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环境重金属污染物的生物有效性

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摘要：利用生态系统研究了白银有色金属冶炼矿区周围环境中重金属的分布及生物有效性。结果表明，工厂在冶炼过程中已造成 Pb、Cd、Cu、Zn 对周围环境不同程度的污染，其含量与距工厂的距离呈负相关；重金属在各种生物体内均有不同程度的吸收和累积，其吸收累积量随重金属和生物种类的不同而有差异；土壤的污染，使农作物和牧草中 Pb、Cd 含量超过动物的最大耐受量和中毒的临界值；动物研究发现，肾脏、骨骼和肝脏是机体内重金属蓄积的主要器官。因此，放牧动物可作为环境重金属污染状况的标识，对评价重金属环境污染对当地人群的危害也有重要意义。

关键词：重金属；环境污染；生物有效性

The bioactivity of environment heavy metal pollutants in the vicinity of non-ferrous metal smelters

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Abstract: Baiyin in Gansu Province was an important base producing non-ferrous metals in China. This region contains extensive mineral resources characterized by large quantities of ores containing copper, lead, zinc, and iron, with attendant gold, silver and a small quantity of platinoids. A number of very large industrial enterprises were formed for lead zinc, copper, and polymetallic extraction in the 1970s. During a few decades of intensive development metallurgical industries soon occupied a very wide area. There were deaths of a large number of grazing sheep and horses on farmland in the vicinity after the smelters went into operation. Accordingly, it was concluded that the disease was probably related with environmental heavy metal pollution caused by industry activities in the region. The national state of environment data for emissions and ambient environment have shown that the region is exposed to high levels of a range of pollutants, including heavy metals. The objectives of the present study were to evaluate the effect of heavy metals on biotoxicity and bioavailability in the region.

In this study, the concentrations of lead, cadmium, copper and zinc in soils, water, forages, feed and blood, hair and tissues of affected sheep and horses were determined in the surroundings of the smelters in Baiyin and controls. The concentrations of these elements in soils, forages, water and feed were significantly higher than those in the control area ($p<0.01$). The contents of lead and cadmium were 9.3 and 690 times in forages, respectively; 10 and 35.6 times in feed. Meanwhile, the results showed a clear decrease with increasing distance to the smelters. The concentrations of lead and cadmium in blood, hair and tissues of the affected sheep and horses were significantly higher than reference values and control animals ($p<0.01$). Lead and cadmium intake levels, estimated according to the ingestion rates of forages, illustrates that the apported lead and cadmium through the ingestion of vegetation growing in the closest sites to the smelters were approximately 6.0mg Pb/kg body weight/day and 1.1mg Cd/kg body weight/day in horses, 21.4mg Pb/kg body weight/day and 4.0mg Cd/kg body weight/day in sheep, surpassing the fatal dosages for horses of 1.7mg Pb/kg body weight/day and for sheep of 4.4mg Pb/kg body weight/day and 1.0mg Cd/kg body weight/day. Lead and cadmium were mainly accumulated in kidney, liver and

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skeleton of affected sheep and horses in the region. the disease of sheep and horses in this region is caused by lead poisoning combined with cadmium, mainly due to environment heavy metal pollution by industrial activity. It is therefore suggested that as such levels of contamination in animal food and grain pose a significant potential risk to human health, these results have formed the basis for subsequent research on levels of metal contamination in human tissues from affected populations.

In the present study, the concentrations of copper and zinc in soils, forages and feed were significantly higher in Baiyin region than those in control area. In general, the maximum tolerable levels for copper in sheep and horses are 25mg/kg and 800mg/kg, respectively, for zinc 300mg/kg in sheep (NRC, 1980). Whether the levels of copper and zinc in these soils and forages affect the absorption of lead and cadmium in the sheep and horses will be further investigated.

The result showed that the heavy metals in the surroundings of the smelters had an effect on biotoxicity and bioavailability. Thus it can be seen that knowledge of lead and cadmium concentrations in livestock in this region is important for assessing the effects of pollutants on domestic animals themselves and contaminant intakes by humans.

Key words: heavy metals; environmental pollution; bioactivity

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随着现代工业的发展和人类的活动,重金属对生态环境的污染越来越严重。我国环境污染主要来自工业,技术落后,企业管理不善,环境监督管理不力,立法又不够完备,是造成工业污染环境的主要原因[1]。环境中的重金属难降解,可长期残留在环境中,并通过食物链系统进入动物和人体内产生毒害作用。重金属的生物有效性是指重金属对生物产生毒性效应或被生物吸收,包括生物毒性和生物可利用性,通常由毒性数据或生物体浓度数据评价。甘肃白银是我国重要的有色金属冶炼基地,多年来在生产冶炼过程中排放大量的工业“三废”,使周围的水、土壤、农田和植物受到不同程度的重金属污染,导致放牧动物发生铅镉联合中毒[2~3]。本文通过对土壤、牧草、农作物和放牧动物组织等生物样品的检测,揭示该地区环境重金属污染的生物有效性。

1 材料与方法

1.1 样品的采集

1.1.1 水、土壤、牧草和农作物样品 沿工厂排放废水和生活污水灌溉农田的东大沟灌区,选择距工厂不同距离 1km、5km、10km、10km 和 30km 的 5 个采样点,采集当地 0～20cm 和 20～40cm 深的土壤、农田灌溉用水、农作物秧苗(小麦、荞麦等)、牧草(冰草、岌岌、禾草等)、粮食和油料(小麦、荞麦、胡麻等)样品。植物样品采集时离地表 1～2cm,避免土壤污染。

1.1.2 动物样品 从污染最严重的地区选择长期放牧的马 5 匹、绵羊 10 只,采集全血和被毛,屠宰后采集心脏、肺脏、肝脏、肾脏、肌肉、肋骨和牙齿等样品。

1.2 元素分析

被毛样品 1%洗涤剂清洗后用蒸馏水和无离子水各冲洗 3 遍,在 80℃干燥箱中烘干。土壤、牧草、粮食和动物组织样品均在 80℃干燥箱中烘干。土壤样品用玛瑙研钵反复研磨,并过 100 目筛。所有样品均用湿法消化(HNO_3-$HClO_4$),AA-640 原子吸收分光光度计测定 Cu、Zn、Pb、Cd 含量,同时用美国国家标准局(NBS)提供的牛肝粉(1577a)和国际原子能机构(IAEA)提供的草粉(V-10)进行质量控制。

2 结果

2.1 水、土壤中重金属元素的含量 对农田灌溉用水和土壤中矿物元素含量的测定表明(表 1～表 3),Pb、Cd、Cu、Zn 含量与距工厂的距离呈负相关,距工厂越近,上述元素的含量越高。从土壤各层元素分布情况看,耕作土壤表层(0～20cm)金属元素含量均高于深层土(20～40cm),主要是含较高重金属物质的污水灌入土壤后,在表土层的机械截留、胶体吸附等作用下,于土壤表层沉积下来,导致土壤表层重金属元素含量增高[4],由此可见,该地农田土壤中铅镉等元素的污染主要来自废水的灌溉和大气的降尘。

2.2 重金属的生物可利用性

2.2.1 牧草中重金属元素的含量 牧草中元素含量的分析表明,Pb、Cd、Zn、Cu 含量极显著高于对照样品($p<0.01$)(表 4)。通过对不同季节牧草的测定,发现牧草中有害元素的含量具有明显的季节性变化,总的变化趋势是冬春季节较高,夏秋季节较低;经统计学分析,夏季牧草中 Pb、Cd、Zn、Cu 含量与春季、秋季和冬季相比具有显著差异($p<0.05$ 或 $p<0.01$),这一变化与动物发病的季节相一致。

按照采食量,马 21g dw/(kg 体重・d)[5],绵羊 74.3g dw/(kg 体重・d)[6],当地放牧马和绵羊每天 Pb、Cd 的吸收率见表 5。

2.2.2 粮食中重金属元素的含量 对粮食中矿物元素含量的分析表明,Pb、Cd、Zn、Cu 含量极显著高于对照样品($p<0.01$)(表 6),粮食中 Pb、Cd 平均含量分别是对照区的 10 和 35 倍,其余元素含量差异不显著($p>0.05$)。

表 1　农田灌溉用水中元素含量(mg/L)

Table 1　The concentrations of trace elements in irrigation water

采样点 Sampling sites	**样品数** *n* No. of samples	Pb	Cd	Zn	Cu
1	5	6.23±1.24^{c}	8.86±2.14^{c}	17.26±3.67^{c}	4.67±2.12^{c}
2	7	4.24±1.12^{c}	7.66±2.18^{c}	15.44±3.87^{c}	3.21±1.04^{c}
3	10	3.10±0.88^{c}	3.44±1.75^{c}	13.21±4.12^{c}	3.11±0.99^{c}
4	10	1.47±0.93^{c}	2.32±0.99^{c}	10.61±3.80^{c}	2.65±0.67^{c}
5	10	0.83±0.65^{c}	1.35±0.65^{c}	9.21±4.11^{c}	1.21±0.32^{c}
总计 All samples	42	1.12±0.95^{c}	3.18±1.25^{c}	11.04±3.93^{c}	3.01±1.63^{c}
对照 Controls	10	0.05±0.01	0.004±0.001	0.015±0.01	0.018±0.01

C　$P<0.01$,**下表同** the same below

表 2　农田表层土壤(0～20cm)**中元素含量**(mg/kg)

Table 2　The concentrations of heavy metals in agricultural soils(0～20cm)

采样点 Sampling sites	**样品数** *n* No. of samples	Pb	Cd	Zn	Cu
1	5	301.8±36.7^{c}	54.7±21.3^{c}	328.6±57.4^{c}	498.8±87.1^{c}
2	5	282.4±51.6^{c}	38.6±12.9^{c}	314.5±67.9^{c}	357.8±91.3^{c}
3	5	201.4±34.7^{c}	27.4±10.7^{c}	289.6±66.8^{c}	297.6±78.2^{c}
4	5	156.7±43.9^{c}	10.9±2.7^{c}	157.3±25.7^{c}	145.6±34.2^{c}
5	5	99.8±31.8^{c}	10.7±3.2^{c}	110.5±34.7^{c}	139.6±28.7^{c}
总计 All samples	25	163.7±45.1^{c}	22.1±1.6^{c}	200.7±113.2^{c}	181.2±87.9^{c}
对照 Controls	10	9.4±2.7	0.6±0.2	35.3±9.9	13.3±1.2

表 3　农田深层土壤(20～40cm)**中元素含量**(mg/kg)

Table 3　The concentrations of heavy metals in agricultural soils(20～40cm)

样点 Sampling sites	**样品数** *n* No. of samples	Pb	Cd	Zn	Cu
1	5	102.3±32.3^{c}	3.18±0.21^{c}	145.8±10.2^{c}	197.8±13.5^{c}
2	5	87.8±21.4^{c}	2.32±0.11^{c}	143.6±9.7^{c}	161.2±10.7^{c}
3	5	71.6±14.8^{c}	2.12±0.28^{c}	100.4±8.6^{c}	98.9±12.7^{c}
4	5	52.5±12.1^{c}	1.97±0.10^{c}	41.7±7.9^{c}	80.6±5.8^{c}
5	5	42.5±10.1^{c}	1.99±0.18^{c}	38.9±10.6^{c}	62.4±7.5^{c}
总计 All samples	25	54.7±25.1^{c}	2.10±1.2^{c}	98.5±23.2^{c}	100.2±23.4^{c}
对照 Controls	10	5.2±1.1	0.4±0.1	21.2±8.3	9.2±1.5

表 4　牧草中元素的含量(mg/kg,DM*)

Table 4　The concentrations of trace elements in forages

样点 Sampling sites	**样品数** *n* No. of samples	Pb	Cd	Zn	Cu
1^{b}	12	180.3±107.2^{c}	32.7±16.9^{c}	496.3±212.4^{c}	40.3±12.5^{c}
2	10	138.4±98.5^{c}	20.7±9.5^{c}	378.5±123.9^{c}	37.6±9.8^{c}
3	12	67.4±21.9^{c}	10.8±3.8^{c}	231.4±98.3^{c}	29.7±7.9^{c}
4	11	44.3±12.8^{c}	6.9±2.2^{c}	134.5±76.4^{c}	26.4±5.8^{c}
5	13	33.6±16.7^{c}	5.4±1.7^{c}	100.3±34.5^{c}	13.9±5.7^{c}
总计 All samples	58	59.42±32.1^{c}	8.3±5.4^{c}	166.8±117.3^{c}	24.8±15.3^{c}
对照 Controls	15	6.41±2.71	0.012±0.004	24.4±5.6	6.34±2.36

* DM **干物质** Dry matter

表 5　马和绵羊 Pb、Cd 吸收率和致死量(mg/(kg BW*·d))

Table 5　The ingestion rates and fatal dosage of lead and cadmium in horses and sheep

元素 Element	**吸收率** The ingestion rate		**最小蓄积致死量** Minimum cumulative fatal dosage	
	马 Horses	**绵羊** Sheep	**马** Horses	**绵羊** Sheep
Pb	0.5～6.0	1.7～21.4	1.7	4.4
Cd	0.1～1.1	0.2～4.0	ND	1.0

ND　**无数据** no available data;*　BW　**体重** Body weight

表 6 粮食中元素的含量(mg/kg,DM)

Table 6 The concentrations of trace elements in grain

样点 Sampling sites	样品数 n No. of samples	Pb	Cd	Zn	Cu
1[b]	4	7.24±2.43[c]	4.12±2.11[c]	129.3±43.6[c]	26.2±8.5[c]
2	5	6.12±2.37[c]	3.67±1.33[c]	100.9±56.7[c]	22.3±7.4[c]
3	5	5.12±1.45[c]	3.10±0.89[c]	107.4±45.7[c]	20.5±3.3[c]
4	5	4.23±1.67[c]	2.35±0.56[c]	99.6±24.8[c]	13.2±2.1[c]
5	5	2.96±0.98[c]	1.98±0.38[c]	87.3±31.2[c]	12.0±1.9[c]
总计 All samples	24	4.75±2.61[c]	2.49±0.88[c]	93.2±43.7[c]	14.0±9.0[c]
对照 Controls	10	0.47±0.20	0.07±0.04	42.4±8.6	6.06±1.36

另外,尽管牧草和粮食中 Cu、Zn 含量极显著高于对照区,但 Cu、Zn 是人和动物的必需微量元素,且对动物的毒性较低,一般认为日粮中 Zn 含量 300～1000mg/kg、Cu 含量 100mg/kg 对动物是安全的[8]。同时,日粮中较高水平的 Zn、Cu 可预防 Pb、Cd 对机体的损害。因此,当地 Cu 和 Zn 对环境的污染不会对动物健康造成危害。

2.2.3 动物组织中重金属的含量 在调查中发现,20 世纪 80 年代初铅锌冶炼厂投产,当年厂矿附近放牧的羊和马属动物开始发病。羊主要表现极度消瘦,被毛粗乱,可视黏膜苍白,心率加快(104.3±5.8 次/min),多数节律不齐,门齿和臼齿严重磨灭不齐,有的呈波浪状,骨、关节均无异常。马主要表现精神沉郁,渐进性消瘦,易疲劳出汗,在放牧过程中突然出现呼吸困难,严重者喘气,有些病畜伴发食道阻塞和咳嗽。

动物组织样品元素含量的测定表明,当地放牧的羊和马全血、被毛和组织中 Pb、Cd 含量极显著高于对照($p<0.01$)(表 7～表 9),其中肾脏、骨骼、牙齿和肝脏 Pb、Cd 含量显著高于其他组织($p<0.01$),表明肾脏、骨骼和肝脏是机体内重金属蓄积的主要器官。Cu、Zn 含量在部分组织中也高于对照($p<0.01$ 或 $p<0.05$)。

3 讨论

Pb、Cd 为慢性蓄积性毒物,进入人和动物机体后排泄速度极慢,在机体内的半衰期很长,体内缺少有效的平衡控制机制,长期摄入可发生慢性中毒。同时,二者对动物的毒性呈现协同作用[7,8]。本研究结果表明,当地农田灌溉用水 Pb、Cd 含量分别是对照区的 22 和 800 倍,表层土壤(0～20cm)Pb、Cd、Cu、Zn 含量明显高于深层土壤(20～40cm),牧草中 Pb、Cd 的平均含量是对照区的 9 倍和 680 倍,粮食中为 10 倍和 35 倍。并且绝大多数采样点牧草和粮食作物中 Pb、Cd 含量超过了动物中毒的临界范围[8,9]。由此可见,工厂排放的废气和废水已造成 Pb、Cd、Cu、Zn 对周围环境不同程度的污染,导致重金属在各种生物体内均有不同程度的吸收和累积,其吸收累积量随重金属和生物种类的不同而有差异。

土壤的污染,使农作物和牧草中 Pb、Cd 含量超过动物的最大耐受量和中毒的临界值。一般认为,牧草中 Pb、Cd 含量分别低于 3～7mg/kg 和 0.64mg/kg 则对动物是安全的[7,9]。本文报道的当地牧草中 Pb、Cd 平均含量分别为 59.42±32.1mg/kg 和 8.29±5.43mg/kg。同时发现,土壤、废水和牧草中 Pb、Cd 含量与距工厂的距离呈负相关,距工厂越近,上述元素的含量越高。Farmer[10]和 Palacios[11]均报道牧草中 Pb、Cd、Zn 含量与污染源之间的距离呈高度相关性,Farmer 的结果显示相关系数(r)分别为 0.97、0.99 和 0.99。

由于金属冶炼使当地土壤和植物中铅、镉等重金属的含量明显增加,长期放牧的动物从牧草中不断摄入这些毒性元素。据报道[7～9],马和绵羊对铅的最大致死剂量分别为 1.7 和 4.0mg Pb/kg 体重/d,镉仅为 1.0mg Cd/kg 体重/d。而在白银地区放牧的马摄入的铅镉分别为 0.5～6.0mg Pb/kg 体重/d 和 0.1～1.1mg Cd/kg 体重/d,绵羊分别为 1.7～21.4mg Pb/kg 体重/d 和 0.2～4.0mg Cd/kg 体重/d。因此,当地放牧动物,特别是靠近冶炼厂附近的放牧动物,通过采食牧草摄入的铅镉超过了动物的最大耐受量,导致血液、被毛和组织中铅镉含量超过了报道的临界值和对照动物,表明当地牧草对放牧动物具有潜在的毒性。由于马和绵羊是当地主要的放牧动物,上述结果不仅反映铅镉对家畜的毒性损伤,而且动物性食品中残留的 Pb、Cd 将直接危害食用者的健康。因此,放牧动物可作为环境重金属污染状况的标识,对评价重金属环境污染对当地人群的危害也有重要意义。

土壤、牧草和水中 Cu、Zn 含量显著高于对照区($p<0.01$),动物组织中这些元素的含量也有一定的变化,但均未达到动物中毒的范围[7～9]。另外,Cu、Zn 为人和动物必需的微量元素,在体内发挥重要的生物学效应。NRC 报道[12],绵羊和马对铜的最大耐受量分别为 25mg/kg 和 800mg/kg,锌为 300mg/kg,测定值除靠近冶炼厂附近的牧草铜含量高于羊最大耐受量外,其余均在安全范围。因此,认为这些元素对机体不会造成明显的损伤,但与 Pb、Cd 的相互作用仍有待进一步研究。

综上所述,有色金属冶炼过程中排放的工业“三废”造成当地环境不同程度的重金属污染,尤其是 Pb、Cd 具有较高的生物毒性和生物可利用性,生物通过水、土壤或食物链直接或间接地吸收重金属。因此,有色金属冶炼厂矿周围的区域性生态修复对确保当地动物健康和人们食品的质量与安全具有重要意义。

表7 绵羊软组织中元素含量(mg/kg DM)

Table 7 The concentrations of trace elements in soft tissues in sheep

元素 Element	心脏 Heart		肺 Lung		肝 Liver		肾 Kidney		肌肉 Muscle		脾 Spleen	
	CA(15)^{a}	Control(10)	CA(15)^{a}	Control(10)	CA(15)^{a}	Control(10)	CA (15)^{a}	Control(10)	CA(15)^{a}	Control(10)	CA(15)^{a}	Control(10)
Pb	4.30±1.63^{b}	1.54±0.70	4.35±1.68^{b}	1.45±0.87	15.30±1.14^{b}	0.72±0.23	39.50±2.87^{b}	0.96±0.40	1.85±0.71^{b}	0.86±0.41	3.94±2.71^{b}	1.01±0.45
Cd	0.38±0.17^{c}	0.30±0.10	3.02±1.25^{b}	0.61±0.11	7.92±2.36^{b}	0.49±0.25	25.39±10.53^{b}	1.83±0.59	0.62±0.19^{b}	0.17±0.09	0.59±0.24^{c}	0.45±0.25
Cu	28.8±4.4^{b}	15.7±0.9	23.2±2.4^{b}	10.6±1.6	248.1±35.9^{b}	120.6±57.7	25.2±13.2^{b}	11.8±1.7	8.0±1.4	5.9±1.9	9.6±1.0^{b}	5.9±0.8
Zn	99.6±7.5	101.9±10.2	123.8±25.2	108.8±18.6	217.9±35.7^{b}	140.0±10.5	147.1±67.4^{b}	115.0±20.6	117.1±21.6	123.5±25.8	117.3±18.4	124.9±12.6

CA 污染区域 Contaminated area;a 样品数 Number of samples;b $p<0.01$; c $p<0.05$;下同 the same below

表8 绵羊全血、被毛和骨组织中元素含量(mg/kg DM)

Table 8 The concentrations of trace elements in blood, hair and bones in sheep (mean±SD)

元素 Element	血液 Blood (mg/L)		毛发 Hair (mg/kg)		骨 Rib (mg/kg)		脉 Radius (mg/kg)		牙齿 Teeth (mg/kg)	
	CA(15)^{a}	Control(10)	CA(15)^{a}	Control(10)	CA(15)^{a}	Control(10)	CA(15)^{a}	Control(10)	CA(15)^{a}	Control(10)
Pb	0.34±0.03^{b}	0.05±0.03	3.64±1.90^{b}	1.01±0.21	13.30±3.93^{b}	5.06±2.19	21.64±5.52^{b}	6.23±2.12	24.6±5.67^{b}	6.13±3.21
Cd	0.37±0.02^{b}	0.02±0.01	2.03±0.45^{b}	0.37±0.02	3.87±1.60^{b}	1.54±0.75	4.68±0.99^{b}	1.87±0.65	4.73±0.61^{b}	1.33±0.97
Zn	4.6±3.4	10.6±3.0	101.5±31.4	95.3±21.2	85.6±17.9	93.6±24.7	96.4±15.6	105.3±28.6	104.7±34.6	110.4±25.2
Cu	1.65±0.9^{b}	0.76±0.25	9.62±3.10^{b}	3.68±0.74	8.15±1.51^{b}	4.30±1.76	10.21±1.15^{b}	4.53±1.04	7.32±3.56	6.02±1.07

表9 马全血、被毛和组织中元素含量(mg/kg,DM)

Table 9 The concentrations of trace elements in blood, hair and tissues in horses (mean ± SD)

元素 Element	血液 Blood(mg/L)		毛发 Hair(mg/kg)		心脏 Heart(mg/kg)		肝 Liver(mg/kg)		肾 Kidney(mg/kg)		骨 Rib(mg/kg)	
	CA(10)^{a}	Control(5)	CA(10)^{a}	Control(5)	CA(10)^{a}	Control(5)	CA(10)^{a}	Control(5)	CA(10)^{a}	Control(5)	CA(10)^{a}	Control(5)
Pb	0.28±0.10^{b}	0.04±0.01	5.76±1.27^{b}	0.95±0.33	3.27±0.21^{b}	2.12±0.27	23.72±2.30^{b}	1.05±0.35	68.83±13.32^{b}	3.21±1.09	26.8±4.23^{b}	6.21±2.02
Cd	0.17±0.04^{b}	0.03±0.01	3.47±0.55^{b}	0.28±0.02	2.13±0.38^{b}	0.79±0.21	8.30±2.10^{b}	1.13±0.24	27.2±2.4^{b}	1.02±0.33	4.76±2.61^{b}	1.59±0.43
Cu	11.6±7.4	11.6±2.5	89.3±20.4	85.7±19.2	85.6±17.9	90.7±12.7	136.8±32.6	124.9±22.1	133.8±41.0	126.3±17.8	99.4±22.1	91.2±13.9
Zn	0.95±0.40^{b}	0.75±0.13	7.64±2.21^{b}	5.36±1.24	5.34±1.29^{b}	4.12±1.10	124.6±23.6^{b}	98.7±14.5	21.8±9.7^{b}	16.4±3.12	9.23±1.42^{b}	4.78±2.67

References:

[1] Qu G P. *Environmental Management in China*. Beijing: China Environmental Science Press, 1989. 474～478.

[2] Liu Z P, Ma Z, Li W F, *et al*. Studies on lesd-cadmium poisoning in sheep. *Chinese Journal of Veterinary Science*, 1997, **17**(2):166～169.

[3] Liu Z P. Lead poisoning combined with cadmium in sheep and horses in the vicinity of nonferrous metal smelters. *The Science of the Total Environment*, 2003, **309**:117～126.

[4] Nan Z R, Li J J. Study on the distribution and behavior of selected metals (Cd,Ni,Pb) in cultivated soil profile in arid zone (take Baiyin region as an example). *Arid Zone Research*, 2000, **17**(4):39～45.

[5] Aronson A L. Lead poisoning in cattle and horses following long term exposure to lead. *Am. J. Vet. Res.*,1972;**33**(3):627～629.

[6] Liu J X, Hu Z Z, Ren J Z, *et al*. The series studies of grazing ecology and digestion and metabolism of sheep on alpine pasture Ⅳ. Seasonal dynamics of intake and digestion and metabolism of grazing sheep. *Acta Prataculturae Sinica*, 2001,**3**:65～71.

[7] Blood D C. *Veterinary Medicine*. 7^{th} edition, Balliere Tindall, London, England, 1989. 1242～1275.

[8] McDoll L R. *Mineral in Animals and Human Nutrition*. Academic Press, Inc., New York, 1992. 359～364.

[9] Buck W B, Osweiller G D, Van Gelder G A. Clinical and diagnostic veterinary toxicology. Dubuque: Kendall-Hunt, 1973. 345～369.

[10] Farmer A A, Farmer A W. Concentrations of cadmium, lead and zinc in livestock feed and organs around a metal production center in eastern Kazakhstan. *The Science of the Total Environment*, 2000,**257**:53～60.

[11] Palacios H, Iribarren I, Olalla M J, *et al*. Lead poisoning of horses in the vicinity of a battery recycling plant. *Sci. Total Environ.*, 2002,**290**:81～89.

[12] NRC. *Mineral Tolerance of Domestic Animals*. National Academy of Sciences-National Research Council, Washington, D.C., 1980. 93～130, 257～276.

参考文献:

[1] 曲格平. 中国的环境管理. 北京:中国环境科学出版社,1989. 474～478.

[2] 刘宗平,马卓,李文范,等. 绵羊铅镉联合中毒的研究. 中国兽医学报,1997,**17**(2):166～169.

[4] 南忠仁,李吉钧. 干旱区耕作土壤中重金属镉铅镍剖面分布及行为研究——以白银市区灰钙土为例. 干旱区研究,2000,**17**(4):39～45.

[6] 刘金祥,胡自治,任继周,等. 高山草原绵羊放牧生态及消化代谢研究. Ⅳ. 采食量和消化代谢季节动态. 草业学报,2001,**10**(3):65～71.