"This is peer reviewed version of the following article: [Vilaysouk, X., H. Schandl, and S. Murakami. 2018. A Comprehensive Material Flow Account for Lao PDR to Inform Environmental and Sustainability Policy. Journal of Industrial Ecology Online first(0)], which has been published in final form at [doi:10.1111/jiec.12764]. This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Use of Self-Archived Versions."

A comprehensive material flow account for Lao PDR to inform environmental and sustainability policy

Xaysackda Vilaysouk[1,2], Heinz Schandl[2,3] and Shinsuke Murakami[1]

[1] Department of Systems Innovation, Graduate School of Engineering, the University of Tokyo,
7-3-1 Hongo, Bunkyo, Tokyo 113-8656, Japan
*e-mail: xaysackda@g.ecc.u-tokyo.ac.jp
[2] CSIRO, Black Mountain Science and Innovation Park, Clunies Ross Street, Acton, ACT 2601, Canberra, Australia
[3] Australian National University Fenner School for Environment and Society, Acton, ACT 2601, Canberra, Australia

Summary

Modern environmental and sustainability policy that acknowledges the linkages between socioeconomic processes and environmental pressures and impacts, and designs policies to decouple economic activity from environmental pressures and impacts, requires a sophisticated and comprehensive knowledge base. The concept of industrial metabolism provides a sound conceptual base and material flow accounting – including primary material inputs and outflows of waste and emissions – provides a well-accepted operationalization. Studies presenting a comprehensive material flow account for a national economy are rare, especially for developing countries. Countries such as Lao PDR face dual objectives of improving the material standard of living of their people while managing natural resources sustainably and mitigating adverse environmental impacts from growing resource throughput. Our research fills a knowledge gap, presents a comprehensive account of material inputs and outflows of waste and emissions for the Lao PDR national economy, and applies the accounting approach for a low-income economy in Asia. We present a material balance for the years 2000 and 2015. For this research, we used data from Lao PDR national statistics and the accounting guidelines of the European Statistical Office (Eurostat), which pioneered the use of material flow data as part of its official statistical reporting. We demonstrate the feasibility of the accounting approach and discuss the robustness of results using uncertainty analysis conducted with statistical approaches commonly used in the field of industrial ecology including Gauss's law of error propagation and Monte Carlo simulation. We find that the fast changing scale and composition of Lao PDR material flows, waste and emissions presents challenges to the existing policy capacity and will require investment into governance of changed patterns of material use, waste disposal and emissions. We consider the data analysis sufficiently robust to inform such a change in policy direction.

Keywords: *National Material Flow Accounts, MFA, environmental and sustainability policy, uncertainty, developing countries*

Introduction

Natural resources are fundamental inputs to fuel socioeconomic systems and build up physical infrastructure but their use results in unintended environmental consequences. Environmental and sustainability policy needs to manage and mitigate these consequences. Global material extraction increased approximately three-fold during the last four decades and most growth in global resource use over the past three decades took place in Asia and the Pacific (UNEP 2016), influenced by the industrial transformation and urbanization of the giant developing economy of China and many other emerging economies (Schandl et al. 2017). The results in the UNEP (2016) report shed light on resource use patterns in other newly developing nations based on internationally available data. Informing national policy, however, requires robust and reliable information, which ideally uses locally available statistics and data sources.

The Lao People's Democratic Republic (Lao PDR or Laos) economy has long relied on primary resources including hydropower, the mining industry, agriculture and forestry. Fast growing resource extraction, energy production and population growth, as well as an increase in domestic resource consumption caused a recent escalation of environmental problems in Lao PDR. These new environmental issues of pollution and waste have created new challenges for policy makers. Environmental policy in Lao PDR, despite its lack of capacity, needs to deal with the speed and magnitude of increasing natural resource extraction, increased air pollution, growing municipal solid waste and toxic waste from industries, the fast accumulation of materials in buildings and infrastructure (in-use stocks), and climate change. The paucity of information on the sheer magnitude of primary material extraction, waste flows and emissions presents a profound limitation for policy makers in Lao PDR trying to address and manage the new environmental challenges. Presenting a full set of material flow accounting indicators is a way to strengthen the knowledge base of the policy community. It could allow for integrated policies that simultaneously address economic growth and the mitigation of environmental pressures and impacts.

Material flow accounting (MFA) was developed to capture the movement of materials in a defined socioeconomic system. A national MFA provides information on all material inputs to an economy from the domestic environment, outputs from the socioeconomic system to the environment, and material exchanges with other economies through imports and exports, compatible with the System of National Accounts at the macro level (Eurostat 2001).

Early foundational MFA research for Austria (Steurer 1992), Japan (Japan Environment Agency 1992), and Germany (Bringezu 1993) employed the material flow balance principle; this was also a focus of the seminal comparative study of five industrial economies organized by the World Resources Institute (Matthews

"This is peer reviewed version of the following article: [Vilaysouk, X., H. Schandl, and S. Murakami. 2018. A Comprehensive Material Flow Account for Lao PDR to Inform Environmental and Sustainability Policy. Journal of Industrial Ecology Online first(0)], which has been published in final form at [doi:10.1111/jiec.12764]. This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Use of Self-Archived Versions."

et al. 2000) driving the harmonization of methods. Since then, however, studies have focused on the input side of material flow accounts.

The growing availability of national MFA data has enabled an increasing number of policies such as the Sound Material-Cycle Society high-level policy framework in Japan (Takiguchi and Takemoto 2008), the European Union's Sustainable Use of Natural Resources directive, and more recently the European Resource Efficiency Scoreboard (European Commission 2017).

A good example of the growing policy impact of MFA data and indicators in Asia is China, where the National Bureau of Statistics of China developed a set of indicators to evaluate the progress of circular economic development in China. This has also encouraged numerous scholarly studies in the field of industrial ecology and enabled robust MFA measures for China (Mathews and Tan 2016; Wang et al. 2012; Huang et al. 2008; Li et al. 2010; Chen and Qiao 2001). In other developing countries, MFA has also been adopted using both national and international statistics to show trends in resource use and resource efficiency, but again focusing mainly on input indicators (Martinico-Perez et al. 2017; Maung et al. 2015; Raupova et al. 2014; Russi et al. 2008; Wang et al. 2012). The output side of MFA has largely been ignored.

To address this knowledge gap and to enhance the capacity of MFA to inform environmental policy in Lao PDR, we explore the feasibility and establish a full set of MFA data and indicators including inputs and outputs. The new dataset created may assist the Lao PDR policy community in designing integrated policies for economic development and the environment. The harmonization of economic and environmental objectives have become a focus of the newly agreed United Nations Sustainable Development Goals (Griggs et al. 2013). The new dataset also provides an essential information base for an economy characterized by mining and energy-led economic development.

The objectives of this study are three-fold. Firstly, to establish a full MFA dataset and indicators for Lao PDR's economy using national statistics and country-based coefficients. Secondly, to assess the uncertainty of the accounts using Monte Carlo simulation and to assess the sensitivity of the assumptions made in the model. Thirdly, to inform policy makers about trends in resource use, resource efficiency, and waste and emissions to promote the use of MFA indicators in environmental policy design.

By doing so, we provide the first comprehensive MFA dataset for the Lao PDR, as well as the first such study for a lower middle-income country in the Asia-Pacific region. We establish an evidence base about the relationship between material use, growth in material stocks, waste and emissions, and the role of trade to assist policy makers to establish socioeconomic development policies to guide development in the Lao PDR

"This is peer reviewed version of the following article: [Vilaysouk, X., H. Schandl, and S. Murakami. 2018. A Comprehensive Material Flow Account for Lao PDR to Inform Environmental and Sustainability Policy. Journal of Industrial Ecology Online first(0)], which has been published in final form at [doi:10.1111/jiec.12764]. This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Use of Self-Archived Versions."

toward a sustainable pathway. Our study also contributes to a better understanding of the feasibility and current limitations of preparing MFA in developing countries, and reveals the influence of data quality on the uncertainty of MFA results.

Methodology and data sources

This study applies the Eurostat compilation guidelines of 2013 to construct full material flow accounts for Lao PDR. Regarding availability of data, we were able to compile material flow data for all years from 1988 to 2015. We calculated uncertainty values for all MFA indicators based on available statistics and information from the literature using Monte Carlo simulation (MCS), a stochastic analytical tool. For the calculation of material inputs to the Lao economy we relied on our previous study (Vilaysouk et al. 2017) where the methods are described in detail. Here we focus on data and methods for the output side and balancing items of the accounts. All indicators considered in this study are listed in Table 1, including abbreviations, accounting rules and the data sources used for compiling the MFA.

Table 1. Full MFA indicators, accounting rules and data sources

	Abbreviation	Accounting identity	Data sources
Input indicators			
Domestic Extraction	DE		Lao PDR agriculture, forestry and fisheries statistics[1], energy and mining statistics[2] and industry statistics[3]
Imports	IMP		Lao PDR trade statistics[3] supplemented by UN COMTRADE
Balancing items for inputs	BI_{in}		Estimated based on national data and Eurostat coefficients
Direct material input	DMI	DMI = DE + IMP	
Territorial indicators			
Domestic Material Consumption	DMC	DMC = DE + IMP - EXP	
Output indicators			
Domestic Processed Output	DPO		Lao PDR waste and emission accounts
Exports	EXP		Lao PDR trade statistics[3] supplemented by UN COMTRADE
Balancing items for outputs	BI_{out}		Estimated based on national data and Eurostat coefficients
Stock indicators			
Net Addition to Stock	NAS	NAS = DE + IMP + BI_{in} – DPO – EXP - BI_{out}	
Other indicators			

---

[1] Ministry of Agriculture and Forestry of Lao PDR (2015a, 2015b)
[2] Ministry of Energy and Mines of Lao PDR (2015)
[3] Ministry of Industry and Commerce of Lao PDR (2015a,2015b)

"This is peer reviewed version of the following article: [Vilaysouk, X., H. Schandl, and S. Murakami. 2018. A Comprehensive Material Flow Account for Lao PDR to Inform Environmental and Sustainability Policy. Journal of Industrial Ecology Online first(0)], which has been published in final form at [doi:10.1111/jiec.12764]. This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Use of Self-Archived Versions."

Physical Trade Balance	*PTB*	PTB = IMP - EXP	Lao PDR trade statistics supplemented by UN COMTRADE

Inputs indicators

As outlined in Table 1 the dataset for material inputs includes the domestic extraction of biomass, fossil fuels, metal ores and non-metallic minerals that are further used in economic processes as outlined in Eurostat's MFA guide. The accounts for domestic extraction (DE), imports (IMP) and exports (EXP) used data from national statistics provided by government agencies including agricultural, forestry, fishery, and mining and energy statistics. Remaining data gaps were filled by using data from international organizations and some educated assumptions were established for missing data. Eurostat's guidelines were improved for the estimation of grazed biomass (UNEP 2016) and construction materials using national-based factors (Vilaysouk et al. 2017) and new methods (Miatto et al. 2017). The biggest advancement to the accounting approach occurred for metal ores, using detailed information for mines and ore grades, and for trade estimation techniques using unit prices and monetary values from national trade accounts in combination with data from UN COMTRADE. All further details on accounting for material inputs indicators are discussed in Vilaysouk et al. (2017).

Outputs indicators

In this study the outputs indicators consist of domestic processed output (DPO), exports (EXP), and balancing items for outputs (BI_{out}). DPO covers all materials generated during processing, manufacturing, use and final disposal in a socioeconomic system that are released to the domestic environment (Matthews et al. 2000). To calculate outflows, we used the most recent 2016 version of Eurostat's MFA guide (Eurostat 2016), which provides step-by-step guidance to estimate DPO and balancing items. Due to gaps in the data, we accounted only for emissions to air, waste disposal, and dissipative use of products, while emissions to water, which are insignificant in magnitude, were not calculated.

Due to the lack of a national air emissions inventory, emissions to air were mainly compiled using the dataset from the Emissions Database for Global Atmospheric Research version 4.3.2 provided by the European Commission (2016). We classified the waste into two major categories, municipal solid waste (MSW) and industrial waste (IW). We used waste generation rates from literature for major cities in the north, south, and the capital city of Lao PDR (Babel and Vilaysouk 2016; Sang-Arun and Pasomsouk 2012; Vilaysouk and Babel 2017) and population data from the Lao Statistics Bureau (2015) to estimate the annual MSW generated. Industrial waste was also calculated using a similar approach using data from various studies (Babel and Vilaysouk 2016; Khanal and Souksavath 2005). In addition to MSW and industrial waste, we classified mining waste as another category in the DPO accounting to highlight the environmental concerns and massive amount of waste related to the mining sector. Policy makers in related sectors may need to allow for this. Dissipative use of products, which basically consists of inorganic and organic fertilizer such as manure, compost, sewage sludge, and pesticides, was estimated based on the coefficient provided in the Eurostat guidelines (Eurostat 2016). Explicit step-by-step explanations for the estimation of DPO are shown in section 1 of the supporting information.

Balancing Items

Balancing items, as the name implies, is the additional indicator in MFA for balancing materials on the input and output sides. Generally, these indicators are reported in specific tables and are not included in the accounting of MFA aggregate indicators (Eurostat 2016). Balancing items are important when the NAS is calculated as the balancing of inputs and outputs. Balancing items are required both on the inputs and outputs sides.

Balancing items for inputs (BI_{in}) consist of oxygen for combustion processes and respiration of humans and livestock, nitrogen for the Haber-Bosch process, and water requirements for the domestic production of exported beverages. In our study, only oxygen for combustion processes and respiration of humans and livestock were accounted for BI_{in}. Balancing items for outputs (BI_{out}) were calculated for the amount of water vapor from combustion of energy carriers, gases and vapor from humans and livestock respiration. BI_{in} and BI_{out} were estimated mainly based on the coefficients provided in the guidelines (Eurostat 2016).

Derived National MFA Indicators

The derived national MFA indicators considered in our study are indicators calculated from the material flow balancing principle of the MFA model, including direct material input (DMI), domestic material consumption (DMC), and last but not least NAS. Following is the explanation of the indicators and the calculation rules as seen in Table 1.

DMI is developed to quantify total direct material input to an economic system. DMI accounts only for materials that have economic value, thus does not include balancing items and unused domestic extraction.

The DMC indicator measures apparent consumption of materials in a defined economic system. As mentioned in Eurostat (2001), the term consumption is not defined as final consumption but instead actual consumption in the economic system as a whole. DMC is calculated as the sum of all material extraction domestically and total imports including raw materials, semi-raw materials, and finished products.

NAS is the indicator that measures the growth of physical stocks in a society (Eurostat 2001). The consumption of energy and materials during the lifetime and end-of-life disposal processes of a product makes the NAS indicator one of the most important indicators in many industrialized countries (Krausmann et al. 2017). NAS can be calculated directly from gross additions to stocks, minus removals of stocks, or can be indirectly calculated from balancing inputs and outputs with appropriate balancing items (Eurostat 2016, 2001). In this study, due to limitations in the data, we calculated NAS indirectly from inputs and outputs following a material balancing approach.

Assessing uncertainty of national MFA indicators

Uncertainty commonly exists in MFA due to the nature of the data used in the accounting, for instance various data sources, different measurement methods, and the quality of the data itself (Laner et al. 2014). Rechberger et al. (2014) stated that "…MFA should now enter into an era where reporting uncertainty ranges of stocks and flows is mandatory …". Laner and colleagues published several papers reviewing the literature on applied uncertainty in MFA studies, and Monte Carlo simulation (MCS) was suggested as one systematic approach to handle the uncertainty in MFA (Laner et al. 2016; Laner et al. 2014, 2015).

Some recent studies have incorporated uncertainty analysis. Krausmann et al. (2017) employed MCS in their global dynamic stock model to propagate uncertainty of their results by assuming uncertainty ranges for some parameters (for instance material inputs, mean of lifetime, recycling and down-cycling fraction) and the authors suggested performing a sensitivity analysis to check for systematic errors in the assumed parameters. Patrício et al. (2015) used the data imputation method and error propagation techniques to quantify the uncertainty of a regional MFA study.

Generally, the dataset for compiling MFA in developing countries, including in our case, is not completely available, and estimations and assumptions need to be made. In this study, due to concerns about the quality of official statistics and estimated data used in the model, MCS was performed to test the robustness of the model results. Another benefit of including uncertainty analysis in national MFA is that it can inform practitioners at the country level which indicators influence the uncertainty of the results and need to be carefully checked before performing the accounting. MFA results with plausible ranges also help users in making decisions when using the indicators. The systematic step of the calculation is shown in section 4 of the supporting information.

MCS was run one thousand times simultaneously for the entire MFA model to obtain the uncertainty (standard deviation(σ)) of DMI, DMC, and NAS. In order to perform MCS, the mean (μ) of the normal distribution, uncertainty parameter, and standard deviation (σ) must be known (Rechberger et al. 2014). In our study, we treated the model input data as the mean of the normal distribution and uncertainty ranges were assumed for each indicator (except for uncertainty of imports and exports) as explained in the following paragraphs.

The uncertainty range of MFA indicators in our study was assumed following common practices of uncertainty analysis in MFA when uncertainty data is not available (Patrício et al. 2015; Krausmann et al. 2017; Kovanda et al. 2008). We attribute uncertainty ranges to the indicators based on their sources. Data gathered from official statistics was considered to be good and ±10% was chosen as the uncertainty range, while data obtained from estimation was considered to have higher uncertainty with ±30% (uncertainty of DE). DPO and balancing items were almost completely estimated based on available information (except mining waste). The uncertainty range chosen for these indicators was based on the number suggested in literature (±15%) (Patrício et al. 2015; Kovanda et al. 2008; Krausmann et al. 2017). For imports and exports, we calculated the uncertainty directly based on the trade dataset from our previous study (Vilaysouk et al. 2017). Details of the assumption approach for the uncertainty range and the Monte Carlo simulation are explained in the supporting information.

After preparing all the data required for MCS, the MCS was performed to generate a set of random values of DE, IMP, EXP, DPO, and balancing items using mean values and the uncertainty ranges given. After that, the aggregated MFA indicators (DMI, DMC, and NAS) were calculated following an equation modified from the Eurostat compilation guidelines as follows:

$$DMI_c^{mc}(t) = IMP_c^{mc}(t) + DE_c^{mc}(t) \quad \text{(Eq.1)}$$

where $DMI_c^{mc}(t)$ is DMI of MCS mc at year t, $IMP_c^{mc}(t)$ is IMP of MCS at year t, $DE_c^{mc}(t)$ is DE of MCS at year t, and cohort c=t.

The mean value of the cohort of DMI at year t was calculated as:

$$\overline{DMI}_{\bar{c}}(t) = \frac{1}{n}\sum_{i=mc}^{n} DMI_c^{mc}(t) \qquad \text{(Eq.2)}$$

As mentioned earlier, the uncertainty ranges of aggregated MFA indicators in this study were assumed as the standard deviation of the normal distribution. The uncertainty of DMI ($\sigma_{DMI}(t)$) was calculated using equation 3.

$$\sigma_{DMI}(t) = \pm\sqrt{\frac{1}{n}\sum_{i=mc}^{n}\left(DMI_c^{mc}(t) - \overline{DMI}_{\bar{c}}(t)\right)^2} \qquad \text{(Eq.3)}$$

The calculation of DMC_c^{mc} is as follows:

$$DMC_c^{mc}(t) = IMP_c^{mc}(t) + DE_c^{mc}(t) - EXP_c^{mc}(t) \qquad \text{(Eq.4)}$$

where $DMC_c^{mc}(t)$ is domestic material consumption of MCS mc at year t, $IMP_c^{mc}(t)$ is imports of MCS at year t, $DE_c^{mc}(t)$ is domestic extraction of MCS at year t, $EXP_c^{mc}(t)$ is exports of MCS at year t, and cohort c=t.

The NAS indicator is calculated mainly based on other indicators. The calculation was performed by equation 5.

$$NAS_c^{mc}(t) = IMP_c^{mc}(t) + DE_c^{mc}(t) + {BI_{in}}_c^{mc}(t) - {BI_{out}}_c^{mc}(t) - DPO_c^{mc}(t) - EXP_c^{mc}(t)$$

(Eq.5)

where ${BI_{in}}_c^{mc}(t)$ and ${BI_{out}}_c^{mc}(t)$ are balancing items on the inputs side and outputs side of MCS at year t, and cohort c=t. The uncertainty of DMC and NAS from MCS were calculated using the same approach as with DMI (see details of calculation process in supporting information section 4).

Sensitivity analysis of changing parameters used in the estimated indicators

In this study, we performed sensitivity analyses of changes in parameters used in the estimation of DE, DPO, and balancing items to check the robustness of our MCS results. We included six sensitivity analysis cases by changing the harvest factor used in estimation of crop residues, the feeding intake factor used for estimation of fodder and grazing biomass for animals, the material intensity factor for the estimation of sand and gravel for the DE indicator; emissions to air, solid waste, and dissipative use of products for DPO indicators; and finally the parameter used in the estimation of balancing items. We adjusted the parameters to the maximum by increasing +30% and the minimum by decreasing -30%, which are the maximum uncertainty values assumed in our MCS. We did not include IMP and EXP in the sensitivity analysis due to the minor amounts compared to the indicators mentioned above, and also because the uncertainty of IMP and EXP were calculated directly from the dataset itself. The results of DMI, DMC, and NAS from the sensitivity analysis were compared with the results from the MCS.

Results

Trends in selected MFA indicators from 1988 to 2015

We first present a set of standard headline MFA indicators covering material inputs and outputs. Figure 1.a shows trends in these headline indicators for Lao PDR for the years 1988 to 2015. The rapid growth in domestic extraction of materials in Lao PDR was caused by a combination of factors, including the material demands of infrastructure development, and material flows related to the energy- and mining-oriented

"This is peer reviewed version of the following article: [Vilaysouk, X., H. Schandl, and S. Murakami. 2018. A Comprehensive Material Flow Account for Lao PDR to Inform Environmental and Sustainability Policy. Journal of Industrial Ecology Online first(0)], which has been published in final form at [doi:10.1111/jiec.12764]. This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Use of Self-Archived Versions."

economy. Over a period of 25 years, DE grew by an order of magnitude from 11 million tonnes to about 120 million tonnes. Trade volumes have been insignificant when compared to material extraction. DMC, the most widely used MFA headline indicator, mirrors trends in DE.

In 1988, DMC was only 11.3 million tonnes, reflecting the pre-industrial, agricultural economy of Lao PDR, and it remained under 35 million tonnes until 2004. The year 2005 marked a spike in DMC of 71.5 million tonnes (almost doubling within one year). This coincides with the start of construction of a mega hydropower project – Nam Theun 2 – and the opening of the large-scale Sepon copper mine in Savannakhet Province. These very large investments into mining and energy generation capacity ratcheted up demand for metal ores and non-metallic minerals. Note that the spike in DMC was temporary, related to investment in the development of hydropower plants and mining operation. DMC has continued on a sharp upward trend, reflecting the transition of the Lao economy toward export-oriented extractive sectors of mining and energy.

Domestic processed output (DPO) reflects the fast-increasing resource base of the Lao economy and so do net additions to stock (NAS). DPO in Lao PDR remained constant at less than six million tonnes for more than two decades and started to grow around 2006. The structure of DPO is characteristic of the economic development path of Lao PDR. Since the start of the mining boom in Lao PDR, massive amounts of waste rock and mine tailings have accumulated at mine sites, reaching 70% of DPO by 2015. DPO in 2015 was 41.1 million tonnes, of which more than 74% was industrial waste, followed by 15% of emissions to air, 7% of organic material, mineral fertilizers and pesticides, and 4% of municipal solid waste (see Figure 1.b). The structure of DPO is perhaps atypical compared to other developing countries, and mining-related flows are a potential source of large and long-lasting environmental issues (Koide et al. 2012).

NAS in Lao PDR in the early 1990s was around one million tonnes. This low level of material accumulation was visible throughout Lao PDR. Houses, especially in villages, were simple and made from local materials; road infrastructure was lacking and industrial capital mostly non-existent. As Lao PDR transitioned to an industrial and services economy stock accumulation increased. International donors such as the World Bank brought large investments into the road network and hydropower capacity, resulting in a constant increase in NAS throughout the period. In 2005, the year of the mega hydropower construction project, NAS reached its first peak at 50.7 million tonnes (nearly 70% of total DMC, see Figure 1a). NAS was at 64.6 million tonnes in 2015, and is expected to continue to increase to fuel the development of national infrastructure, especially the first high speed rail system in Lao PDR which will connect the southwest of China with Lao Northern provinces and Vientiane, the capital of Lao PDR. Lao infrastructure development

"This is peer reviewed version of the following article: [Vilaysouk, X., H. Schandl, and S. Murakami. 2018. A Comprehensive Material Flow Account for Lao PDR to Inform Environmental and Sustainability Policy. Journal of Industrial Ecology Online first(0)], which has been published in final form at [doi:10.1111/jiec.12764]. This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Use of Self-Archived Versions."

figures prominently in the plan to increase the connectedness of ASEAN economies and to enhance trade, transport and communication.

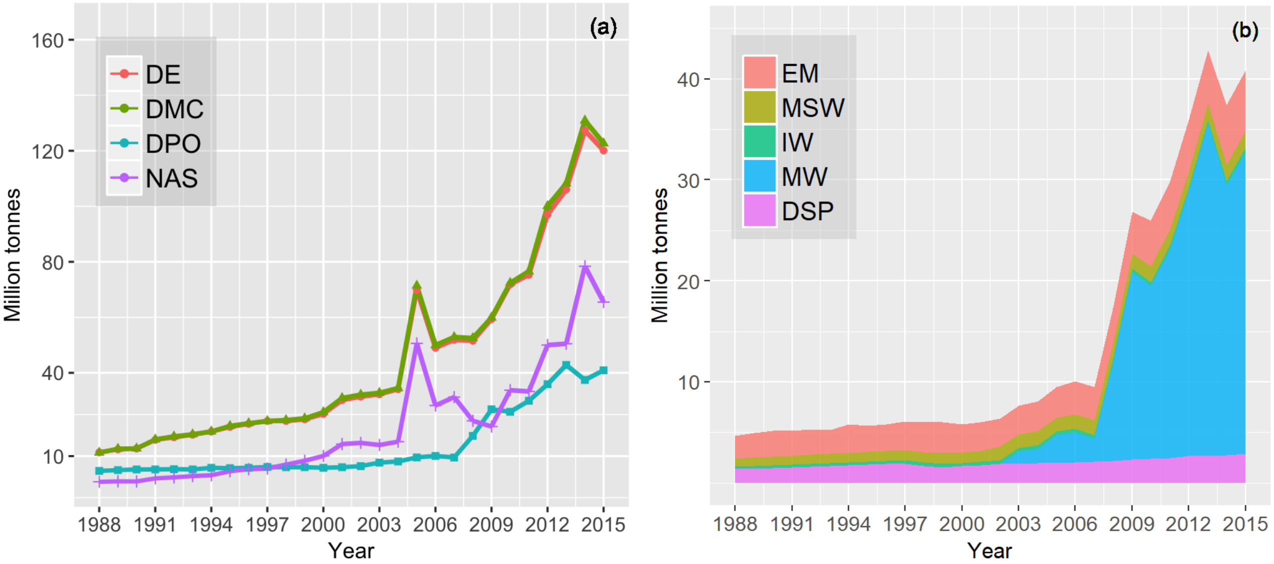

Figure 1. (a) Trends in selected MFA indicators and (b) shares of DPO in Lao PDR from 1988 – 2015; DSP – dissipative use of products, EM – emission to air, IW – industrial waste, MSW – municipal solid waste, MW – mining waste

National material flow analysis and its uncertainty for Lao PDR

Figure 2.a shows the full set of material flow accounting indicators for Lao PDR for the year 2000 at the onset of the mining and hydroelectricity growth and for the year 2015 to provide two snapshots of material use, waste and emissions of the Lao economy. The results include uncertainty ranges obtained from the Monte Carlo simulation.

In 2000, DE was 25.2±3.8 million tonnes and accounted for more than 72% of total inputs. Imports were negligible at that time. Balancing items on the input side include oxygen for combustion processes and oxygen for respiration of humans and livestock, but do not include nitrogen for the Haber-Bosch process or water requirements for the domestic production of exported beverages.

DPO in 2000 was 5.8±0.9 million tonnes, dominated by emissions to air and the dissipative use of products, i.e. chemical and organic fertilizers. Exports amounted to 0.3±0.1 million tonnes, which was relatively low compared to other indicators. Balancing items are important for the calculation of NAS. The outputs balance, including water from fossil fuels combustion and gases from respiration of humans and livestock, is high at 18.7±2.8 million tonnes. When NAS is calculated without the balancing items, the result is higher than the DMI of metal, non-minerals, and timber (potential stock materials) which is unrealistic. Following the Eurostat guidelines, we thus included balancing items in our NAS accounting. From the balancing of the MFA in 2000, NAS was 10.0±5.0 million tonnes. These materials have accumulated in society in the form of buildings, roads, infrastructure systems, and machinery, along with home appliances.

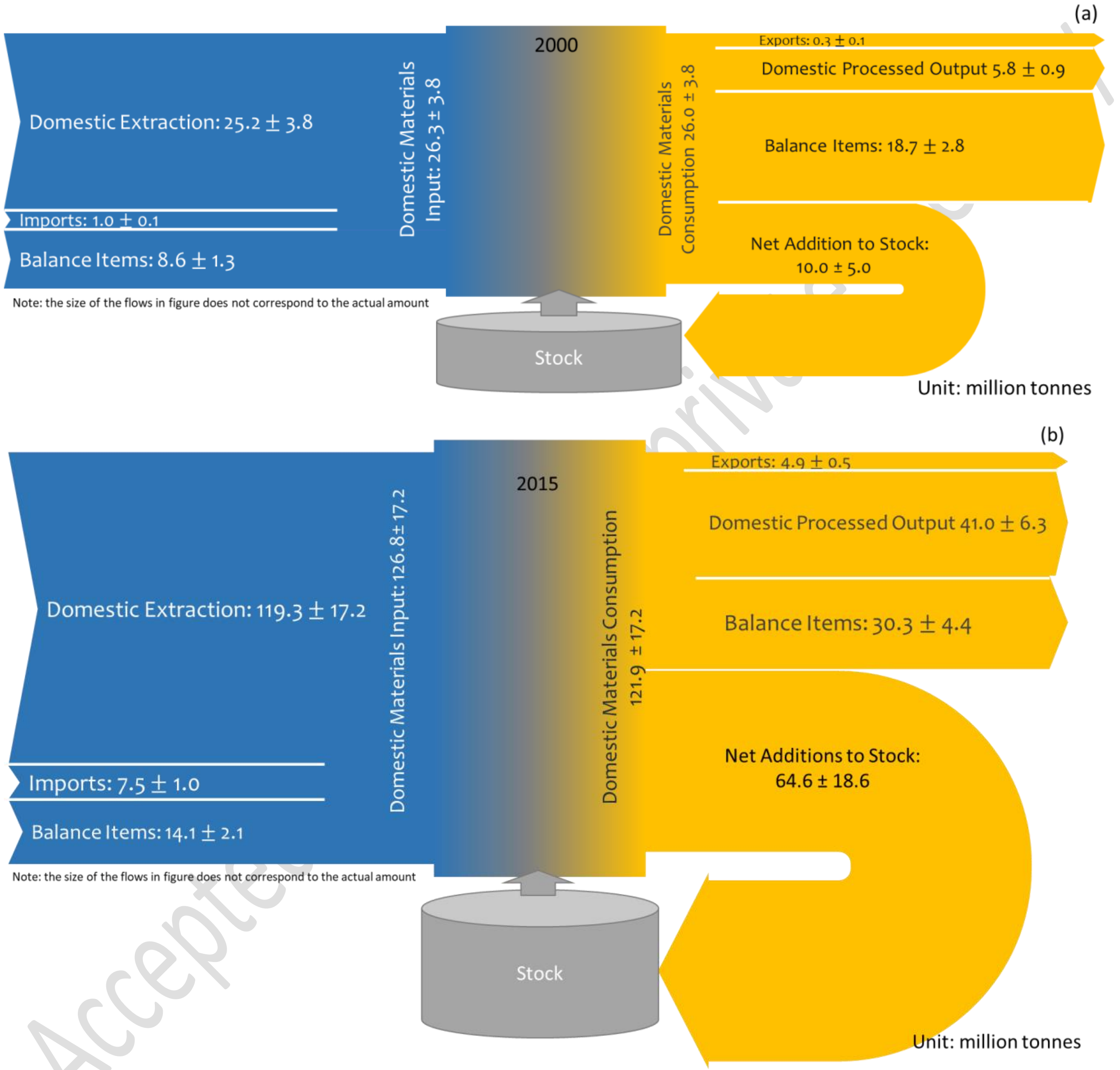

Figure 2. Economy-wide MFA of Lao PDR in 2000, 2015

In 2015, all input indicators increased significantly. DE grew close to five-fold to 119.3±17.2 million tonnes (see Figure 2.b). Imports grew to 7.5±1.0 million tonnes. On the output side DPO increased massively, caused by mining sector extraction and associated waste flows, and was at 41.0±6.3 million tonnes. As discussed above, the majority of DPO in 2015 was industrial and mining waste, followed by emissions to air, dissipative use of products, and municipal solid waste. Exports also increased rapidly, more than 16-fold compared to the year 2000, illustrating the growing role of products from Lao PDR in international commodity markets. About half of all material inputs accumulated in societal stocks, as indicated by a 6-fold growth of NAS at 64.6±18.6 million tonnes. Uncertainty ranges increased in line with growing material throughput.

Material intensity and waste intensity

As Lao PDR establishes its infrastructure and industrial capital and delivers a higher material standard of living to its people, material use will grow, as has been the case in many other Asian developing economies (Schandl and West 2010). For such countries in transition resource efficiency, i.e. the value of GDP realized by each unit of material use, becomes an important measure of sustainability (UNEP 2011). Material intensity (MI) measures the amount of materials required to generate each unit of GDP. We calculate MI using an exchange rate based GDP at 2005 prices (UNSD 2017) and DMC for resource use. The higher the MI, the lower the resource efficiency at the level of the whole economy. Since 1988, MI in Lao PDR has aggressively increased. It has almost doubled from 12.2 kg per USD in 1988 to 21.1 kg per USD in 2015 (see Figure 3). The material intensity of the Lao PDR economy is an order of magnitude higher compared to the global average and also well above material intensity in the Asia-Pacific region (UNEP 2016). The growing MI indicates that economic development in Lao PDR during the past two decades relied on large throughputs of metal ores and bulk materials.

The waste intensity of the national economy is expressed as DPO per unit of GDP. From 1988 to 2000, there was a gradual improvement in the waste intensity of the Lao economy, with GDP growing faster than the associated waste flows. Soon after the large-scale mining industries started operation, however, there was a remarkable increase in waste intensity. From 2000 until now, waste and emissions intensity rose from a level of 2.8 kg per USD to 8.5 kg per USD in 2013, slightly decreasing thereafter to 7.1 kg per USD in 2015.

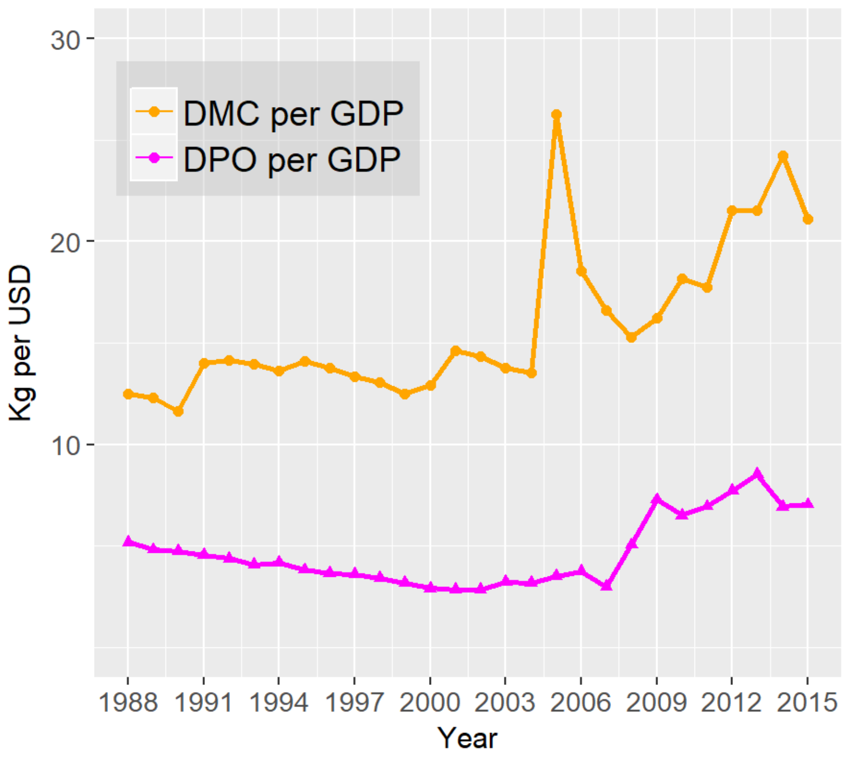

Figure 3. Material intensity and DPO intensity of Lao PDR

Uncertainty and sensitivity of national MFA derived indicators

The quality of MFA results depends on the quality of primary inputs data and appropriate estimation approaches being used in estimating unavailable data. In this study, we employed a Monte Carlo simulation (MCS) to assess the uncertainty of the model results. We found that the level of uncertainty varied for different indicators (see Figure 4).

Figure 4(a) shows the results from MCS and sensitivity analysis of DMC indicators. As illustrated in the figure, from MCS the uncertainty of DMC ranges between ±12% and ±22% throughout the period; it is lower at the beginning of the studied period and highest in the year 2005. Regarding the characteristics of Lao PDR, as it is ongoing in its transition from a biomass based economy to an industrial based economy, the massive amount of materials for infrastructure development is highly dependent on domestic materials as well as some imports of machinery and other construction materials. DE clearly played an important role in the uncertainty of DMC in 2005 when the amount of construction materials required, on which the amount used in the accounting was estimated, rapidly accelerated due to many construction activities in the country. Another aggregated indicator on the input side is DMI. Due to the small amount of imports, DMI almost mirrors DMC (see Figure 4(c)).

Taking the uncertainty level of DE and IMP, and EXP into consideration showed that the uncertainty of our results was mainly influenced by uncertainty in DE. This is the general phenomenon seen in national MFA when trading is less than DE. The Patrício et al. (2015) study also mentioned that the uncertainty of DMC is highly dependent on the relationship between trade and materials consumption. The uncertainty of DMI and DMC in 2015 was ±14% (Figure 4(b), (d)). The recent MFA study at the country level that perform uncertainty analysis was limited. Thus, we have to compare our results to an available study at regional level, which had uncertainty ranges from 1.9% to 5.3% for DMI, and 4.2% to 22.6% for DMC (Patrício et al. 2015).

In order to check whether the assumptions made for DMI and DMC calculations would over- or under-estimate, we performed a sensitivity analysis. The sensitivity analysis for DMI and DMC included sensitivity analysis case 1(Sen1), Sen2, which assumed the parameters used in the estimation changed ±30%, but does not include Sen3 to Sen6, which assumed changes in DPO and balancing items, because the calculation rule has no relation to DPO or balancing items (see Table 1).

"This is peer reviewed version of the following article: [Vilaysouk, X., H. Schandl, and S. Murakami. 2018. A Comprehensive Material Flow Account for Lao PDR to Inform Environmental and Sustainability Policy. Journal of Industrial Ecology Online first(0)], which has been published in final form at [doi:10.1111/jiec.12764]. This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Use of Self-Archived Versions."

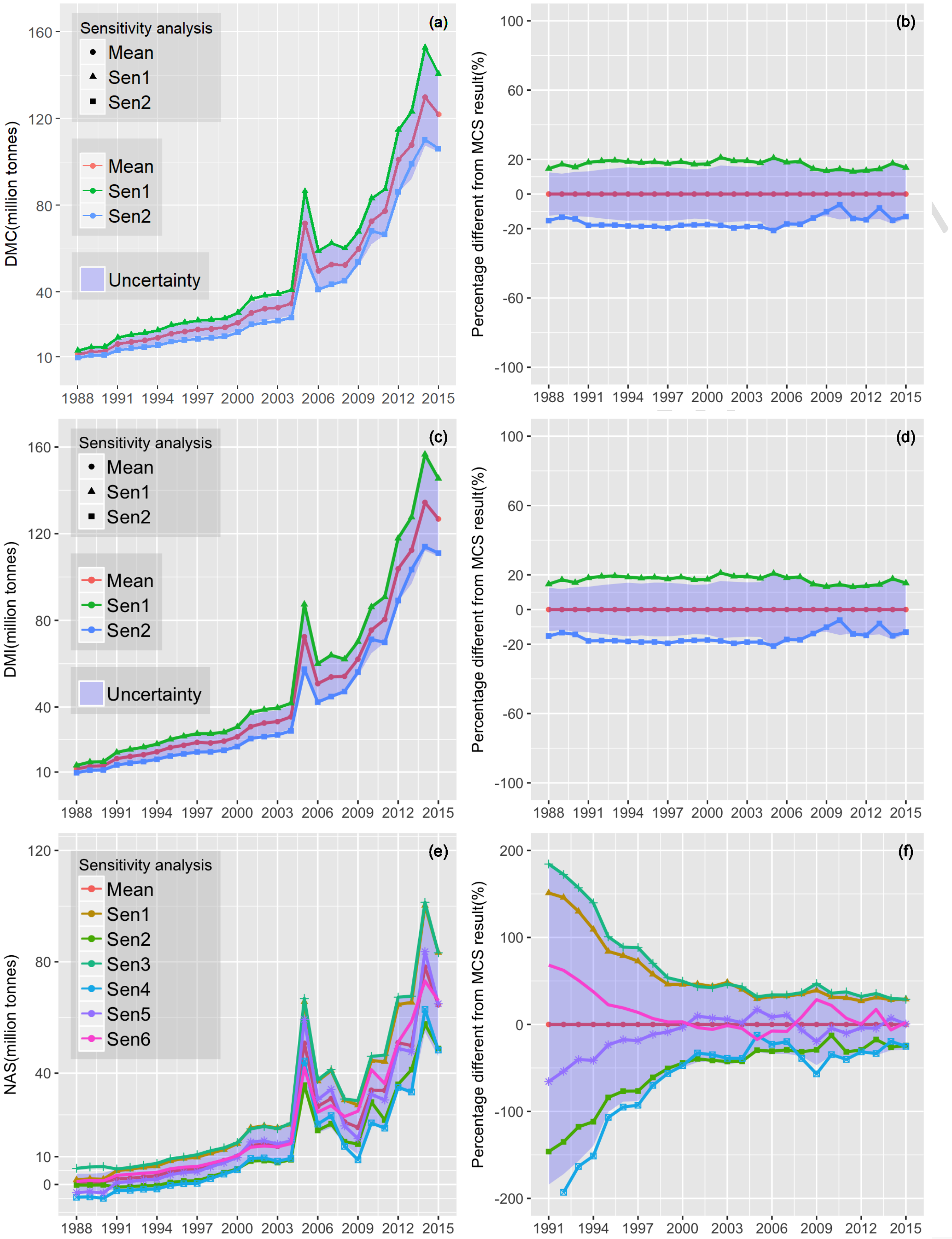

Figure 4. Comparison of MCS with sensitivity analysis and Percentage different from MCS: (a) and (b) are DMC results; (d) and (e) are DMI results; (e) and (f) are NAS results, respectively.

By adjusting the parameters, the results of DMI and DMC from the traditional MFA model without MCS do not seem to yield significantly different results compared to the mean and uncertainty range of MCS. The result of Sen1 is higher than the upper bound of MCS by about 1% to 5% for DMC and DMI, except for 2005, 2011, 2012, when Sen1 was lower than the highest range of MCS by approximately 1%. For the results of Sen2, it was lower than the lower bound of MCS by about 1% to 4% but higher by about 9% and 6% in 2010 and 2013, respectively. By comparing all the results from the sensitivity analysis to the MCS results, it appears that the assumptions of uncertainty ranges of DE that we made for MCS are able to handle the sensitivity of the assumption of the parameters.

Figure 4.e shows results for NAS from the MCS as well as the sensitivity analysis. In our study, due to limitations of the data, NAS was calculated by balancing inputs and outputs indicators of the national economy systems boundary. Patrício et al. (2015) mentioned that most MFA studies calculated using the material balancing approach simply did not take this into account. Following the common balancing approach, many levels of uncertainty were aggregated into NAS, and our calculations resulted in high uncertainty. The highest uncertainty range is more than ±100% in the 1990s, decreasing to under ±50% in 2000, and around ±29% in 2015 (see Figure 4.f). The high level of uncertainty indicated how much poor data quality and high uncertainty affect uncertainty levels of NAS. The reason behind such abnormal uncertainty levels in the late 1990s is that when low quality data such as DPO and balancing items dominate other flows in the system such as DE, IMP, and EXP, the high uncertainty of those indicators will likely to take the lead in the uncertainty of NAS. On the other hand, when higher quality data indicators dominate other flows, high uncertainty in estimated data has less influence on the results, as seen in the decreasing uncertainty level of NAS in Figure 4.f.

Due to the characteristic of material flow balancing, the results for NAS from the MCS contains the highest uncertainty among the indicators. The results from the sensitivity analysis for all cases also showed a high level of uncertainty. With many processes and levels of aggregation of NAS indicators, high uncertainty exists in almost all sensitivity analysis cases. With confirmation that high uncertainty exists in all sensitivity analysis cases and MCS we suggest that using estimated data for DPO and balancing items to calculate NAS and for the material balancing approach should be considered the least preferred option.

All the MCS results shows that when DE becomes a more important indicator in terms of supplying resources national economic development, strong characteristics of DE such as the availability of official statistics, and better estimation approaches, will allow practitioners and policy makers to focus on resources targets to accelerate and improve the quality of MFA studies. This will provide valuable information to use in

"This is peer reviewed version of the following article: [Vilaysouk, X., H. Schandl, and S. Murakami. 2018. A Comprehensive Material Flow Account for Lao PDR to Inform Environmental and Sustainability Policy. Journal of Industrial Ecology Online first(0)], which has been published in final form at [doi:10.1111/jiec.12764]. This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Use of Self-Archived Versions."

policy decisions as well as planning tools. However, considering the high uncertainty of NAS from materials balancing, further investigation should seek other approaches for NAS accounting.

Discussion

This study represents the most comprehensive material flow account for Lao PDR and perhaps for any Asian developing country to date. The results are relevant for environmental and economic policy in Lao PDR in several ways.

In the context of the new Sustainable Development Goals countries have committed to establish policies that allow for continuous increasing resource productivity (the inverse of Material Intensity indicators) until 2030 (target 8.4 of the SDGs), progress in sustainable natural resource management (target 12.2 of the SDGs) and waste minimization (target 12.5 of the SDGs). Our analysis shows that the Lao economy has fast decreasing resource productivity, i.e. it has become more material intensive over time. If the trends keep growing at current levels, Lao PDR will fail to achieve target 8.4 of the SDGs. This is a result of economic planning which favors an economic development path based on mining and energy generation, which is a high-risk strategy in the context of the development needs of the country. A recent study (Hatfield-Dodds et al. 2017) has shown that in a world that takes resource efficiency and greenhouse gas abatement seriously, low-income and resource-dependent countries will lose economic competitiveness, and human development and well-being will decline. Lao PDR also has quite a high per-capita DMC of 18 tonnes, compared to other countries with same level of economic development, which translates into large waste volumes and considerable levels of emissions at 6 tonnes per capita in 2015. Because of this, Lao PDR will also face difficulty in archiving targets 12.2. and 12.5 despite the fact that the material-, waste- and emission-intensive economy does not translate into a high standard of living for Lao households and also goes hand in hand with a lack of housing and transport infrastructure. Analysis of Lao PDR's material footprint (UNEP 2016) shows a large gap between direct material flow indicators and consumption-based material flow indicators, indicating the large extent to which the Lao economy and resource use services economies and consumers abroad.

An assessment of future trends in material use in the Lao economy based on the aspirations expressed in the 8th Five-Year National Socio-Economic Development Plan (2016–2020) for GDP (Ministry of Planning and Investment of Lao PDR 2016) and current trends in the material intensity of the Lao economy suggest further growth in DMC and DPO and an additional decline in resource productivity.

DMC in 2025 would range from 168.5 million tonnes to 290.4 million tonnes and DPO would grow to 88.3 million tonnes. Resource productivity would continue to decline from 47 USD per tonne to 41 USD per tonne. Even an ambitious improvement of raising resource productivity(RP) by 50% and reducing DPO by 50% would bring DMC to 168.5 million tonnes (a 3.7% annual increase, on average). DPO will reduce by a factor of two, and RP will increase to 71 USD per tonne (see details in supporting information).

This shows the large investment into sound environmental policies that is required in Lao PDR in the domains of resource management, waste management and pollution control. This is a massive challenge for the Lao policy community, which is focused on human development outcomes and earning foreign income to finance infrastructure development and is characterized by a lack of human capacity, financial means, knowledge gaps and weak institutions (UNEP 2013). Policy mechanisms for pollution control and waste management will be insufficient for managing the growing environmental pressures. The integration of environmental policies into the national economic development plan needs to be prioritized to avoid contradictory policies and programs. Currently, Lao PDR has the Environmental Protection law (revised 2013) as key legislation to monitor and control environment-related issues generated from anthropogenic activities, specifically from the industrial sector as well as massive urban and infrastructure development. The Minister of Natural Resources and Environment issued a Ministerial Instruction for Pollution Control in 2015 aiming to prevent, control and reduce unavoidable pollution generated from hazardous substances and reduce impacts in a timely manner in order to meet the Environmental Quality and/or National Pollution Control Standards (Ministry of Natural Resources and Environment of Lao PDR 2015). Ten environment-related laws that have been enacted to control environment-related issues (Monemany et al. 2012). In the 8th Five-Year National Socio-Economic Development Plan (2016–2020), the Government of Lao PDR set a Ten-Year Socio-Economic Development Strategy (2016–2025) which included environment-related policies in a total of seven strategies, consisting of strategies on quality, inclusive, stable, sustainable and green economic growth, strategy on sustainable and green environment with effective and efficient use of the natural resources and strategy on industrialization and modernization. Historical trends of resource use in socioeconomic development through MFA provide important information for policy makers in setting targets for these strategies.

The dual objective of social and economic development and environmental integrity needs to be supported by well-designed policies, which will include strategies for economic diversification and traditional environmental management including waste and emission policies (European Commission 2017; Takiguchi and Takemoto 2008). Economic diversification will allow Lao PDR to add value to its natural resources and to engage in higher income, lower resource use activities that drive decoupling of economic growth from accelerating material use. This promises a triple dividend of higher incomes, a better quality of life and more

"This is peer reviewed version of the following article: [Vilaysouk, X., H. Schandl, and S. Murakami. 2018. A Comprehensive Material Flow Account for Lao PDR to Inform Environmental and Sustainability Policy. Journal of Industrial Ecology Online first(0)], which has been published in final form at [doi:10.1111/jiec.12764]. This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Use of Self-Archived Versions."

benign environmental outcomes. Material flow accounts will assist Lao policy makers to establish high-level targets to provide guidance and to measure progress toward improving the sustainability of materials management in Lao PDR at the aggregate level.

The sole full MFA study in a developing country, national MFA of China in 2002 (Xu and Zhang 2007), was chosen for comparison with the results from our study. The comparison, which was carried out in terms of tonnes per capita, shows interesting and similar patterns of resource use in both countries (see Figure 5).

Comparing the size of the two economies in 2002, GDP per capita in Lao PDR was 407 USD per capita, about one third of China's GDP. Taking resource use into consideration, DE per capita was only 4.7 tonnes in Lao PDR and it was 18.8 tonnes in China. The significant difference in DE between Lao PDR and China was influenced by the different stage of infrastructure and economic development. Looking at imports, they were also low for both countries, which indicated that the required amount of materials for development in these two countries relied on their domestic resources.

Due to the higher level of industry in China, DPO, which was dominated by landfilled waste and mining dumping, was already high in 2002, more than 14 times higher than Lao PDR in 2000. Even though mining has already started in Lao PDR, in 2015 its total DPO was still lower than China.

The amount of materials transformed to capital stock in China was also higher in 2002, following the trends of other indicators. Resource use acceleration in Lao PDR took place in 2003 to 2005 and the continuous growth contributed to Lao PDR catching up to the level of resource use in China in the early 2000s. DE per capita of Lao PDR increased to 17.7 tonnes, mainly driven by the extraction of metal ores and construction materials. Imports and exports per capita also increased and have surpassed the level of China. As Lao PDR was making progress in economic and infrastructure development, NAS also rapidly increased from 1.9 tonnes per capita to 9.6 tonnes per capita. As resource use increased rapidly, especially in resource-intensive sectors such as mining, DPO per capita increased almost six-fold. Comparing the DMC per capita between China (UN Environment (2017) database) and Lao PDR, it shows that both countries have been accelerated their resources consumption. If the annual growth of resource consumption in Lao PDR increase at current level, DMC per capita of Lao PDR would likely to step-up a head China but when looking at per capita GDP is still far behind, which is indicating an early alarm for the declining in resource efficiency in Lao PDR.

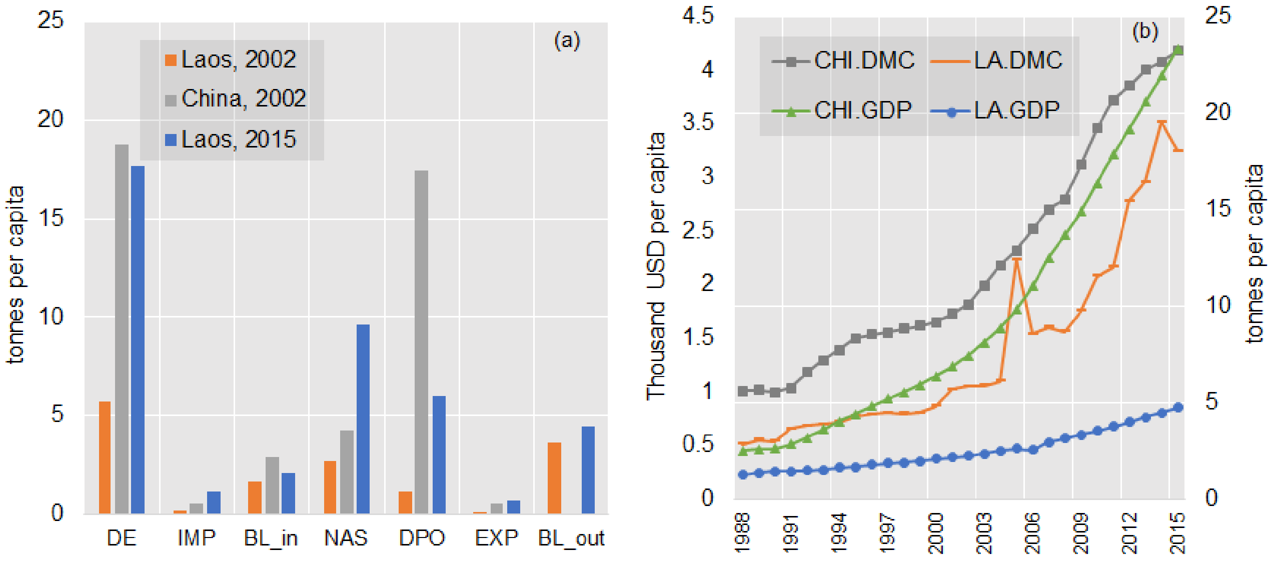

Figure 5. Comparison of (a) national MFA indicators, (b) GDP and DMC per capita (Note: CHI-China, LA-Lao PDR)

Limitations of study

Using all available national data and up-to-date accounting methodologies, our study yields a full picture of material use in the Lao PDR. There are, however, limitations of our study that need be addressed in future research. Waste data, except for mining waste, was estimated using the literature. Emissions to air, which are becoming more important in their contribution to total DPO, were sourced from an international database. MCS helped in identifying sources of uncertainty, but assumptions of uncertainties were made whenever uncertainty data was not available. Especially for NAS calculated from the material flow balance, the uncertainty is significant. The sensitivity analysis results show that the assumption made for the uncertainty range of DE could handle the error of DMC and DMI by more than +30% and -30%. Improving the knowledge base for material stocks accounting by employing direct accounting techniques would definitely help to reveal a deeper understanding of stock accumulation in Lao PDR. All this should be considered as the priority agenda for future work. In addition, a detailed analysis of economic sectors would further enhance the integration of socioeconomic and environmental knowledge into the socioeconomic policies in Lao PDR.

Conclusions

This study has successfully delivered a new understanding of resource use in Lao PDR, mainly by using national statistical data, and supplemented by international databases using up-to-date industrial ecology knowledge. Our results show that all MFA indicators were continuously increasing between 1988 to 2015 with an acceleration taking place at the beginning of the 2000s. In recent decades, domestic resource consumption has increased by almost 11 times, mainly due to reliance on domestic extraction for bulk materials and crops, and imports of finished products including food, construction materials and fossil fuels. Resource efficiency in Lao PDR (21.1 kg per USD of GDP) has already surpassed regional and global levels, by factors of eight times and 14 times respectively. The high level of MI in Lao PDR was mainly led by the extraction of bulk materials and metals. If the Lao government were to follow the most ambitious scenario (increase resource productivity by 50% and decrease DPO by 50%), in 2025 Lao PDR could archive 1 USD of GDP by using only 14 kg of materials (a reduction of almost 60%). Integrating MFA indicators into Lao PDR's national statistics system will require technical knowledge and financial inputs but will provide valuable information for policy makers to monitor environmental pressure from resource use, which will support the concept of "Green Economy" as proposed in the latest Five-Year National Socio-Economic Development Plan. MFA indicators, at the same time, could be used to report against the United Nations SDGs.

Acknowledgements

This research was financially supported by the Environment Research and Technology Development Fund (1-1402) of the Ministry of the Environment, Japan. The first author is grateful for the PhD scholarship provided by the Ministry of Education, Culture, Sports, Science, and Technology (MEXT), Japan. The authors wish to thank Karin Hosking of CSIRO for editing the final manuscript.

References

Babel, S. and X. Vilaysouk. 2016. Greenhouse gas emissions from municipal solid waste management in Vientiane, Lao PDR. *Waste Management & Research* 34(1): 30-37.
Bringezu, S. 1993. Towards increasing resource productivity: How to measure the total material consumption of regional or national economies. *Fresenius Environmental Bulletin* 2(8): 437–442.
Chen, X. and L. Qiao. 2001. A Preliminary Material Input Analysis of China. *Population and Environment* 23(1): 117-126.
European Commission. 2017. Resource Efficiency Scoreboard. http://ec.europa.eu/environment/resource_efficiency/targets_indicators/scoreboard/index_en.htm. Accessed 10 July 2017.
European Commission. 2016. Emission Database for Global Atmospheric Research (EDGAR). http://edgar.jrc.ec.europa.eu/overview.php?v=CO2ts1990-2015. Accessed 28 April 2017.
Eurostat. 2001. *Economy-wide Material Flow Accounts and derived indicators: A methodological guide*. Luxembourg: Eurostat.
Eurostat. 2016. *Economy-wide Material Flow Accounts: Manual 2016 Draft version (13 September 2016) on DPO and Balancing items*. Luxembourg: Eurostat.
Griggs, D., M. Stafford-Smith, O. Gaffney, J. Rockstrom, M. C. Ohman, P. Shyamsundar, W. Steffen, G. Glaser, N. Kanie, and I. Noble. 2013. Sustainable development goals for people and planet. *Nature* 495(7441): 305-307.
Hatfield-Dodds, S., H. Schandl, D. Newth, M. Obersteiner, Y. Cai, T. Baynes, J. West, and P. Havlik. 2017. Assessing global resource use and greenhouse emissions to 2050, with ambitious resource efficiency and climate mitigation policies. *Journal of Cleaner Production* 144: 403-414.
Huang, H., J. Bi, X. Li, B. Zhang, and J. Yang. 2008. Material flow analysis (MFA) of an eco-economic system: a case study of Wujin District, Changzhou, China. *Frontiers of Biology in China* 3(3): 367-374.
Japan Environment Agency. 1992. Quality of the environment in Japan 1992. Tokyo: Japan Environment Association.
Khanal, B. R. and B. Souksavath. 2005. Environmental management measures and current practices in solid waste management: A case study from Vientiane, Lao PDR. *Journal of Greater Mekong Subregion Development Studies* 2: 69-89.

Koide, R., C. Tokoro, S. Murakami, T. Adachi, and A. Takahashi. 2012. A Model for Prediction of Neutralizer Usage and Sludge Generation in the Treatment of Acid Mine Drainage from Abandoned Mines: Case Studies in Japan. *Mine Water and the Environment* 31(4): 287-296.

Kovanda, J., T. Hak, and J. Janacek. 2008. Economy-wide material flow indicators in the Czech Republic: trends, decoupling analysis and uncertainties. *International Journal of Environment and Pollution* 35(1): 25-41.

Krausmann, F., D. Wiedenhofer, C. Lauk, W. Haas, H. Tanikawa, T. Fishman, A. Miatto, H. Schandl, and H. Haberl. 2017. Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. *Proceedings of the National Academy of Sciences* 114(8): 1880-1885.

Laner, D., H. Rechberger, and T. Astrup. 2014. Systematic Evaluation of Uncertainty in Material Flow Analysis. *Journal of Industrial Ecology* 18(6): 859-870.

Laner, D., H. Rechberger, and T. Astrup. 2015. Applying Fuzzy and Probabilistic Uncertainty Concepts to the Material Flow Analysis of Palladium in Austria. *Journal of Industrial Ecology* 19(6): 1055-1069.

Laner, D., J. Feketitsch, H. Rechberger, and J. Fellner. 2016. A Novel Approach to Characterize Data Uncertainty in Material Flow Analysis and its Application ato Plastics Flows in Austria. *Journal of Industrial Ecology* 20(5): 1050-1063.

Lao Statistics Bureau. 2015. Lao Population and Housing Census 2015: Provisional Report. Vientiane, Lao PDR: Lao Statistics Bureau.

Li, M., H. Zhang, Z. Li, and L. Tong. 2010. Economy-wide material input/output and dematerialization analysis of Jilin Province (China). *Environmental Monitoring and Assessment* 165: 263-274.

Martinico-Perez, M. F. G., T. Fishman, K. Okuoka, and H. Tanikawa. 2017. Material Flow Accounts and Driving Factors of Economic Growth in the Philippines. *Journal of Industrial Ecology* 21(5): 1226-1236.

Mathews, J. A. and H. Tan. 2016. Circular economy: Lessons from China. *Nature* 531(7595): 440-442.

Matthews, E., C. Amann, S. Bringezu, M. Fischer-Kowalski, W. Hüttler, R. Kleijn, Y. Moriguchi, C. Ottke, E. Rodenburg, and D. Rogich. 2000. *The weight of nations*.

Maung, K., M. Martinico-Perez, T. Komatsu, S. Mohammad, S. Murakami, and H. Tanikawa. 2015. Comparative studies on the driving factors of resource flows in Myanmar, the Philippines, and Bangladesh. *Environmental Economics and Policy Studies* 17(3): 407-429.

Miatto, A., H. Schandl, T. Fishman, and H. Tanikawa. 2017. Global Patterns and Trends for Non-Metallic Minerals used for Construction. *Journal of Industrial Ecology* 21(4): 924-937.

Ministry of Agriculture and Forestry of Lao PDR. 2015a. Technical Standard for National Livestocks Balancing, edited by Department of Livestock and Fisheries. Vientiane, Lao PDR.

Ministry of Agriculture and Forestry of Lao PDR. 2015b. Agriculture statistics 1976-2015, edited by Department of Planning and Cooperation. Vientiane, Lao PDR.

Ministry of Energy and Mines of Lao PDR. 2015. Minerals Productions in Lao PDR 1985-2015, edited by Department of Mines. Vientiane, Lao PDR.

Ministry of Industry and Commerce of Lao PDR. 2015a. Imports and Exports of Lao PDR 2010-2015, edited by Department of Planning and Cooperation. Vientiane, Lao PDR.

Ministry of Industry and Commerce of Lao PDR. 2015b. Industrial Processing Statistics 1985-2015, edited by Department of Planning and Cooperation. Vientiane, Lao PDR.

Ministry of Natural Resources and Environment of Lao PDR. 2015. Ministerial Instruction for Pollution control. Vientiane.

Ministry of Planning and Investment of Lao PDR. 2016. 8th Five-Years National Socio-Economic Development Plan (2016-2020). Vientiane, Lao PDR.

Monemany, N., S. Virany, K. Khampadith, C. Majella, K. Souphaxay, and B. Somvang. 2012. Lao Environmental Outlook 2012: Ministry of Natural Resources and Environment of Lao PDR.

Patrício, J., Y. Kalmykova, L. Rosado, and V. Lisovskaja. 2015. Uncertainty in Material Flow Analysis Indicators at Different Spatial Levels. *Journal of Industrial Ecology* 19(5): 837-852.

Raupova, O., H. Kamahara, and N. Goto. 2014. Assessment of physical economy through economy-wide material flow analysis in developing Uzbekistan. *Resources, Conservation and Recycling* 89: 76-85.

Rechberger, H., O. Cencic, and R. Frühwirth. 2014. Uncertainty in Material Flow Analysis. *Journal of Industrial Ecology* 18(2): 159-160.

Russi, D., A. C. Gonzalez-Martinez, J. C. Silva-Macher, S. Giljum, J. Martínez-Alier, and M. C. Vallejo. 2008. Material Flows in Latin America. *Journal of Industrial Ecology* 12(5-6): 704-720.

Sang-Arun, J. and K. Pasomsouk. 2012. *A guide for improving municipal solid waste management and promoting urban organic waste utilization in Lao PDR*. Institute for Global Environmental Strategies (IGES); Faculty of Engineering, National University of Laos.

Schandl, H. and J. West. 2010. Resource use and resource efficiency in the Asia-Pacific region. *Global Environmental Change-Human and Policy Dimensions* 20(4): 636-647.

Schandl, H., M. Fischer-Kowalski, J. West, S. Giljum, M. Dittrich, N. Eisenmenger, A. Geschke, M. Lieber, H. Wieland, A. Schaffartzik, F. Krausmann, S. Gierlinger, K. Hosking, M. Lenzen, H. Tanikawa, A. Miatto, and T. Fishman. 2017. Global Material Flows and Resource Productivity: Forty Years of Evidence. *Journal of Industrial Ecology*: n/a-n/a.

Steurer, A. 1992. *Stoffstrombilanz Österreich 1988 [Material flow balance for Austria 1988]*. Vienna , Austria: IFF Social Ecology.

Takiguchi, H. and K. Takemoto. 2008. Japanese 3R Policies Based on Material Flow Analysis. *Journal of Industrial Ecology* 12(5-6): 792-798.

UN Environment. 2017. UN Environment Live Database. http://www.uneplive.org/country/data/LA. Accessed 01 April 2017.

UNEP. 2011. *Decoupling natural resource use and environmental impacts from economic growth*. Nairobi: United Nations Environment Programme.

UNEP. 2013. *Capacity Building and Policy Needs Assessment for Sustainable Consumption and Production*. Bangkok: United Nations Environment Programme.

UNEP. 2016. *Global Material Flows and Resource Productivity. An Assessment Study of the UNEP International Resource Panel*. Paris: United Nations Environment Programme.

UNSD. 2017. UNSD Statistical Databases. https://unstats.un.org/unsd/databases.htm. Accessed 01 April 2017.

Vilaysouk, X. and S. Babel. 2017. Benefits of improved municipal solid waste management on greenhouse gas reduction in Luangprabang, Laos. *Environmental Technology*: 1-9.

Vilaysouk, X., H. Schandl, and S. Murakami. 2017. Improving the knowledge base on material flow analysis for Asian developing countries: A case study of Lao PDR. *Resources, Conservation and Recycling* 127: 179-189.

Wang, H., S. Hashimoto, Y. Moriguchi, Q. Yue, and Z. Lu. 2012. Resource Use in Growing China. *Journal of Industrial Ecology* 16(4): 481-492.

Xu, M. and T. Zhang. 2007. Material Flows and Economic Growth in Developing China. *Journal of Industrial Ecology* 11(1): 121-140.

Supporting information: A comprehensive material flow account for Lao PDR to inform environmental and sustainability policy

Xaysackda Vilaysouk[1,2], Heinz Schandl[2,3] and Shinsuke Murakami[1]

[1] Department of Systems Innovation, Graduate School of Engineering, the University of Tokyo,
7-3-1 Hongo, Bunkyo, Tokyo 113-8656, Japan
*e-mail: xaysackda@g.ecc.u-tokyo.ac.jp
[2] CSIRO, Black Mountain Science and Innovation Park, Clunies Ross Street, Acton, ACT 2601, Canberra, Australia
[3] Australian National University Fenner School for Environment and Society, Acton, ACT 2601, Canberra, Australia

Section 1: Estimation of DPO

For emissions to air, Eurostat (2016) suggests using data from air emission accounts and air emission inventories. However, in the Lao PDR such annual statistics are not available. For the air emission inventory in Lao PDR, only the first and second national air emissions inventories reported to the UN Framework Convention on Climate Change are available (Ministry of Natural Resources and Environment of Lao PDR 2000, 2013). The national statistics on air emissions in Lao PDR are not sufficient to construct the time series data, thus we decided to source the data from the Emission Database for Global Atmospheric Research version 4.3.2 provided by European Commission (2016) for the accounting of emissions to air. The database includes time series data for CO2 emissions from 1970 to 2015, and for other greenhouse gases (GHGs) from 1970 to 2008. In our accounting, regarding the defined system boundary, we excluded emissions from short life cycle biomass burning, large-scale biomass burning, carbon emissions/removals of land-use, and land-use change and forestry. The accounting distinguishes 19 specific gases. CO2 data was directly sourced from the database for the whole period but other gases during 2010–2015 were extrapolated from 38 years of historical trends available in the database.

Besides emissions to air, waste disposal issues are becoming common challenges for many developing countries including Lao PDR. In EW-MFA, waste disposal figures are aggregated from municipal solid waste (MSW) and industrial waste. In Lao PDR, there is no MSW database yet, although waste generation rates in recent years are available for some major cities such as Vientiane (Babel and Vilaysouk 2015), Luang Prabang (Vilaysouk and Babel 2017), Savannakhet, and Champasak (Sang-Arun and Pasomsouk 2012), as well as for the country level (Ngoc and Schnitzer 2009) with figures ranging from 0.55 to 0.7 kg per capita·day. Based on these MSW generation rates, we assumed that the generation rate was 0.55 kg per capita·day for 1988 to 2001 (Ngoc and Schnitzer 2009), and 0.67 kg per capita·day from 2002 to 2015 (Babel and Vilaysouk 2015; Vilaysouk and Babel 2017; Sang-Arun and Pasomsouk 2012).

Industrial waste refers to undesired outputs from manufacturing processes at factories as well as at mining sites. The amount of industrial waste is strongly related to the level of industrialization. Based on industrial processing statistics, the main industry in Lao PDR from 1988 to the late 1990s was food processing, while large-scale mining activities took place from 2003 onwards. In Lao PDR, industrial waste data is not available. Khanal and Souksavath (2005) reported that waste from industries and markets accounted for 19.1% of total waste generated in Vientiane. Based on this percentage and the total waste generated in Vientiane in 2012 (Babel and Vilaysouk 2015), we roughly estimated industrial waste in Vientiane to be 44,175 tonnes per year, or 60.4 kg per capita·day. This industrial waste generation rate was used to estimate total industrial waste generated from manufacturing in this study.

Another important industrial waste in Lao PDR is mining waste. Lao PDR started a large-scale commercial mining industry in 2003 (Sepon mine in Savannakhet Province). Based on the S&P Global Market Intelligence database (SNL), there are more than fifteen active mining projects (including copper, gold, potash, platinum, alumina, bauxite, phosphate, lanthanides), and four of them are operating (SNL 2017). Total gross ores processed and commodity production are recoded in the SNL database. We calculated the mining waste simply by subtracting total commodity products from total ores processed.

Dissipative use of products includes inorganic and organic fertilizer such as manure, compost, sewage sludge, and pesticides. The first accounting for dissipative flows in MFA was carried out by Matthews et al. (2000) for Japan, Austria, Germany, and the Netherlands. The systematic accounting for dissipative use of products in Eurostat (2016) consists of organic fertilizer, mineral fertilizer, sewage sludge, compost, pesticides, seeds, salt, other thawing materials spread on roads, solvents, laughing gas and other. In Lao PDR, agricultural inputs, especially pesticides and chemical fertilizers, are relatively low and imported from neighboring countries (Somsak Kethongsa 2005). In our accounting, we accounted for organic fertilizer (animal manure) by estimating based on daily manure production coefficients. We used the manure production rate of the smallest cattle size in Queensland (Department of Agriculture and Fisheries: The State of Queensland 2017) as it is similar to the average size of cattle in Lao PDR. For other small animals, including pigs, goats and sheep, and poultry, we used the default coefficients provided by Eurostat (2016). Chemical and mineral fertilizers and pesticides are mainly imported, thus we accounted for these materials based on import data from our trade dataset (Vilaysouk et al. 2017).

Section 2: Assumption of uncertainty in DE

MFA indicators are calculated from linear combination of tonnage of materials (Patrício et al. 2015). To assess the uncertainty of DE, we have assigned to uncertainty for different materials at sub-category level. We assumed the uncertainty based on data sources and estimation methods. For data obtained from statistics reports, we assigned the lower uncertainty at ± 10%. For the materials that estimated from coefficients, the uncertainty was assumed to be ± 30% (see Table S1). The data for DE was assumed to be independently from one another. We assumed that the uncertainty remains constant all the year in the observed period. The uncertainties at sub-category level were propagated using Gauss's law of error propagation (Equation 1).

$$\sigma_{DE}(\mathrm{t}) = \sqrt{\sigma_{crops}(t)^2 + \sigma_{crop\ residues}(t)^2 + \cdots + \sigma_{coal}(t)^2} \qquad (1)$$

Table S1. Assumption of uncertainty for DE at sub-category level

Material	Sub-category	Data source	Uncertainty Range (%)
Biomass			
	Crops	[1]	± 10%
	Crops residues	[2]	± 30%
	Grazing and fodder crops	[2]	± 30%

	Wood and timber	3	± 10%
Metal			
	Ferrous metal	1	± 10%
	Non-ferrous	3	± 10%
Non-metallic		1,2	± 30%
Fossil		1	± 10%

Note: [1]Lao national statistics, [2]estimated based on coefficients, [3]international statistics

Section 3: Calculation approach of uncertainty in Import-Export

Imports and Exports data used in this accounting were calculated using the conversion approach to convert the monetary value into physical weight. The details for the conversion were discussed in (Vilaysouk et al. 2017). We calculated the uncertainty for imports and exports using confidence interval approach. From the "tonne price" of every transaction, we grouped this calculated "tonne price" into the same group of the product based on HS-Code. From the group of "tonne price" of the same product, we were able to calculated mean of "tonne price" ($\hat{\mu}_i$). In the trade dataset used in our study, there are about five thousand products at HS-Code 8-digits level. However, some of the products contained few transactions. For example, in the import data set, airplane spare parts imported to Lao PDR in 2015 contained less than 50 transactions and the price were extremely different among them. Thus, we filtered the products that have the transaction less than 100 and ignored from the standard imports/exports deviation calculation. The uncertainty for different products was calculated using confidence interval with 95% confidence level (Eq.1). We then calculated the uncertainty of imports by combining the standard deviation of all products using Gauss's law of error propagation (Eq.2). For the exports, the same concept was applied. From the calculation, uncertainty for imports in 2015 was ± 13%, and ± 10% for exports. Due to the insignificant amount of imports and exports in the past decade, we assumed that the uncertainty for imports and exports are the same for the observed period.

$$\sigma_i = \frac{\left[\left(\hat{\mu}_i - Z_{\frac{\alpha}{2}} * \frac{\hat{\sigma}_i}{\sqrt{n_i}}\right) + \left(\hat{\mu}_i + Z_{\frac{\alpha}{2}} * \frac{\hat{\sigma}_i}{\sqrt{n_i}}\right)\right]}{2 * 1.96} \qquad \text{(Eq.1)}$$

$$\sigma_{imp} = \sqrt{{\sigma_1}^2 + {\sigma_2}^2 + \cdots + {\sigma_n}^2} \qquad \text{(Eq.2)}$$

Section 4: Monte Carlo Simulation of EW-MFA

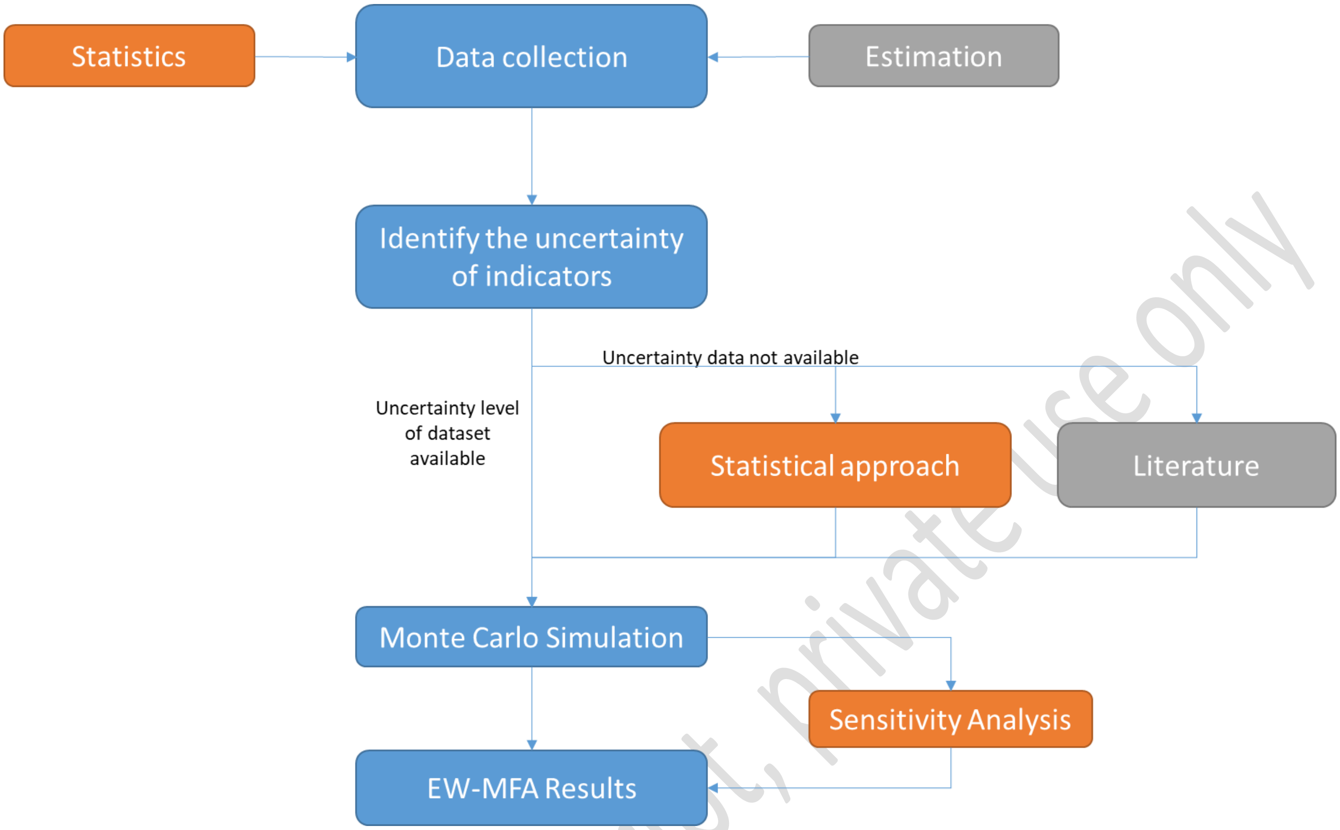

Figure S-1. EW-MFA calculation process

Incorporate Monte Carlo Simulation into EW-MFA required additional works than tropical MFA. As could be seen in the Figure S-1, the study started from data collection. For some indicators that the data was not available, we followed the estimation approaches provided in the Eurostat guideline, accompanied by the national coefficients. During data collection process, another important information that needed for MCS is the uncertainty value of the collected data. The uncertainty value could be obtained at the same time with official statistics data if it is available, if not other studies and some statistical approaches could be used.

After preparing the all the data required for MCS, finally we could obtain DMI, DMC, and NAS from the equation below:

$$DMI_c^{mc}(t) = \ IMP_c^{mc}(t) + DE_c^{mc}(t) \qquad \text{(Eq.s-1)}$$

where $DMI_c^{mc}(t)$ is DMI of MCS mc at year t, $IMP_c^{mc}(t)$ is IMP of MCS at year t, $DE_c^{mc}(t)$ is DE of MCS at year t, and cohort c=t.

Average value of DMI at year t than calculated as:

$$\overline{DMI}_{\bar{c}}(t) = \frac{1}{n}\sum_{i=mc}^{n} DMI_c^{mc}(t) \quad \text{(Eq.s-2)}$$

Uncertainty of DMI at year t could be obtained by:

$$\sigma_{DMI}(t) = \pm\sqrt{\frac{1}{n}\sum_{i=mc}^{n}\left(DMI_c^{mc}(t) - \overline{DMI}_{\bar{c}}(t)\right)} \quad \text{(Eq.s-3)}$$

For DMC, the calculation processes are as follow:

$$DMC_c^{mc}(t) = IMP_c^{mc}(t) + DE_c^{mc}(t) - EXP_c^{mc}(t) \qquad \text{(Eq.s-4)}$$

where $DMC_c^{mc}(t)$ is DMC of MCS mc at year t, $IMP_c^{mc}(t)$ is IMP of MCS at year t, $DE_c^{mc}(t)$ is DE of MCS at year t, $EXP_c^{mc}(t)$ is IMP of MCS at year t, and cohort c=t.

Average value of DMI at year t than calculated as:

$$\overline{DMC}_{\bar{c}}(t) = \frac{1}{n}\sum_{i=mc}^{n} DMC_c^{mc}(t) \quad \text{(Eq.s-5)}$$

Uncertainty of DMI at year t could be obtained by:

$$\sigma_{DMC}(t) = \pm\sqrt{\frac{1}{n}\sum_{i=mc}^{n}(DMC_c^{mc}(t) - \overline{DMC}_{\bar{c}}(t))} \qquad \text{(Eq.s-6)}$$

NAS is calculated by equation s-7:

$$NAS_c^{mc}(t) = IMP_c^{mc}(t) + DE_c^{mc}(t) + {BI_{in}}_c^{mc}(t) - {BI_{out}}_c^{mc}(t) - DPO_c^{mc}(t) - EXP_c^{mc}(t)$$

(Eq.s-7)

where ${BI_{in}}_c^{mc}(t)$ and ${BI_{out}}_c^{mc}(t)$ are the balancing items at the inputs side and outputs side of MCS at year t, and cohort c=t.

Average value of NAS at year t than calculated as:

$$\overline{NAS}_{\bar{c}}(t) = \frac{1}{n}\sum_{i=mc}^{n} NAS_c^{mc}(t) \quad \text{(Eq.s-8)}$$

Uncertainty of NAS at year t could be obtained by:

$$\sigma_{NAS}(t) = \pm\sqrt{\frac{1}{n}\sum_{i=mc}^{n}(NAS_c^{mc}(t) - \overline{NAS}_{\bar{c}}(t))} \qquad \text{(Eq.s-9)}$$

Section 5: Assumption of uncertainty in DE

Table S-2. Sensitivity analysis parameter adjustment in each sensitivity case

	Sensitivity Case 1	Sensitivity Case 2	Sensitivity Case 3	Sensitivity Case 4	Sensitivity Case 5	Sensitivity Case 6
Harvest factor	+30%	-30%	-	-	+30%	-30%
Feed intake for animal	+30%	-30%	-	-	+30%	-30%
Material intensity for estimation of Sand and Gravel	+30%	-30%	-	-	+30%	-30%
Emission to Air	-	-	-30%	+30%	+30%	-30%
Solid Waste	-	-	-30%	+30%	+30%	-30%
Dissipative use of products	-	-	-30%	+30%	+30%	-30%
Balancing items	-	-	-30%	+30%	+30%	-30%

Section 6: Scenarios development to inform policymakers on future DMC, DPO, and RP for 2016-2025

We developed three scenarios to represent the future trends of three main indicators including DMC, DPO, and RP. We used the annual growth rate of GDP proposed by the Government of Lao PDR in latest Five-Years National Socio-Economic Development Plan (2016-2020) (Ministry of Planning and Investment of Lao PDR 2016) to estimate the future GDP from 2016 to 2025. Using estimated GDP and estimated RP, DMC could be roughly estimated.

Business as usual scenario (BAU) assumed that RP and DPO will increase as the historical growth trends from 1988 to 2015 as 9% per year, and 8% per year, respectively. Scenario RP50, assumed that RP will improve 50% and DPO will decrease 50% by year 2025 compared to 2015. For the third scenario, Scenario RP20%, it was assumed that the RP will increase 20% and DPO will decrease by 20% within 10 years. From all three scenarios, DMC were calculated as RP divided by calculated GDP.

The results show that in all scenarios, DMC will continuously increase. The forecasted DMC in 2025 is range from 168.5 million tonnes to 290.4 million tonnes (see Figure 1). As proposed in BAU scenario, DPO will be more than doubled in 2025, increase from 40.9 million tonnes to 88.3 million tonnes. In scenario RP 50 and scenario RP 20, the DPO in 2025 will decrease to 20.4 million tonnes and 32.7 million tonnes, respectively. For RP, if Lao PDR will follow the most ambitious target as Japan (scenario RP 50), in 2025 from 1 tonne of materials, it will generate about 70 USD (50% increase). But for Lao PDR, as country have certainly low RP, to increase RP by 20% as proposed in scenario RP20 could be considered as achievable target.

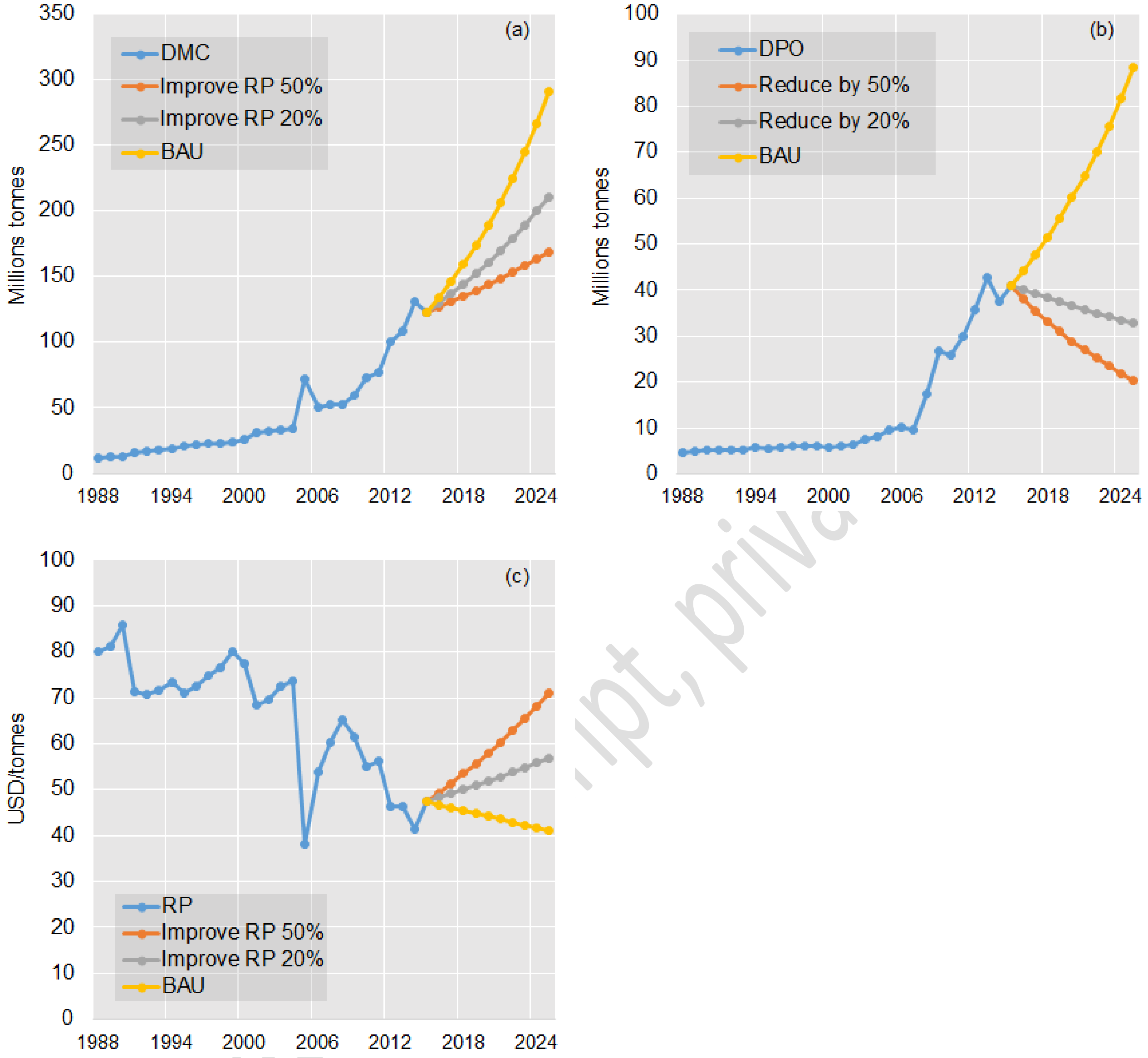

Figure S-2. DMC, DPO, and resource productivity in Lao PDR from 1989 to 2015 and results from scenarios for 2016-2025

References

Babel, S. and X. Vilaysouk. 2015. Greenhouse gas emissions from municipal solid waste management in Vientiane, Lao PDR. *Waste Management & Research*.

Babel, S. and X. Vilaysouk. 2016. Greenhouse gas emissions from municipal solid waste management in Vientiane, Lao PDR. *Waste Management & Research* 34(1): 30-37.

Bringezu, S. 1993. Towards increasing resource productivity: How to measure the total material consumption of regional or national economies. *Fresenius Environmental Bulletin* 2(8): 437–442.

Chen, X. and L. Qiao. 2001. A Preliminary Material Input Analysis of China. *Population and Environment* 23(1): 117-126.

Department of Agriculture and Fisheries: The State of Queensland 2017. Manure production data. https://www.daf.qld.gov.au/environment/intensive-livestock/cattle-feedlots/managing-environmental-impacts/manure-production-data. Accessed 18 May 2017.

European Commission. 2017. Resource Efficiency Scoreboard. http://ec.europa.eu/environment/resource_efficiency/targets_indicators/scoreboard/index_en.htm. Accessed 10 July 2017.

European Commission. 2016. Emission Database for Global Atmospheric Research (EDGAR). http://edgar.jrc.ec.europa.eu/overview.php?v=CO2ts1990-2015. Accessed 28 April 2017.

Eurostat. 2001. *Economy-wide Material Flow Accounts and derived indicators: A methodological guide*. Luxembourg: Eurostat.

Eurostat. 2016. *Economy-wide Material Flow Accounts: Manual 2016 Draft version (13 September 2016) on DPO and Balancing items*. Luxembourg: Eurostat.

Griggs, D., M. Stafford-Smith, O. Gaffney, J. Rockstrom, M. C. Ohman, P. Shyamsundar, W. Steffen, G. Glaser, N. Kanie, and I. Noble. 2013. Sustainable development goals for people and planet. *Nature* 495(7441): 305-307.

Hatfield-Dodds, S., H. Schandl, D. Newth, M. Obersteiner, Y. Cai, T. Baynes, J. West, and P. Havlik. 2017. Assessing global resource use and greenhouse emissions to 2050, with ambitious resource efficiency and climate mitigation policies. *Journal of Cleaner Production* 144: 403-414.

Huang, H., J. Bi, X. Li, B. Zhang, and J. Yang. 2008. Material flow analysis (MFA) of an eco-economic system: a case study of Wujin District, Changzhou, China. *Frontiers of Biology in China* 3(3): 367-374.

Japan Environment Agency. 1992. Quality of the environment in Japan 1992. Tokyo: Japan Environment Association.

Khanal, B. R. and B. Souksavath. 2005. Environmental management measures and current practices in solid waste management: A case study from Vientiane, Lao PDR. *Journal of Greater Mekong Subregion Development Studies* 2: 69-89.

Koide, R., C. Tokoro, S. Murakami, T. Adachi, and A. Takahashi. 2012. A Model for Prediction of Neutralizer Usage and Sludge Generation in the Treatment of Acid Mine Drainage from Abandoned Mines: Case Studies in Japan. *Mine Water and the Environment* 31(4): 287-296.

Kovanda, J., T. Hak, and J. Janacek. 2008. Economy-wide material flow indicators in the Czech Republic: trends, decoupling analysis and uncertainties. *International Journal of Environment and Pollution* 35(1): 25-41.

Krausmann, F., D. Wiedenhofer, C. Lauk, W. Haas, H. Tanikawa, T. Fishman, A. Miatto, H. Schandl, and H. Haberl. 2017. Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. *Proceedings of the National Academy of Sciences* 114(8): 1880-1885.

Laner, D., H. Rechberger, and T. Astrup. 2014. Systematic Evaluation of Uncertainty in Material Flow Analysis. *Journal of Industrial Ecology* 18(6): 859-870.

Laner, D., H. Rechberger, and T. Astrup. 2015. Applying Fuzzy and Probabilistic Uncertainty Concepts to the Material Flow Analysis of Palladium in Austria. *Journal of Industrial Ecology* 19(6): 1055-1069.

Laner, D., J. Feketitsch, H. Rechberger, and J. Fellner. 2016. A Novel Approach to Characterize Data Uncertainty in Material Flow Analysis and its Application ato Plastics Flows in Austria. *Journal of Industrial Ecology* 20(5): 1050-1063.

Lao Statistics Bureau. 2015. Lao Population and Housing Census 2015: Provisional Report. Vientiane, Lao PDR: Lao Statistics Bureau.

Li, M., H. Zhang, Z. Li, and L. Tong. 2010. Economy-wide material input/output and dematerialization analysis of Jilin Province (China). *Environmental Monitoring and Assessment* 165: 263-274.

Martinico-Perez, M. F. G., T. Fishman, K. Okuoka, and H. Tanikawa. 2017. Material Flow Accounts and Driving Factors of Economic Growth in the Philippines. *Journal of Industrial Ecology* 21(5): 1226-1236.

Mathews, J. A. and H. Tan. 2016. Circular economy: Lessons from China. *Nature* 531(7595): 440-442.

Matthews, E., C. Amann, S. Bringezu, M. Fischer-Kowalski, W. Hüttler, R. Kleijn, Y. Moriguchi, C. Ottke, E. Rodenburg, and D. Rogich. 2000. *The weight of nations*.

Maung, K., M. Martinico-Perez, T. Komatsu, S. Mohammad, S. Murakami, and H. Tanikawa. 2015. Comparative studies on the driving factors of resource flows in Myanmar, the Philippines, and Bangladesh. *Environmental Economics and Policy Studies* 17(3): 407-429.

Miatto, A., H. Schandl, T. Fishman, and H. Tanikawa. 2017. Global Patterns and Trends for Non-Metallic Minerals used for Construction. *Journal of Industrial Ecology* 21(4): 924-937.

Ministry of Agriculture and Forestry of Lao PDR. 2015a. Technical Standard for National Livestocks Balancing, edited by Department of Livestock and Fisheries. Vientiane, Lao PDR.

Ministry of Agriculture and Forestry of Lao PDR. 2015b. Agriculture statistics 1976-2015, edited by Department of Planning and Cooperation. Vientiane, Lao PDR.

Ministry of Energy and Mines of Lao PDR. 2015. Minerals Productions in Lao PDR 1985-2015, edited by Department of Mines. Vientiane, Lao PDR.

Ministry of Industry and Commerce of Lao PDR. 2015a. Imports and Exports of Lao PDR 2010-2015, edited by Department of Planning and Cooperation. Vientiane, Lao PDR.

Ministry of Industry and Commerce of Lao PDR. 2015b. Industrial Processing Statistics 1985-2015, edited by Department of Planning and Cooperation. Vientiane, Lao PDR.

Ministry of Natural Resources and Environment of Lao PDR. 2000. The first national communication on climate change submitted to the United Nations Framework Convention on Climate Change. Vientiane, Lao PDR.

Ministry of Natural Resources and Environment of Lao PDR. 2013. The second national communication on climate change submitted to the United Nations Framework Convention on Climate Change. Vientiane, Lao PDR.

Ministry of Natural Resources and Environment of Lao PDR. 2015. Ministerial Instruction for Pollution control. Vientiane.

Ministry of Planning and Investment of Lao PDR. 2016. 8th Five-Years National Socio-Economic Development Plan (2016-2020). Vientiane, Lao PDR.

Monemany, N., S. Virany, K. Khampadith, C. Majella, K. Souphaxay, and B. Somvang. 2012. Lao Environmental Outlook 2012: Ministry of Natural Resources and Environment of Lao PDR.

Ngoc, U. N. and H. Schnitzer. 2009. Sustainable solutions for solid waste management in Southeast Asian countries. *Waste Management* 29(6): 1982-1995.

Patrício, J., Y. Kalmykova, L. Rosado, and V. Lisovskaja. 2015. Uncertainty in Material Flow Analysis Indicators at Different Spatial Levels. *Journal of Industrial Ecology* 19(5): 837-852.

Raupova, O., H. Kamahara, and N. Goto. 2014. Assessment of physical economy through economy-wide material flow analysis in developing Uzbekistan. *Resources, Conservation and Recycling* 89: 76-85.

Rechberger, H., O. Cencic, and R. Frühwirth. 2014. Uncertainty in Material Flow Analysis. *Journal of Industrial Ecology* 18(2): 159-160.

Russi, D., A. C. Gonzalez-Martinez, J. C. Silva-Macher, S. Giljum, J. Martínez-Alier, and M. C. Vallejo. 2008. Material Flows in Latin America. *Journal of Industrial Ecology* 12(5-6): 704-720.

Sang-Arun, J. and K. Pasomsouk. 2012. *A guide for improving municipal solid waste management and promoting urban organic waste utilization in Lao PDR*. Kanagawa, Japan: Institute for Global Environmental Strategies (IGES); Faculty of Engineering, National University of Laos.

Schandl, H. and J. West. 2010. Resource use and resource efficiency in the Asia-Pacific region. *Global Environmental Change-Human and Policy Dimensions* 20(4): 636-647.

Schandl, H., M. Fischer-Kowalski, J. West, S. Giljum, M. Dittrich, N. Eisenmenger, A. Geschke, M. Lieber, H. Wieland, A. Schaffartzik, F. Krausmann, S. Gierlinger, K. Hosking, M. Lenzen, H. Tanikawa, A. Miatto, and T. Fishman. 2017. Global Material Flows and Resource Productivity: Forty Years of Evidence. *Journal of Industrial Ecology*: n/a-n/a.

SNL. 2017. S&P Global Market Intelligence Databse. https://www.snl.com. Accessed 16 May 2017.

Somsak Kethongsa. 2005. Country Report: Lao People's Democratic Republic. Paper presented at Proceedings Asia Regional Workshop on the Implementation, Monitoring and Observance of the International Code of Conduct on the Distribution and Use of Pesticides, 26 - 28 July, Bangkok.

Steurer, A. 1992. *Stoffstrombilanz Österreich 1988 [Material flow balance for Austria 1988]*. Vienna , Austria: IFF Social Ecology.

Takiguchi, H. and K. Takemoto. 2008. Japanese 3R Policies Based on Material Flow Analysis. *Journal of Industrial Ecology* 12(5-6): 792-798.

UN Environment. 2017. UN Environment Live Database. http://www.uneplive.org/country/data/LA. Accessed 01 April 2017.

UNEP. 2011. *Decoupling natural resource use and environmental impacts from economic growth*. Nairobi: United Nations Environment Programme.

UNEP. 2013. *Capacity Building and Policy Needs Assessment for Sustainable Consumption and Production*. Bangkok: United Nations Environment Programme.

UNEP. 2016. *Global Material Flows and Resource Productivity. An Assessment Study of the UNEP International Resource Panel*. Paris: United Nations Environment Programme.

UNSD. 2017. UNSD Statistical Databases. https://unstats.un.org/unsd/databases.htm. Accessed 01 April 2017.

Vilaysouk, X. and S. Babel. 2017. Benefits of improved municipal solid waste management on greenhouse gas reduction in Luangprabang, Laos. *Environmental Technology*: 1-9.

Vilaysouk, X., H. Schandl, and S. Murakami. 2017. Improving the knowledge base on material flow analysis for Asian developing countries: A case study of Lao PDR. *Resources, Conservation and Recycling* 127: 179-189.

Wang, H., S. Hashimoto, Y. Moriguchi, Q. Yue, and Z. Lu. 2012. Resource Use in Growing China. *Journal of Industrial Ecology* 16(4): 481-492.

Xu, M. and T. Zhang. 2007. Material Flows and Economic Growth in Developing China. *Journal of Industrial Ecology* 11(1): 121-140.