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Changes in functions, forms, and locations of lead during its anthropogenic flows to provide services

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Abstract: Knowledge of the changes in a material's function, form, and location during the transfer and transformation of materials to generate human services will improve our understanding of how humanity interacts with the environment and of how services are formed by human activities. We compared lead's anthropogenic and biogeochemical cycles and found that the services, pathways, and changes in form requiring the most attention. We traced lead through its life cycle and identified the changes in its functions, forms, and locations by examining technology and engineering information. Lead ore and scrap were the two main anthropogenic sources of lead. When lead provides human services, its main functions included the storage and delivery of electricity, anti-corrosion treatments, and radiation protection; the main forms of lead in these products were Pb, PbO_2 and $PbSO_4$, and the main location changed from lithosphere in central China to regions in eastern China.

Key words: service economy; material flow analysis; anthropogenic cycle; human activity; life cycle; transformation

1 Introduction

Along with the implementation of sustainable development strategies, the development of a services-oriented society is becoming an important measure to conserve natural resources and reduce environmental pollution [1]. A variety of studies on this topic have been carried out in recent years, and have focused mainly on the following aspects. 1) In terms of industrial economics, the goal is to increase the proportion of the economic structure accounted for by service industries, so that these sectors play a more important role in the economy [2]. 2) For products and services, it is important to improve the product's performance or the service's quality by means of ecological innovation, particularly if this can increase services and decrease the importance of the least-efficient or most polluting products [3]. 3) To guarantee that these processes occur, policies and regulations have been adopted to promote the implementation of a services-oriented society [4]. These researches have emphasized the services that materials can provide to humanity. In other words, the fate of these materials in the anthrosphere, i.e., the human socioeconomic system and the parts of the environment that are affected by humans, is as final products with specific functions [5] that are capable of meeting human needs for specific services.

In hybrid human–natural systems, most materials that flow through the anthrosphere originate in nature [6,7]. When a material flows from its natural state into the anthrosphere to satisfy human needs, the substance undergoes three main processes: 1) extraction from nature; 2) transformation into products with specific functions that meet human needs by means of a series of processes that extend from design to fabrication and manufacturing [5]; and 3) performance of these functions to provide human services in the form of final products. During these processes, materials inevitably undergo a series of important changes [8], which involve redistribution within the anthrosphere at different temporal and spatial scales, forming different service patterns [9−12]. The chemical and physical properties of the substance change, as do its states, the services that it provides, its functions, and the locations where it performs those functions, all are closely related to the substance's form [8]. The quantitative changes have been extensively studied for various anthropogenic cycles

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[10,11,13,14], but changes related to the form of a substance have also been studied by experts in engineering, technology, and basic sciences such as physics and chemistry [15]. However, due to a lack of communication among these disciplines, it is difficult to create a thorough picture of the main changes in a substance that result from human activities, thereby making it difficult to systematically analyze all the changes to a substance that occur during its flow through the anthrosphere to provide human services.

Lead is a good example of a material that flows through the anthrosphere and links it with the natural environment. Lead originates as a nonrenewable resource, in the form of lead ore [10], and its emission into the environment creates a high level of ecological risk, including threats to human health [16]. From the perspective of the human services that it provides, lead is mainly used to manufacture lead-acid batteries (LABs), which store and deliver electrical energy, and because good records are maintained for these products, they can be used to quantitatively describe the services provided by lead [17]. Lead also enters the economic components of the anthrosphere through trading of materials and marketing of products. Lead offers an additional advantage for such studies: its flows are easier to trace than those of compounds such as polymers and complex molecules. Furthermore, many previous studies on the anthropogenic lead cycle provide a sound foundation for a study of lead's life-cycle processes, uses, and service patterns, which make it easier to trace lead through the stages of its life cycle and, thus, to identify the functions, forms, and locations of lead. Such research represents a useful approach to understanding the interactions between humanity and nature that result from flows of materials for providing human services.

2 Analogy between anthropogenic flows and environmental flows

2.1 Factors influencing environmental lead flows

In natural systems, a substance such as lead has a certain temporal and spatial distribution patterns. The places where the substance is concentrated are termed "reservoirs", and the flows of the substance between reservoirs are called "fluxes" [7]. A substance generally flows in a certain direction, which is determined by the direction of the natural forces responsible for these flows (e.g., geological processes that concentrate minerals in certain locations, downhill flows of water that carries dissolved substances). These flows produce trends in the accumulation of the substance in specific locations, such as in deposits of lead-containing ore or in products.

Traditional studies on the fate of a material as a result of these processes originate in the fields of geochemistry and environmental chemistry, and include research that focuses on environmental pollutants and the sources, pathways, fates, and possible ecological risks of these substances in the environment [7]. Although there are some natural sources of pollution, most concentrated pollutants are anthropogenic, and enter the environment as gaseous emissions, wastewater discharges, solid wastes, and residues produced by human activities [18,19]. The pollutants then follow pathways between environmental components such as soils, plants, and water [18,19]. The environmental fates of the pollutants reflect the results of their flows through the environment. Many studies have shown that the main factors influencing the flows of pollutants through the environment are their physical and chemical properties, forms and locations [7]. The physical and chemical properties of a material reflect its internal atomic or molecular structure, which in turn determines the material's environmental behavior [20]. The existing forms of a substance affect the chemical bonds that form between the substance and various other substances in the environment [21]. The location of a substance determines its surrounding environment and how it contacts the environment, which in turn determines the kinds of natural forces that it will experience. The forms and locations of a substance change in responses to changes in the state of the environment. Thus, all flows of a material through the environment result from interactions between the natural attributes of the substance and those of the environment, which also determine the eventual fate of the material.

2.2 Relationships between anthropogenic and biogeochemical lead cycles

In nature, lead flows between the lithosphere, atmosphere, hydrosphere, pedosphere, and biosphere; these flows are referred to as the "biogeochemical" or "natural" cycle of lead [21]. Humans are the most active component of the biosphere, and both accelerate flows of lead into the anthrosphere and promote flows through the hybrid socioeconomic–environmental system; these flows are called the "anthropogenic" lead cycle [11,12]. The environment acts as both the source of lead to the anthrosphere and a sink for lead released from the anthrosphere, leading to important interactions between the anthropogenic and biogeochemical lead cycles (Fig. 1). In this work, we will focus on the anthropogenic part and how lead changes its role in response to providing human services.

2.3 Comparison of anthropogenic and environmental flows of lead

From the perspective of system theory [22], both the anthropogenic lead cycle and the flows of lead after it

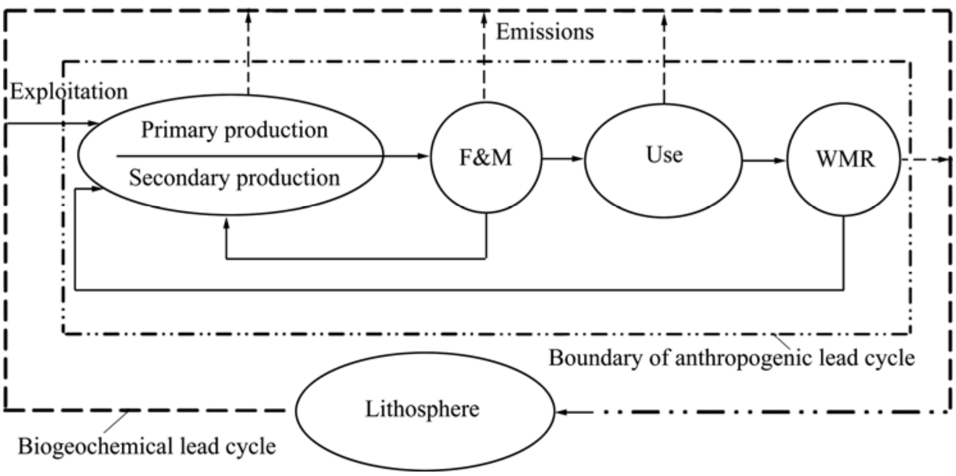

Fig. 1 Illustration of conceptual relationship between anthropogenic and biogeochemical lead cycles (F&M= fabrication & manufacture, WMR=waste management & recycling)

enters are important components of the overall biogeochemical cycle of lead; that is, the human system is a component of the natural system that contains, as shown in Fig. 1. Thus, the two cycles should exhibit similar phenomena, behaviors, processes, essential characteristics, and factors that influence the flows; this can be deduced from the homologous similarity principle in similarity theory [23]. The anthropogenic lead cycle extends from extraction of lead from ore to the final use of lead products that provide specific services, including the recycling of wastes to provide inputs for other services; the biogeochemical lead cycle extends from the release of lead from a source into the environment (analogous to human extraction from a source) to the subsequent flows of lead through the various components of that environment and the associated chemical transformations (analogous to human transformations of lead to provide services).

The anthropogenic lead flows result from human activities that are designed to meet specific human needs. This observation suggests three main differences from the environmental components of the lead cycle.

1) Different dynamic mechanisms: Human needs are the primary driving forces of anthropogenic flows which purpose to provide specific human service. To reach such a target, lead flows result from the extraction of lead ore, which occurs more rapidly and on a larger scale than biogeochemical processes. This is followed by processing of the ore into intermediate materials and fabrication of products using these materials; in contrast with natural processes, these processes reverse entropy as a result of external energy inputs. In addition, the flows include artificial processes that do not occur in nature, such as trade and transportation of both primary and secondary materials, and the use and disposal of lead products [8]. In contrast, environmental flows once lead enters the environment are driven primarily by natural forces.

2) Different sources, pathways, and fates: In the environment, lead pollutants may be focused and they may pass through air, water and so on, and finally be dispersed in the pedosphere, bodies of water, and other components of the ecosystem [7]. However, in the anthrosphere, lead ore is the original source, supplemented by lead scraps generated by obsolete lead products or recovery of lead-contained wastes as the secondary source. The in-use stock of lead represents the immediate fate of this material [24] before the end of a product's life cycle and acts as the place where its anthropogenic functions and final services are provided to humans. Thus, the two main anthrosphere pathways flowing from extraction of lead ore and from the recovery of lead scraps will lead to the production and subsequent use of lead products to provide services to humans [8].

3) Different factors influencing the flows and fates of lead: In the environment, the main factors that influence the fate of lead are its property, forms and locations in the environment. In the anthrosphere, the lead is used to meet human needs, so the primary factors influencing its fate are how the lead is used to meet these needs and what happens to the lead at the end of a product's useful life (i.e., after it becomes obsolete). Because the function of a material depends on its physical and chemical structure [20], the anthrosphere forms of lead differ from their natural forms. The new functions and forms are created through design, processing, manufacturing, and engineering activities [15], all of which are directly shaped by the required human services the that lead will provide in its new form. In this work, we consider the functions, chemical structures or compositions, and locations where lead is

used as the main factors influencing the flows and fate of lead in the anthrosphere.

3 Factors influencing anthropogenic lead flows

3.1 Tracing flows of lead through its life cycle

Before we can identify the specific function, chemical structure, and location of lead within the anthrosphere, it is necessary to know what service a product provides and the stage of lead within its life cycle for that product. This information drives us to trace the flows of lead through the anthrosphere.

In our analysis, we paid attention to the following life cycle stages (Fig. 2 and Table 1): lead production from ore, manufacturing and use of lead products, treatment of wastes containing lead, and recycling of scrap lead [10,11]. During primary and secondary lead production, lead metal will be produced through smelting, concentration, and refining [25,26]. During manufacturing and fabrication, lead metal is transformed into lead products with new forms that can provide specific services. Lead will sometimes be combined with other materials to meet a specific need, resulting in a specific chemical structure that supports the function [15]. The lead metal will be allocated to various products during the manufacturing and fabrication stage, creating different usage patterns [10].

During use stage, lead products with different functions and life-spans flow into the hands of customers, where they provide services until they become obsolete at the end of a product's lifespan. The balance between the amount of lead entering and leaving use stage determines the accumulation of lead in-use stocks [24]. The amount of lead in-use stock may increase as products are in growing periods and decrease in dropping periods [14].

During the waste treatment and recycling stages, obsolete lead products are collected, disassembled, and sorted, and then the useful parts are returned to upstream processes for reuse or sent to secondary production processes as raw materials. Components that cannot be recovered are discharged into the environment after various treatments, including burning and disposal in landfill sites.

Throughout these stages, lead flows between regions (e.g., from mines to cities) and between components of the anthrosphere (e.g., from a battery manufacturing plant to a car assembly plant). Differences in the trends for these flows result from differences in the distribution of sources of a material that becomes the input for a process, and in the location of the industry the input will be used or the population will use a given product. These differences change in response to changes in socioeconomic conditions, which determine the trade in materials and products and the resulting transportation needs. Tracing lead through these stages of its life cycle provides a framework that can be used to support subsequent analysis of the quantitative changes in flows of lead through the anthrosphere.

3.2 Factors influencing flows of lead for providing human services

In this section, we will describe how the functions, forms (chemical structure or composition), and locations of lead (the factors influencing the flows) can be identified in the flows of lead through the anthrosphere. We will discuss this from the perspective of the services that the lead provides as a result of these flows.

3.2.1 Functions

In the course of lead flowing for providing anthropogenic services, the basic property of lead that attracts humans is its ability to satisfy some specific human demands, which includes further production

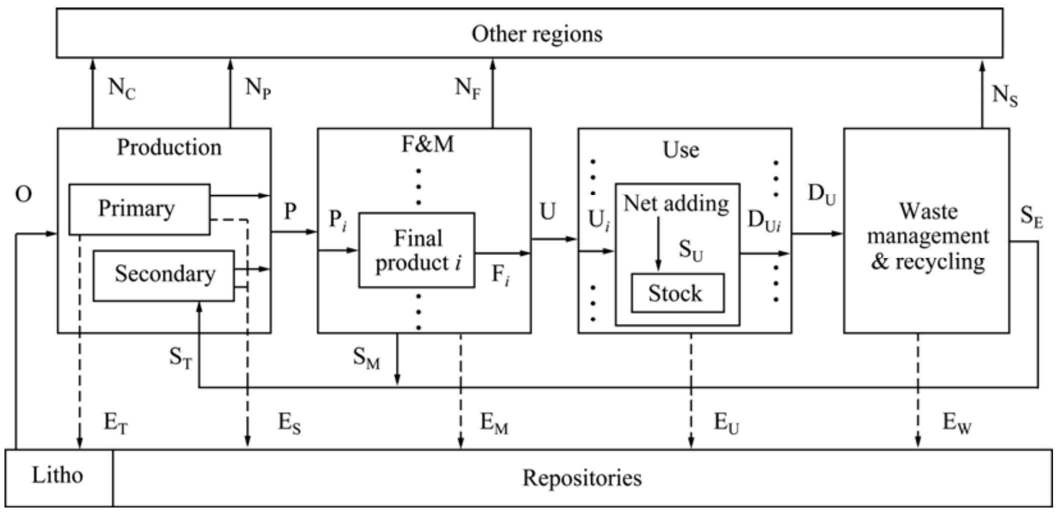

Fig. 2 Conceptual framework for flows of lead through anthrosphere during product life cycle

Table 1 Symbols and definition in Fig. 2

Symbol	Definition
O	Lead from ore
P	Refined lead (P_i, for that in product i)
U	Lead entering its use phase (U_i, for use of product i)
D_U	End-of-life lead flows to waste management &
S_U	Lead entering the in-use stock
N	Lead in net exports (exports minus imports)
N_C	Lead in net exports of concentrates
N_P	Lead in net exports of refined lead
N_F	Lead in net exports of products
N_S	Lead in net exports of lead scraps
E	Lead in emissions to the environment
E_T	Lead in tailings
E_S	Lead in slag
E_M	Lead in fabrication and manufacture (F&M) emissions
E_U	Lead in emissions from use stage
E_W	Lead in WMR emissions
S_T	Lead in total scrap flowing to production
S_M	Lead in new scrap from F&M
S_E	Lead in end-of-life scrap
F	Final products (F_i, for product i)

Table 2 Sources of information for functions, forms, and locations of lead

Type	Name and example	Information source
Function	Galena, cerussite, wulfenite, obsolete lead products[a]	Ref. [28]
	Lead ingots, bars, powder, pipes, and sheets	Ref. [27]
	Lead-acid batteries	Ref. [30]
	Cables	Ref. [31]
	Lead alloys	Ref. [32]
	Others[b]	Ref. [33]
Form	Galena, cerussite, wulfenite	Ref. [26]
	Obsolete lead products[a]	Ref. [25]
	Ingots, bars, powder, pipes, and sheets	Ref. [27]
	Lead-acid batteries	Ref. [29]
	Cables	Ref. [27]
	Lead alloys	Ref. [32]
	Others[b]	Ref. [23]
Location	Galena, cerussite, wulfenite	Ref. [34]
	Lead in service, end-of-life scrap lead[c]	Ref. [35]
	Lead metal[d]	Ref. [34]
	Lead products[e]	Ref. [36]

a: including mainly obsolete lead-acid batteries, but also including obsolete pipes and sheets, cables, and lead residues; b: referring to lead in paints, polyvinyl chloride (PVC), and gasoline as components or additives; c: represented by lead-acid batteries used in vehicles; d: represented by the location of refineries, including primary and secondary production; e: represented by the location of production of lead-acid batteries

needs and immediate use needs. To meet the first type of need, the function of lead is performed as it can be further processed by transforming its chemical structure or components based on its physical and chemical nature, through technological processes such as designing and engineering [27]. For example, the boiling point of lead is around 1740 °C, and it can thus be extracted from lead ore or scrap lead by controlling the range of smelting temperature [28]. Lead is ductile and malleable, thus it can be used to make products such as lead pipes and sheets that provide services such as transport of fluids and protection against radiation [27]. Various references describe the physical and chemical properties of lead compounds, and these can be compared with the requirements for specific engineering or chemical applications that will provide such services. To meet the second type of needs, a final product which requires no further processing is put into direct use. The functions of lead to meet human use need specifically the performance characteristics of a product [5]. For example, the lead acid battery taking lead as its main components has the function to store and transform electricity [29]. All the functions of lead meeting the human use needs are identified in professional manuals related to different lead products. The source of the main function related information is listed in Table 2.

3.2.2 Forms

The main properties of lead that make it useful for providing human services are related to its chemical structure, electrovalence structure and its ability to form other compounds when combined with other substances. This lays a foundation for its specific functions. All the forms in the anthrosphere are mainly obtained through a series of human activities such as designing and engineering. For example, Pb exists in galena but can be transformed into elemental Pb after smelting and refining it [28]. Industrial processing technology manuals provide forms' related information for designers or engineers in metal smelting and other processing factories. A summary of the sources for different forms of Pb is given in Table 2.

In most products, the form of lead does not change during use. However, some forms of lead change during use. For example, for the lead–tin alloys that are used in soldering of metal parts, the initial form is $Sn_{60}Pb_{40}$ or $Sn_{63}Pb_{37}$ before use, but during soldering, Pb_2O_3, Pb_3O_4, or PbO is generated and lead is emitted into the environment during the joining. In this article, we will use the forms of lead in the final products to represent the forms of in-use lead.

3.2.3 Locations

Differences in the regional distribution of natural resources such as lead ore and in human factors determine the sources of supply for these resources. However, the needs for services are determined by human factors such as the locations of population centers and industries, and differences between regions in the economic development level and the industrial structure. As a result of these differences, lead-containing materials must be transported from source areas to destination areas that will use these materials to provide a service. These flows take two types: transportation between regions (e.g., exports of lead-acid batteries from China to Europe) and flows between components of the biogeochemical and anthropogenic systems (e.g., the flow of lead from the lithosphere into the anthrosphere as a result of mining). Trends in the flows between sources and destinations result from differences in the availability of and demand for services that require a given form of lead. Flows between components of the anthrosphere arise from pathways between primary and secondary industries and from the creation and emission of products and wastes. Although it is theoretically possible to describe the changes in the location of lead by tracking lead from mining and processing through product manufacturing to use and disposal, this is difficult in practice because of the diversity in lead use patterns, the distribution of enterprises, and the locations where lead products are used. In addition, precise statistics are not available for all locations of lead flows.

To solve these problems, we chose lead-acid batteries as our case for examining the regional changes in the anthropogenic flows, since batteries represent the main use of lead in China, accounting for 80% of the total lead consumption [17]. We used China's provinces, autonomous regions, and municipalities as the regional units, and used government statistics to define the five most important locations for mining of lead ore, smelting of the ore, and manufacture and use of the batteries as representative locations. Because batteries are mainly used in vehicles, we used regional vehicle ownership statistics to represent the amount of in-use lead to provide a service in the form of electricity storage and delivery via batteries, and identified the three locations with the highest vehicle ownership to represent the main locations where final use of the batteries to provide this service occurs. On this basis, we determined trends in the directions of the lead flows between the main locations where lead is produced and used.

4 Results

4.1 Changes in functions of lead

The properties and functions of lead change as it flows through the stages from the extraction of ore to manufacturing of the final products (Table 3). For example, raw ore has few direct uses, but can provide services as an input for the smelting and refining processes; because the resulting lead metal is both ductile and malleable, it can be transformed into clothing that provides the service of protection against radiation. As another example, paint that contains lead may appear red or yellow as a result of adding Pb_3O_4 or PbO, respectively [27]. Other functions include storage and transfer of electrical energy in batteries and the provision of resistance to corrosion and radiation.

4.2 Changes in forms of lead

Lead also changes form in response to the need for different functions, since different forms offer different properties. For example, the form of lead in galena is PbS, and this is transformed into lead metal (Pb) by smelting and refining. The lead can also be transformed into PbO_2, Pb, and $PbSO_4$ when it is incorporated into batteries. Table 4 summarizes the main forms of lead and the corresponding chemical structures. The various forms that lead takes in a battery, which represent the major use of lead, include Pb metal, PbO_2 in fully charged batteries, and $PbSO_4$ in fully discharged batteries. The lead metal (Pb) in lead plates, pipes, and sheets is the next most common form. The next most common forms are lead oxides such as PbO_2 and PbO.

4.3 Changes in locations of lead

The changes in the location of lead start with the mining of lead ore. It was reported that the total production of mine concentrates containing lead in China was 1.85 Mt of lead in 2010, mainly from the Inner Mongolia autonomous region and Hunan Province. Figure 3 shows the locations of the five largest producers of lead ore (Inner Mongolia, Hunan, Sichuan, Guangxi, and Guangdong provinces), which together contributed about 64% of China's total domestic production of lead concentrates. An additional 1.6 Mt of lead is imported from Australia and North America to meet the domestic demand.

A total of 4.20 Mt of refined lead was produced in 2010 in China, of which 2.84 Mt represented primary lead and 1.36 Mt represented secondary lead [34]. The primary lead was mainly produced in Henan, Hunan, and Yunnan provinces, which contributed around 75% of China's total primary lead. The secondary lead was mainly produced in Anhui and Jiangsu provinces, which contributed around 70% of the total secondary lead. These five provinces were the largest sources of refined lead, and accounted for 79% of China's total refined lead.

A total of 144 gigavolt ampere hours of batteries are produced in 2010 of China [36]. The main battery production centers are Zhejiang, Guangdong, and Hebei

Table 3 Main functions of lead for providing human services in anthrosphere

Type	General function	Example	Specific function description
Lead ore and scrap lead	Sources of lead metal in anthrosphere to meet production needs and be further processed into refined lead metal	Ore: galena, cerussite, wulfenite	Primary sources of lead metal in the anthrosphere. For example, galena can be made into lead metal through mining, concentration, smelting, and refining.
		Scraps: obsolete lead products, such as lead-acid batteries, cables, and lead residues	Secondary sources of lead metal in the anthrosphere. For example, lead−calcium and lead−antimony electrode plates and lead sulfate in obsolete lead-acid batteries can be made into lead metal through collection, disassembly, melting, and refining.
Lead metal	Raw material for industrial production. It can meet production needs and can be further processed into industrial lead products.	Lead ingots	Lead ingots can be used to manufacture lead-acid batteries, lead pipes, tubes, sheets, and radiation-proof shielding.
		Lead bars	Lead bars can be used to manufacture cable sheathings, printed circuit boards, and cathode-ray tubes.
		Lead powder	Lead powder can be used to manufacture lead alloys, pigments, and chemicals, and can be further used to manufacture parts of lead-acid batteries, paints, and lead-based components such as stabilizers in polyvinyl chloride (PVC) and tetraethyl lead as an antiknock additive in gasoline.
Lead product	To provide specific services and meet specific usage needs.	Lead-acid batteries	Lead-acid batteries can store and transfer electric energy.
		Lead pipes	Lead pipes can transport corrosive liquids.
		Lead sheets	Lead sheets can defend against nuclear radiation and corrosive chemicals.
		Cables	Lead sulfate in cable sheathings can protect cables from radiation and corrosion.
		Lead alloys	Lead alloys such as tin–lead solder can be used to repair and join metal pieces.
		Paints, pigments	Lead compounds in paints and pigment can be used to create colors in ceramic glazes and paints; for example, Pb_3O_4 for red and PbO for yellow.
		Televisions	Lead oxide in cathode-ray tubes TV can protect against radiation and stabilize optical effects.
		PVC	Lead is used as a stabilizer in PVC.
		Gasoline	Tetraethyl lead is used as an anti-knock additive for aviation fuel in piston-driven aircraft.
		Photovoltaic cells	Lead can store and transfer energy in lead-based semiconductors, such as lead telluride, lead selenide, and lead antimonide, which are important components of photovoltaic cells.

Table 4 Main forms of lead in anthrosphere

Form of lead	Material	Main chemical structure or components
Lead ore	Galena, cerussite, wulfenite	PbS, PbCO, $Pb[MoO_4]$
Lead scraps	Obsolete lead products, such as lead-acid batteries, cables, and lead residues	$PbSO_4$, Pb, PbO_2, Pb_xSb_y, Pb_xCa_y
Lead metal	Lead ingots, bars, powder	Pb
Lead products	Lead-acid batteries	$PbSO_4$, Pb, PbO_2, $Pb_xSb_y^*$, $Pb_xCa_y^*$
	Lead pipes	Pb
	Lead sheets	Pb
	Cables	$3PbO·PbSO_4·H_2O$, $2PbO·PbHPO_3·H_2O$
	Lead alloys	$Pb_{96}Sn_4$, $Pb_{93}Sn_7$, $Sn_{60}Pb_{40}$, $Sn_{63}Pb_{37}$, $Sn_{30}Pb_{50}Zn_{20}$
	Paint, pigment	Pb_3O_4, PbO
	Televisions	PbO
	PVC	$3PbO·PbSO_4·H_2O$, $2PbO·PbHPO_3·H_2O$
	Gasoline	$(CH_3CH_2)_4Pb$
	Photovoltaic cells	PbTe, PbSe, PbSb

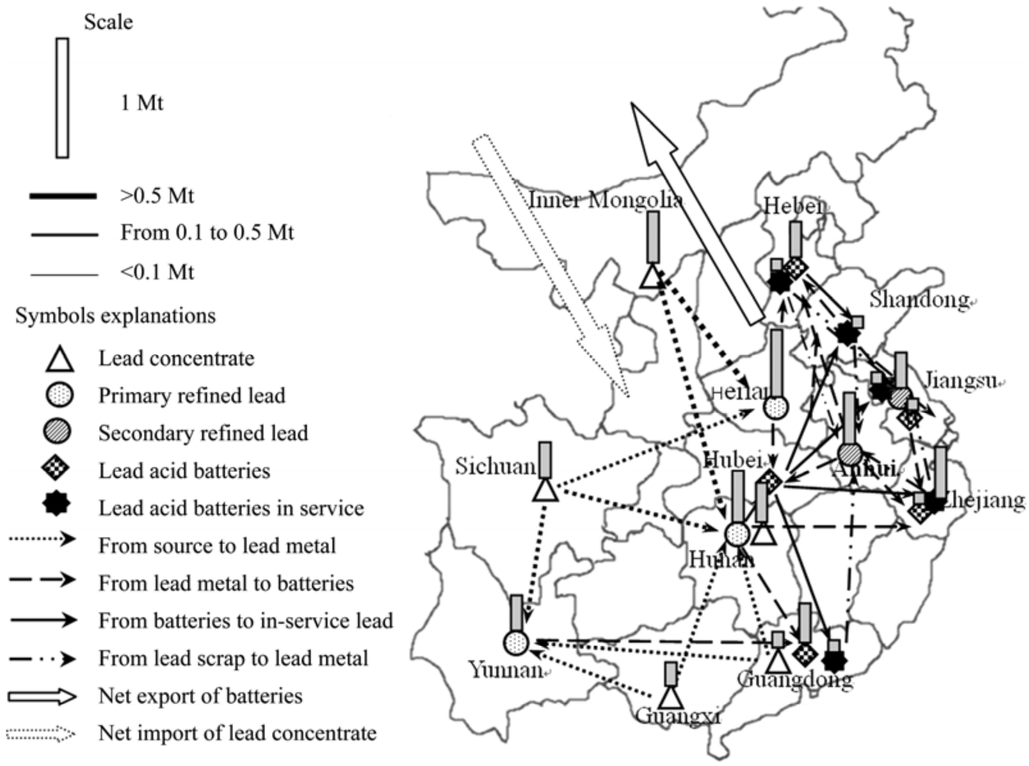

Fig. 3 Main spatial transfers of lead related to flows through anthrosphere in China

provinces. The top 5 provinces (Fig. 3) accounted for about 66% of the total lead-acid battery production.

Lead-acid batteries are mainly used in automobiles [37]. It was reported that the number of automobiles totaled about 110 million in China in 2010 [35]. Figure 3 shows that the main provinces based on automobile number are Guangdong, Shandong, Jiangsu, Zhejiang, and Hebei provinces, which accounted for around 28% of the total automobiles in China and represent an important conceptual final destination of lead in the anthrosphere.

In general, totally about 4 Mt of lead was transferred from lithosphere to anthrosphere to meet China's production need in 2010, in which China itself contributed a rough half in lead concentrates. Meanwhile, 1/3 of this refined lead was transferred to other countries through trade of various lead products.

Figure 3 conceptualizes the trends in the overall flows of lead through the anthrosphere throughout its life cycle. In general, the lead moves from central to eastern China as it moves through anthrosphere to providing final service, companying a rough 2 Mt of lead import of lead concentrates and 0.7 Mt of lead export of various lead products.

4.4 Characteristics of anthropogenic flows for providing service

In contrast with the environmental flows of lead pollutants, the tendency of the anthropogenic service shows the following remarkable characteristics: 1) All of the transformations of lead are driven by human activities that are performed to satisfy needs for specific human services within the anthrosphere; 2) the flow of lead is from various components of the natural system into various components of the anthrosphere; 3) to provide the desired services from lead, the natural forms are transformed into forms with more useful physical and chemical properties; and 4) these transformations have the goal of providing services (i.e., serving different functions), and changes in the forms of lead required to provide these functions are stimulated by engineering and technology demands such as design, production, and transportation, which in turn drive the transformations of lead among its various forms.

5 Conclusions

1) To meet human needs for specific services, lead flows through the anthrosphere, undergoing transfers and transformations in response to design, production, transportation, trade, and utilization needs.

2) The flows of lead through the anthrosphere resemble environmental flows of lead pollutants: both sets of flows include sources, pathways, and service fates. Ore and scrap are the main sources of lead, and the flows from lead ore extraction and collection of scrap, leading to that the final use of lead products is the main pathways for providing human services. The in-service

lead that provides these services represents the final fate of lead in the anthrosphere.

3) The main changes of lead in the anthrosphere occur in its functions, forms, and locations. The changes in function relate to transformations from raw ore into useful products such as batteries, products that provide protection against corrosion, and against radiation. The form of the lead also changes to reflect the properties required by these functions. The changes in location occur in the form of flows of lithospheric ore reserves in central China and to regions with high densities of automobiles in eastern China, companying a rough 2 Mt lead import of lead concentrates and 0.7 Mt lead export of various lead products.

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铅元素人为服务归趋中功能、形态与位置的变化

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摘 要：了解物质在形成人类特定服务的迁移转化过程中功能、形态和位置的变化有助于弄清特定服务的形成过程以及人类活动对自然的影响关系。对比铅元素人为循环与自然循环，关注物质的服务目标、归趋路径和这一过程中物质形态的变化进行分类。追踪铅元素生命周期过程，借助工程技术信息，辨识各阶段铅所发生的功能、形态、地理位置的变化。结果表明，铅矿和废铅资源是人类活动圈中铅元素的两种来源。在向人类提供的服务中，铅元素所具有的主要功能是储存与转移电能、防腐蚀、防辐射，而主要形态则表现为 Pb、PbO_2 和 $PbSO_4$ 等，空间位置呈现为从中国中心区域岩石圈转移到中国东部区域。

关键词：服务型社会；物质流动分析；人为循环；人类活动；生命周期；转化

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