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Industrial Ecosystems and Food Webs: An Ecological-Based Mass Flow Analysis to Model the Progress of Steel Manufacturing in China

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ABSTRACT

Materials and energy are transferred between natural and industrial systems, providing a standard that can be used to deduce the interactions between these systems. An examination of these flows is an essential part of the conversation on how industry impacts the environment. We propose that biological systems, which embody sustainability, provide methods and principles that can lead to more useful ways to organize industrial activity. Transposing these biological methods to steel manufacturing is manifested through an efficient use of available materials, waste reduction, and decreased energy demand with currently available technology. In this paper, we use ecological metrics to examine the change in structure and flows of materials in the Chinese steel industry over time by means of a systems-based mass flow analysis. Utilizing available data, the results of our analysis indicate that the Chinese steel manufacturing industry has increased its efficiency and sustainable use of resources over time at the unit process level. However, the appropriate organization of the steel production ecosystem remains a work in progress. Our results suggest that through the intelligent placement of cooperative industries, which can utilize the waste generated from steel manufacturing, the future of the Chinese steel industry can better reflect ecosystem maturity and health while minimizing waste.

1. Introduction

Life has existed on Earth for more than 3.8 billion years. Through natural selection over millennia, organisms have continuously evolved with the natural environment into the systems that exist today. Through the adaptation and application of ecological principles to human engineered systems, there is the potential to increase efficiency through the intelligent use of energy and resources, in addition to producing an overall reduction of waste [1–4]. Investigating the natural structures by which biological systems organize themselves may provide a more intelligent, sustainable way of formulating systems within the global community. A sustainable global community is one that meets the needs of the present generation without sacrificing those of future generations [5].

Material and energy flows are the fundamental properties affecting environmental sustainability because they are the main physical link between industrial and natural systems [6]. Ecologists can derive multiple structure-based and flow-based metrics from these fluxes in ecosystems through the use of food webs. These metrics describe natural ecosystem structures, properties, and predator-prey relationships within an ecosystem [7,8]. In a similar way, this approach may be used to investigate how nature can provide insight into the creation and enhancement of sustainable, performance-driven engineered systems.

By using a systems-based analysis of the industrial landscape, it is possible to systematically model composite processes in order to design, project, and control mechanisms to produce a system that moves materials and energy more efficiently. In addition, this investigation unveils the stressors, response mechanisms, and environmental impacts of resource exploitation throughout the modeled system. Engineers can use this analysis to make modifications to the industrial structure by designing systems that more closely resemble a healthy ecosystem. Past examples of using measurements of system behavior to influence design changes within the system have been well documented [4,6,9]. Using the analyzed system's metrics, more efficient and effective network configurations have been found to meet the traditional network design goals of reduced cost and increased efficiency [2,3].

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Some scientists argue that the Chinese steel industry (CSI) is currently unsustainable [10], given the current high resource and energy demand of the CSI combined with the cumulative environmental degradation from years past. This paper aims to use a systems-based mass flow analysis (MFA) to model the CSI's progression in order to evaluate the system's performance and health using ecological metrics. We investigate historical integrated steel manufacturing starting from the time when China began to aggressively invest in widespread energy conservation programs in its industrial sector in the Sixth (1981–1985) and Seventh (1986–1990) Five-Year Plans [11]. Next, we examine the current widespread integrated steel manufacturing processes. Finally, we investigate future scenarios.

The steel industry is a pillar of the Chinese economy; however, rapid growth has come at a cost to the environment [12]. Chinese crude steel production has grown rapidly, increasing the output of steel from 31.8 million metric tons in 1978 to 821.99 million metric tons in 2013 [13]. Fig. 1 [13] depicts the increase in crude steel production from 2004 to 2013.

The steel industry accounts for 18.3% of total energy consumption and is one of the top three sources of greenhouse gas emissions from China [14]. In 2012, China accounted for 29% of the entire world's CO_2 emissions [15]; of these emissions, approximately 12% was directly due to steel manufacturing [16]. Thus, approximately 3.48% of global CO_2 emissions originate from Chinese steel manufacturing. The CSI has made significant progress toward conserving energy and the environment, although there is still considerable improvement to be made on an international scale. According to 2007 data, the International Energy Agency determined that China could save 6.1 $GJ \cdot t^{-1}$ of crude steel through the adoption of the best available technologies [17].

Traditional steel manufacturing involves two kinds of processes: the blast furnace (BF)-basic oxygen furnace (BOF) process, which is known as the "long process," or the electric arc furnace (EAF) process, which is known as the "short process." The long process involves procedures such as sintering, coking, and use of the BF, which produce far greater amounts of pollution than the short process, which is more reliant on scrap. China's high energy consumption and heavy pollution within its steel manufacturing industry are primarily due to a lack of scrap supply, which results in over 91% of the steel manufacturing to be reliant on the long process [18]. This paper investigates the steel product life-cycle on a systems level and evaluates the system's structure using ecologically inspired metrics in an effort to provide quantitative insight into potential areas for sustainable improvement.

2. Materials and methods

2.1. Structure-based metrics

Ecologists use an array of metrics to understand the links between ecosystem structure and the resulting behavior of ecological systems [19]. Perhaps the most common representation of material flows used today is the food web (FW), which is a graphical depiction of the linkages between actors within a given ecosystem. The calculation of these structure-based metrics involves the identification of predators, prey, and the links they represent within a particular FW. This method of representation can be shown in matrix form, with 1 denoting a successful link and 0 denoting the absence of a link, and with columns representing predators and rows representing prey (i.e., in Fig. 2 [4], $f_{ij} = 1$ represents a link between prey (i) and predator (j)). The species are numbered and listed above and beside the matrix to show that they are the same species across rows and columns. In this paper, we adapt the FW principle and subsequent matrix analysis to the steel industry in China in an effort to quantify the impacts and potential areas for improvement within its structure.

The structure-based metrics used in this study are defined below:

Number of species (N): The total number of species in an FW. This term is also commonly denoted as "species richness" and can be represented by the number of rows or columns in an FW matrix [20].

Number of links (L): The number of direct links between species in an FW. This term is represented by the number of non-zero interactions in the FW matrix [20].

$$L = \sum_{i=1}^{m}\sum_{j=1}^{n} f_{ij} \tag{1}$$

Linkage density (L_D): The ratio of the total number of links to the total number of species within a network [21].

$$L_D = L/N \tag{2}$$

Prey (n_{prey}): Species that are consumed by at least one other species. This relationship is represented by the number of non-zero rows within an FW matrix [21].

$$f_{row}(i) = \begin{cases} 1 & \text{for } \sum_{j=1}^{n} f_{ij} > 0 \\ 0 & \text{for } \sum_{j=1}^{n} f_{ij} = 0 \end{cases} \tag{3}$$

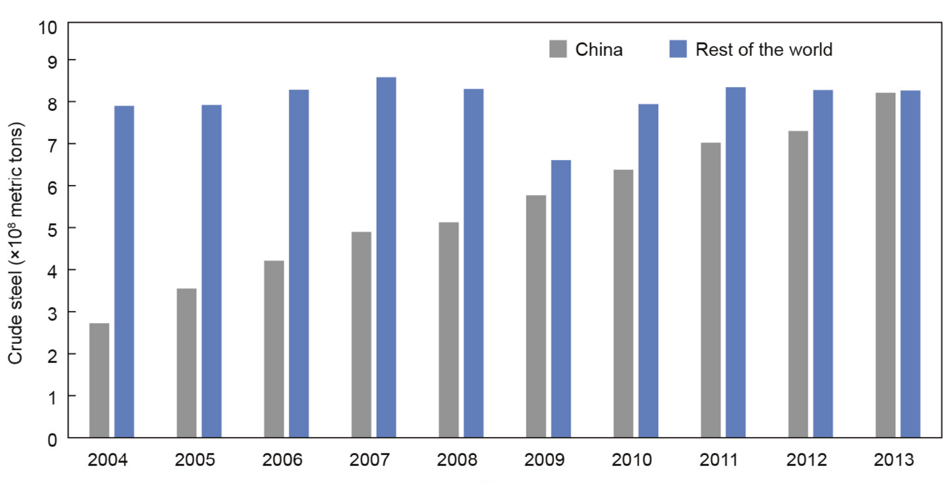

Fig. 1. Crude steel production (10^8 metric tons) in China and other countries. (Adapted from Ref. [13])

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