresholds of 250-350 mg/kg (depending on soil pH). However, in comparison with the European threshold value of 60 Pb mg/kg, the Chinese benchmarks seem high. This has also been acknowledged by the fact that the threshold has been lowered to 80-240 mg Pb per kg in the revised Chinese soil quality standard. It was found that in China, vehicle emissions contribute 78.1% to Pb concentrations in atmospheric dust, whereas coal combustion contributes another 21.9% (Qin et al., 2021). However, the ban of leaded gasoline in 2000 led to a reduction of transportation-related Pb emissions by approx. 30% (Zhang et al., 2019). Soil analysis in European countries has shown that only very few samples exceed the threshold of 60 Pb mg per kg and hence, it is concluded that in Europe, Pb does not pose a risk to food safety at the moment (Tóth et al., 2016).

Pb contamination in soils can negatively affect plant nutrient and water uptake and inhibit germination. However, some crop species are more vulnerable than others and also the level of Pb in the soil is crucial. It has been reported that Pb toxicity can lead to considerable yield reductions. Furthermore, in humans Pb can lead to kidney failure and cardiovascular disease and with severe impacts on children’s brain development (Qin et al., 2020).

Chromium (Cr)

Li et al. (2020) conducted a meta-analysis based on 1799 papers (1989-2016) and found that the screening value (150 mg Cr/kg) was exceeded in 4.31% of the sampling sites in China, whereas a small number of 0.12% exceeded the control value of 800 mg/kg. These values are much higher than those of the *National Soil Contamination Survey* (2005-2013) which found that the 150 mg/kg threshold was exceeded in 1.1% of the samples, referring not exclusively to agricultural soil, but to samples from all kinds of land use. According to the LUCAS survey, in Europe 2.7% of agricultural land is affected by Cr contamination >100 mg Cr/kg, i.e. 2 million ha of Cr contaminated agricultural land (Tóth et al. 2016). For China, it has been found that raised Cr concentrations are not linked to Cr parent rock material, but mainly to atmospheric deposition (43%), livestock manure (36%) and (phosphate and compound) fertilizers (20%) (Luo et al., 2009). The correlation of fertilizer consumption and soil Cr concentrations was confirmed by Li et al. (2020). Looking into the sources of Cr emissions, they found that the main source is the Chromium salt industry, followed by electroplating and leather making. The tanning industry is also the major driver of Cr pollution in Europe, and contaminated sludge and wastewater pose a threat to the environment.

Unlike other heavy metals, Cr mostly occurs in two forms Cr(III) and Cr(VI), while Cr(VI) has a higher solubility and is considered to be 10-100 times more toxic than Cr(III). Plants rather accumulate Cr in the roots than in leaves and can tolerate certain amounts of Cr. However, both forms of Cr have adverse effects on seed germination, root growth and biomass production. Soil pH influences the solubility of Cr(III), whereas Cr(VI) is extremely soluble in all pH values. The higher the organic matter content of the soil, the more Cr(VI) is reduced to the less toxic form of Cr(III). However, the redox reaction in soils is very slow and takes years. Therefore, active remediation treatments are necessary to reduce Cr contamination (Ertani et al., 2017).

Zinc (Zn)

Being an essential element for both humans and plants, the amount of Zn in soils is crucial to assess its toxicity. The Chinese contamination survey found that the thresholds between 200 and 300 mg/kg, depending on soil pH, were exceeded in 0.9% of soil samples. Also, the European LUCAS survey showed excess rates of the 200 mg/kg threshold in less than 1% of the soil samples. However, when looking specifically at agricultural soil, Zn contamination was found in 20% of European soil samples, which makes the connection between agricultural practices and Zn inputs obvious (Tóth et al., 2016). Furthermore, also the distance to industrial activities such as mining or smelting is a relevant factor for soil Zn pollution. As Zn is used as a feed additive in China, especially chicken and pig manure show elevated Zn levels. Furthermore, Zn is a component of (mainly phosphate) fertilizers and fungicides for crops and vegetables (Luo et al., 2009).

In soils, high Zn content is positively correlated with clay content and the abundance of organic matter. Depending on the crop species, the amount of Zn which is necessary for plant growth ranges between 15-70 mg/kg. Deviations from the critical level lead to Zn deficiency or toxicity and negatively affect plant growth, e.g. by inhibiting copper absorption which leads to copper deficiency symptoms (Tóth et al., 2016). Also, earthworms and microorganisms are negatively affected which leads to a reduced breakdown of organic matter.

Nickel (Ni)

In China, soil Ni contents exceed thresholds of 40-60 mg/kg in 4.8% of soil samples. According to Luo et al. (2009) the main source for Ni is atmospheric deposition, followed by livestock manure. Air-borne Ni pollution can be associated to fly ash from the combustion of fossil fuels or dust from metal and cement processing industries. Another source is the production of batteries. The LUCAS survey suggests that European Ni contents are rather of natural origin as the distribution seems to be related to different climatic regions (Tóth et al., 2016). Zhao et al. (2015) argue that also the high proportion of Ni polluted soil samples in China is a result of low threshold value which are actually close to the natural background levels.

Similar to Zn is Ni a crucial micronutrient for plants; however, concentrations above 10 mg/kg in plant biomass are toxic for plants. The mobility of Ni in soils and its uptake by plant roots is facilitated by low pH and oxidizing conditions.

3.3 Organic Pollutants

Besides heavy metals, the second group of pollutants are organic contaminants and as they are often related to non-point source pollution, large agricultural areas in all regions of China are affected. According to the *Report on the National Soil Contamination Survey*, organic pollutants account for 17.2% of soil samples exceeding standards. In this survey, three groups of organic contaminants – Lindane, DDT (dichloro-diphenyl-trichloroethane) and PAH (polycyclic aromatic hydrocarbons) – were assessed, and levels exceeding the threshold were found in 0.5%, 1.9% and 1.4% of the samples, respectively (Fig. 3). However, these figures do not exclusively refer to agricultural soils, but include all kinds of land usage. Furthermore, it can be noted that the threshold in many samples is not only exceeded by two times, but by up to five times. For instance, looking at **DDT** pollution, this could mean that 1,58 million ha of land (all land uses) are contaminated with levels of > 2.5 mg DDT/kg (i.e. five times the threshold of 0.5 mg/kg). Organic contaminants enter soils on various pathways, e.g. as pesticides or herbicides, resulting from incomplete combustion of organic matter or waste disposal. In China's Soil Quality Standard of 2018, with Lindane and DDT, two out of three organic contaminants are organochlorine pesticides which are classified as "persistent organic pollutants" due to their high toxicity, high bioaccumulation and slow degradation rate. In German soil

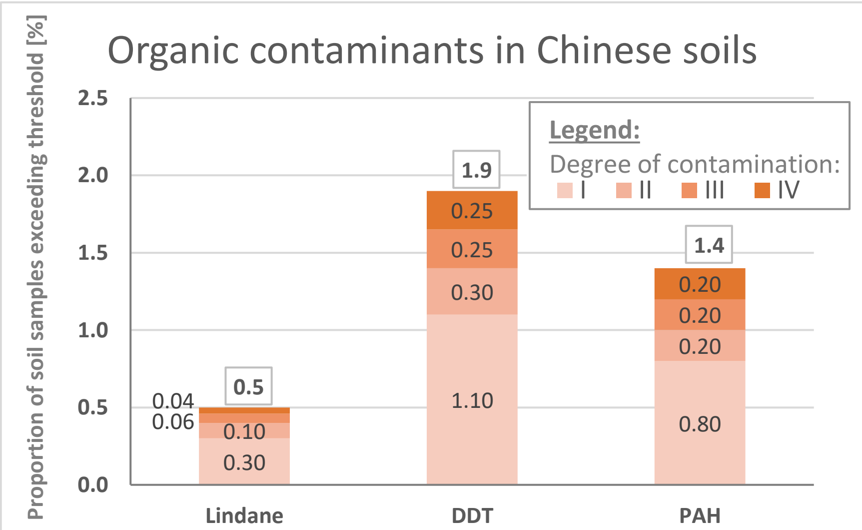

Figure 3: Proportion [%] of Chinese soil samples which exceed the threshold: Lindane (C6H6Cl6), dichloro-diphenyl-trichloroethane (DDT) and polycyclic aromatic hydrocarbons (PAHs) with total numbers above each column. The stacked column sections display the degree of contamination: I= 1-2 times, II= 2-3 times, III= 3-5 times, IV= more than 5 times of threshold value. (Data from MEP & MLR, 2014, National Soil Contamination Survey, own graph).

protection legislation, however, the focus lies on PAH which are assessed by their total amount and on benzo(a)pyrene as well as polychlorinated biphenyls (PCBs), whereas Finnish legislation provides a long list of threshold values of various soil pollutants (MEF, 2007). In their assessment of the most relevant organic contaminants in agricultural soils in China, Sun et al. (2018) focus on the following groups: organochlorine pesticides (e.g. DDT), PAH, PCBs and PAEs (phthalic acid esters). It can be assumed that the number of monitored substances is limited by resources, and hence, the selected contaminants act as indicators to give a general idea of the soil pollution level based on the prevalent pollution sources.

Lindane

Like DDT, Lindane is a pesticide, mainly used as an insecticide. After 1991, it replaced technical HCH (hexachlorocyclohexane) after HCH had been banned. As the production of Lindane is still based on HCH, the production of each ton of lindane causes 8-12 tons of HCH waste (Vijgen et al., 2022). Until 1983, 4 million tons of HCH were produced in China and Li et al. (2015) assume that between 1991 and 2000, 3200 tons of lindane were still used. In the National Soil Contamination Survey, the threshold of 0.5 mg/kg was exceeded in 0.5% of samples. It is assumed that 1.8 to 3 million tons of HCH from Lindane production were disposed in Europe, partly in uncontrolled deposits and landfills. However, no comprehensive assessment about average soil contamination with HCH has been made for Europe or even at member state national level. This is also illustrated by the fact that neither Finnish nor German legislation set a threshold for HCH or Lindane (Table 1). In their meta-analysis of studies on HCH and DDT contamination in Chinese soils, Ma et al. (2020) found that HCH concentrations were below the adjusted threshold of 0.1 mg/kg in all studies but one – values of 0.17 were found in Shandong province.

In contrast to technical HCH, Lindane has the advantage that it does not affect crop quality. However, it is known that HCH can accumulate in free range cattle and chicken, which can be a health risk for humans via the food chain as HCH isomers were found in cow's milk and human blood near HCH production sites. It has been found that HCH isomers cause cancer and neurological and reproductive disorder in humans (Vijgen et al., 2022).

DDT

DDT stands for dichloro-diphenyl-trichloroethane and can be degraded to DDE (dichloro-diphenyl-dichloroethylene) and DDD (dichloro-diphenyl-dichloroethane), which are sometimes assessed together as „DDTs“. According to the Chinese *National Soil Contamination Study*, the threshold of 0.5 mg DDT/kg was exceeded in 1.9% of Chinese soil samples. In Europe, the threshold for soil DDT residues is 0.1 mg/kg, same with the adjusted threshold in the revised Chinese soil quality standard from 2018. In an European assessment of pesticide residues, based on 317 soil samples, residues of DDTs (= sum of DDE, DDD and DDT) were found in 25% of the samples (Silva et al., 2019). Although the proportion of samples exceeding thresholds was not assessed, the European median (0.03 mg/kg) is slightly lower than the Chinese median of 0.04 mg/kg, whereas the assessed maximum contents differ significantly: 0.31 mg/kg in Europe and 3.52 mg/kg in Chinese samples (Silva et al., 2019; Sun et al., 2018).

DDT is a pesticide which was frequently used as an insecticide around the world before its harmful impact on the environment and non-target species was detected. As a consequence, the use and production has been also banned in Europe in 1981, followed by a ban in China in 1983. Due to its long-term residual effect, DDT can still be detected in many soils as well as in animals and throughout the food chain in China as well as Europe. Furthermore, as a result of the ban of DDT, dicofol as "technical DDT" was produced as a substitute which to a small proportion (<5%) consists of DDT and became a significant source of nowadays DDT pollution (Ma et al., 2020). DDT has been banned for its toxicity for various species, including humans, and implications for the ecosystem through its accumulation in the food chain. However, there are no relevant negative impacts specifically on crop growth.

PAH

Polycyclic aromatic hydrocarbons (PAH) are a group of organic compounds which consist of at least two aromatic rings. The most well-studied PAH is benzo(a)pyrene, which is known for its carcinogenetic effects, and hence, it is often taken as an indicator for PAH. In Chinese soils, PAHs exceed the threshold for contamination in 1.4% of the samples. As the 1995 Soil Quality Standard does not provide thresholds for PAHs, the *National Survey* follows oversea standards and it can be assumed that PAH contamination is defined by values above 0.2 mg/kg (Sun et al., 2018). According to German legislation, the contamination is defined by values above 3 or 10 mg/kg depending on soil humus content, whereas the Finnish legislation sets 15 mg/kg as the threshold value. No comprehensive assessment of PAH pollution in agricultural soils has been conducted across several European countries. Average values, e.g., for Benzo(a)pyrene, differ from 0.014 mg/kg in Germany and Switzerland to 0.138 mg/kg in the UK (Maliszewska-Kordybach et al., 2009). In their meta-analysis of data on soil PAH values in China, Zhang & Chen (2017) calculated an average of 0.73 mg/kg with significant differences between Northeast China (1.467 mg/kg) and West China (0.021 mg/kg). These differences were also found by Sun et al. (2018) and could be explained by excessive coal use throughout the winter months as well as the distribution of coal mining areas in China. Furthermore, they found that only 17.2% of the soils could be defined as „non-contaminated“. However, it is assumed that PAH concentrations can be about 30 times less in agricultural soils than in city centres as their abundance is clearly linked to anthropogenic activities, mainly coal combustion and vehicle emissions. PAH enter soil through atmospheric deposition and through plants which accumulate PAH from the air.

PAHs have toxic, mutagenic and carcinogenic properties and also accumulate in humans through dietary intake of contaminated food. Plants, especially vegetables, can take in PAH through their roots. Due to their strong sorption affinity to soil organic matter, PAHs are less mobile in soils with high humus content. This is also illustrated by the two different precautionary values states in German soil protection legislation which allows higher PAH values for soils with humus content >8%.

PAEs

Even though not assessed in the *National Soil Survey*, phthalic acid esters (PAE) become increasingly relevant contaminants in Chinese agricultural soils. They are used in substances such as polyvinyl acetates, polyvinyl chloride, and polyurethanes and enter soils typically as plastic films. These plastic films are widely used across China to cover fields as a protection against wind erosion, while reducing fertilizer and irrigation water use significantly. However, after the planting season these films are often discharged on-site leading to soil pollution. Other sources for PAEs are wastewater irrigation and agricultural chemicals (Sun et al., 2018).

PAE can be accumulated in plants and it was shown by Wang et al. (2021) that concentration in maize roots was significantly higher than in surrounding soil. After uptake, PAE are mainly accumulated in the plant roots and less in stems, leaves and grains. In their study, the consumption of maize grains and potato tubers grown on PAE contaminated soil posed a very low carcinogenic risk.

4. Conclusion

In order to tackle soil pollution in agricultural land it is crucial to firstly get an overview of the pollution status and the sources of pollution. In China, the most comprehensive approach so far is the nationwide survey on soil pollution which was conducted between 2005 and 2013 (MEP & MLR, 2014). However, the published report only gives statistics about percentages of pollution levels, whereas no detailed nor site-specific data has been made available to the public. The comparison with European endeavours to assess soil quality at a large scale showed how challenging it is to produce comparable data. Besides comparable analytical and sampling methods, the choice of indicators and thresholds are key factors. This study has shown that on one hand, the European Union so far lacks a general threshold framework to evaluate the data generated in its comprehensive soil survey, which is also related to the diversity of EU member states. On the other hand, China lacks transparency as no raw data is published, but only the summary report of their soil contamination survey.

Secondly, as these soil assessments aim to lay the basis for safeguarding and improving agricultural soils, they should result in corresponding policies. In China, the *10-Measures for Soil Pollution Action Plan* was published in 2016 as a direct result of the National Soil Contamination Survey. Furthermore, in 2018 the Quality Standard for Soils was updated and provides more detailed risk screening values as well as an additional organic pollutant indicator (GB15618-2018). In 2018, also the new Soil Pollution Prevention and Control Law entered into force and since then, the importance of protecting agricultural land resources has been stressed in all yearly published "Document No.1" as well as in the new 14^{th}-Five-Year Plan. In Europe, besides a general, non-binding Soil Protection Strategy and directives specifically addressing certain soil-related aspects, such as directives on nitrates, industrial emissions or water framework, no legal instrument on soil protection exists (Heuser, 2022). However, this might change within the framework of the European Green Deal which aims to address soil health by legal instruments by 2023.

Thirdly, besides avoiding future soil contamination, governments need to make efforts to reduce adverse impacts of existing pollution and invest in remediation. The first can be achieved by reducing phytoavailability of contaminants, e.g. by liming, and by choosing crops and management techniques which are suitable for local soil pollution conditions. However, heavily polluted soils might not be suitable for growing any food or feedstuffs and could be considered for the cultivation of energy crops. Remediation is on the political agenda in both China and Europe. However, existing techniques are costly and take a long time to show effects.

Scientific publications suggest that in China at least 26 million ha of agricultural land are polluted, whereas in Europe at least 13.5 million ha or up to 127.5 million ha are polluted, depending on the applied thresholds. The review made clear that pollution pathways and contaminants might differ, but the threat and implications of soil pollution are gaining more attention in both regions. In light of the slow and limited options for remediation of agricultural soils, it seems most efficient to tackle pollution sources and make ongoing management practises more sustainable.

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