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LIME2

Life-cycle Impact assessment Method based on Endpoint modeling

Summary

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Summary

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Summary

S1 Introduction

The National Institute of Advanced Industrial Science and Technology's Research Center for Life Cycle Assessment repeatedly examined the development of methods for life cycle impact assessment (LCIA) in cooperation with the research group on the impact assessment of the LCA Project (first term: 1998-2003[*1]; second term: 2003-2006[*2]) and developed a Japanese life-cycle impact assessment method based on endpoint modeling (LIME). This book is the updated version of LIME1, one of the fruits of the first-term LCA Project, and explains the methodology for LIME2, which was developed for the second-term LCA Project.

S2 Social backgrounds

When the LCA Project began in 1998, research on LCIA was divided according to characterization, whereby potential impact levels on specific impact categories, such as global warming and human toxicity, are assessed and integration of various environmental impacts for gaining a single index. The main traditional integration method theme oriented method is a method based on midpoint modeling whereby impact categories are weighted directly from the result of characterization to gain a single index. However, a problem was pointed out concerning the theme oriented method: transparency and reliability were considerably insufficient because the method compared ten or more impact categories simultaneously almost without showing information on how much environmental impact actually arose.

Moreover, the usefulness of the assessment method based on endpoint modeling, which minimizes the number of items for weighting and carries out integration by comparison of the items through assessment of damage to human health and biodiversity at the endpoint level, has been recognized internationally. Although many of the latest methods for LCIA (Eco-indicator 99, EPS, ExternE) are based on endpoint modeling, Japan was required to develop its own LCIA method based on endpoint modeling, because even if inventory is the same, the amount of damage differs depending on environmental conditions (such as weather and population density).

LIME1, which was developed in the first-term LCA Project, was published in 2005 as a method that was developed in Japan and reflected the environmental conditions in Japan and the most advanced methods in the field of environmental science (Itsubo et al., 2005). After that, LIME was used in various ways, mainly by domestic companies (see Chapter I. Summary of LIME2). The National Institute of Advanced Industrial Science and Technology's Research Center for Life Cycle

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[*1] Official title: Development of Assessment Technology of Life Cycle Environment Impacts of Products and so forth; New Energy and Industrial Technology Development Organization, commissioned to the Japan Environmental Management Association for Industry

[*2] Official title: Development of Technology to Assess and Verify Life. Cycle CO_2 Emissions/Development of Methods for Assessment of Impact and Other Environmental Influences; New Energy and Industrial Technology Development Organization, commissioned to the National Institute of Advanced Industrial Science and Technology

Assessment established the LCIA Special Research Unit jointly with Nikkei BP. The LCIA special research group has so far given technical guidance to 20 companies concerning LCA by the use of LIME and the assessment of environmental performance. Nagano Prefecture has been using LIME to support environmental management by small and midsize companies. The use of LIME1 has already spread widely both in the industrial world and the academic world. LIME1 has been used in more than 200 case studies.

Through the accumulation of such case studies, some points to be improved were clarified concerning the assessment method. Of them, priority will be given to the solution of socially important research issues, and the results will be arranged and published as LIME2.

S3 Structure of LIME2 and policy for development of the method

Figure S.1 below shows the concept map of LIME2. The assessment of environmental impact under this method consists of the following steps.

1) Analyze changes in the density of the air, water, and other environmental media due to emergence of an environmentally damaging substance (fate analysis).

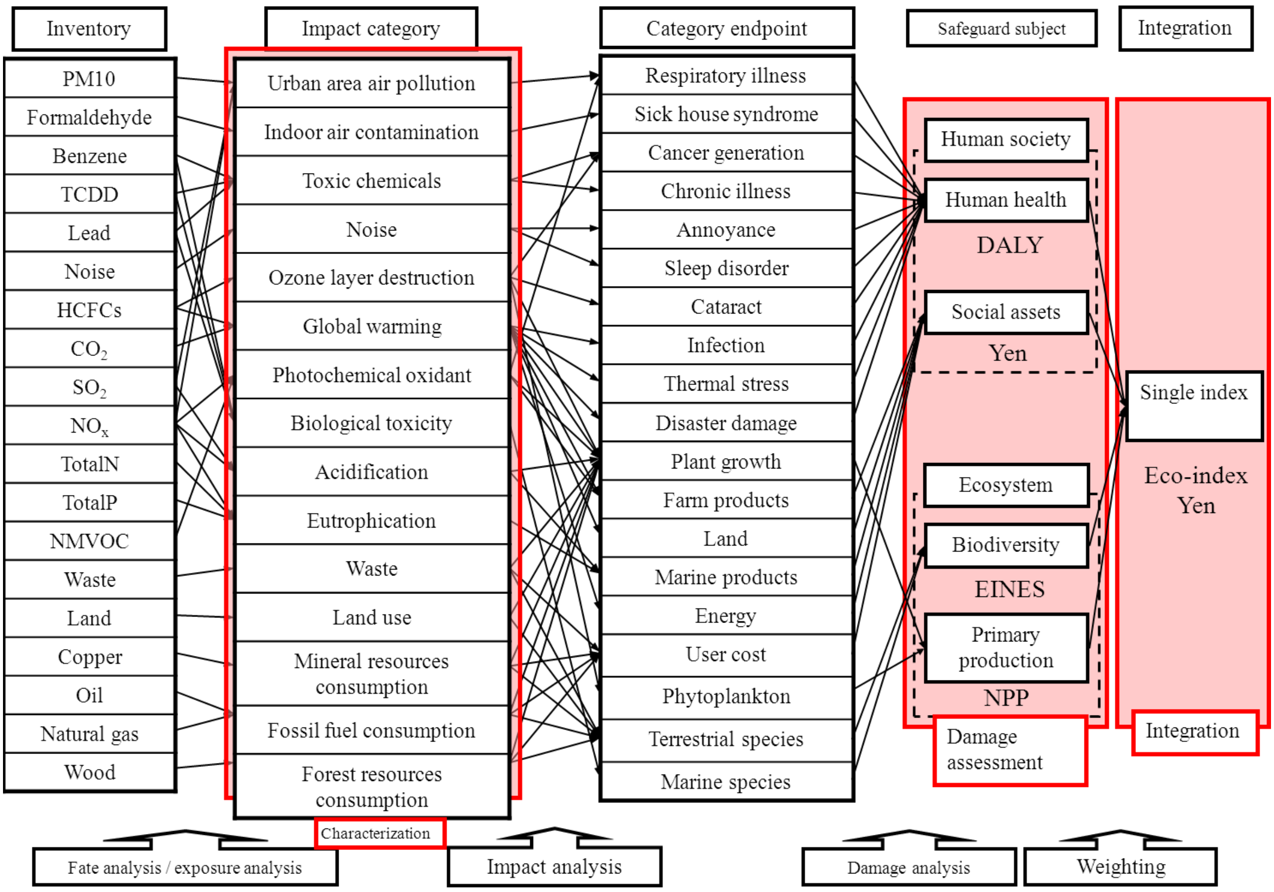


Figure S.1: Concept map of LIME2 and the range of objects of assessment

The result of assessment of environmental impact can be gained concerning characterization, damage assessment, and integration.

2) Analyze changes in the extent of exposure of human beings and other receptors

due to changes in the density of an environmentally damaging substance in environmental media (exposure analysis).

3) Assess changes in the potential impact level of the receptor due to changes in the extent of exposure by type of damage (impact analysis).

4) Total the amount of damage for each common endpoint (for example, human health) (damage analysis).

5) Last, derive an index for integration of environmental impact by applying importance among the endpoints (integration).

To assess the amount of damage arising by environmental burden, and to integrate environmental impact by knowledge of natural science, such as epidemiology, ecology, mathematical biology, toxicology, meteorology, and landscape architecture, among the endpoints, assess environmental impact by the use of social science analysis, such as economics, sociology, and psychology.

Although so far impact assessment methods have been developed mainly by LCA researchers, it was hard to say that the latest research results in the above-mentioned fields were reflected fully and comprehensively.

Therefore, when LIME was developed, several committees were established with consideration for differences in specialized fields, and the most reliable theory was adopted in each category, which made it possible to develop a cross-field and systematic assessment method. Under (1) the Impact Assessment Committee (parent committee) consisting of LCIA researchers, two subcommittees were established: (2) the Damage Function Subcommittee consisting of experts in natural sciences, such as atmospheric environment, soil science, and ecology, and (3) the Economic Assessment Subcommittee consisting of environmental economists. The three research groups proceeded with discussions to develop methods. The parent committee took charge of the development of the framework of LIME and characterization factors, the Damage Function Subcommittee the development of damage assessment methods, and the Economic Assessment Subcommittee the development of weighting factors. Under this organizational system, researches were promoted, which made it possible to effectively introduce into the LCIA field the most advanced theories in each field.

S4 Main fruits and their characteristics

From the viewpoint of the social dissemination of LIME, it is natural to improve the methodology of LCIA. However, at the same time, it is necessary to take into consideration the ease of use of LCA. Under the LCIA method, assessment has been so far made through sum of products of inventory data and corresponding assessment factors for LCIA. If software for LCIA calculation is developed, and LCIA can be carried out by simulation, it might be possible to improve the reliability of LCA. At this time, however, priority was placed on the prevention of damage to the convenience of implementation of LCIA, and the final goal was to provide a list of LCIA assessment factors for each environmentally damaging substance based on the results of the simulation that the developers carried out beforehand by the use of the model they developed for environmental impact assessment. This enables the practitioner to carry out LCIA by linear computation of assessment factors from the list of LCIA factors and inventory. Figure S.2 summarizes the relation between the method developer's tasks and the method practitioner's tasks.

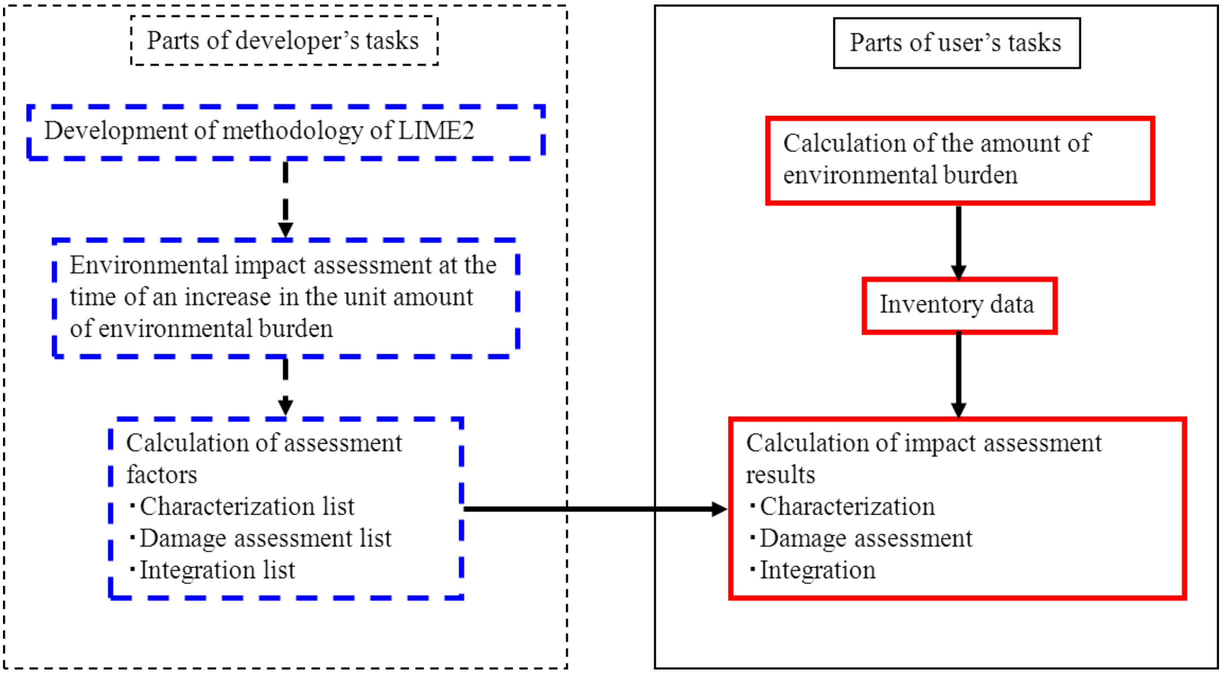


Figure S.2: The method developer's tasks and the method practitioner's tasks

The method developer's final products shown in this figure can be expressed by the following three lists of factors:

1) List of characterization factors
2) List of damage factors
3) List of integration factors [*3]

These three lists enable the LCA practitioner to achieve various purposes. Of the three lists, the practitioner can choose a list most suitable for the purposes and use it for impact assessment. Table S.1 shows the characteristics of each list.

In this way, in order to develop impact assessment factors that have different characteristics, this research has adopted the approach described below.

(i) Characterization and the list of characterization factors

Characterization is a step where potential environmental impact is assessed for each impact category. It is possible to compare or integrate two or more environmentally damaging substances' impact on specific environmental problems. Because judgment is unlikely to be subjective, the reliability of the factors is high, and the International Organization for Standardization (ISO) regards characterization as a

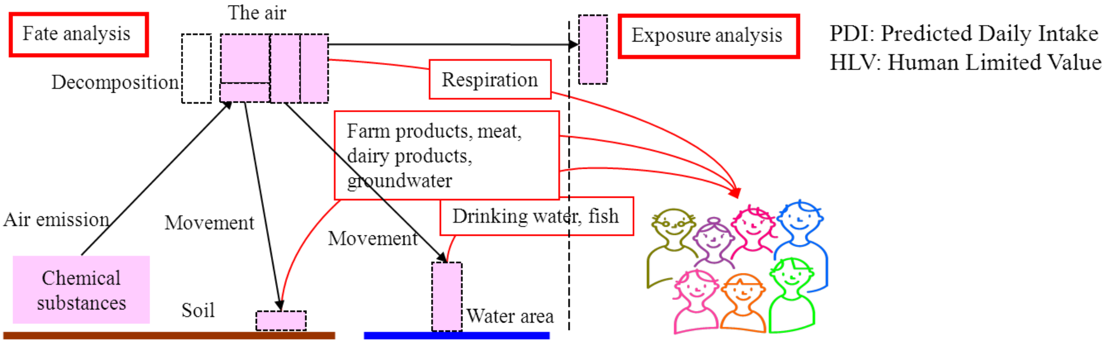
[*3] In LIME2, integration factors are differentiated from weighting factors, which weight the Safeguard subject.

mandatory element for LCIA. Because characterization often does not aim to seek the amount of damage, assessment is usually carried out at an intermediate point of time between the occurrence of environmental burden, such as emission, and the actual occurrence of environmental impact. The point of time of assessment differs according to impact category. As an example, Figure S.3 shows the flow of calculation of characterization factors for toxic chemicals.

Table S.1: Characteristics of the three lists disclosed in LIME2

	List of characterization factors	List of damage factors	List of integration factors
Basic academic fields	Environmental science in general (natural science)	Epidemiology, insurance statistics, landscape architecture, mathematical biology, toxicology, etc. (natural science)	Environmental economics, inferential statistics, computational psychology (social science)
Object of assessment	Each impact category	Each endpoint	Whole environment
Number of result items	15 items	4 items	Single index
Meaning and dimension of assessment result	Equivalent quantum of reference substance (example: in the case of global warming, CO_2 eq. kg, which indicates the equivalent amount (kg) of CO_2 of the greenhouse effect of 1 kg of a substance)	Amount of damage (example: in the case of human health, how many years of life are lost by the burden of 1 kg of a substance)	External cost (example: the equivalent social cost of the burden of 1 kg of a substance)
Relation with ISO 14040, 14044	Mandatory element	Optional element (the step of damage assessment has still not been defined in ISO)	Optional element
Reliability	Relatively high. Based on knowledge of natural science	Moderation between characterization and integration. Largely based on knowledge of natural science	Based on social preference
Comprehensiveness of target substance	About 1,000	About 1,000	About 1,000
Main purpose of use	LCA	LCA	LCA, corporate evaluation, environmental efficiency, full-cost evaluation, cost-benefit analysis
Advantages	•Highly reliable •Essential for ISO-LCA	•Possible to be put together into four items based on knowledge of natural science	•Possible to derive a single index •No trade-off occurs •Wide range of application
Disadvantages	There are many items of assessment results.	International discussions are immature. Uncertainty is said to be relatively high.	Introduction of value judgment is unavoidable.

$$HTP_{i,ecomp} = \frac{\sum_{r} PDI_{i,ecomp,r} / HLV_{i,r}}{\sum_{r} PDI_{benzene,air,r} / HLV_{benzene,r}}$$



Substance	Object of assessment (cancer generation or chronic toxicity)	Human limited value	Air emission			Water emission			Soil emission		
		HLV	PDI_a	PDI_a/HLV	HTP_a	PDI_w	PDI_w/HLV	HTP_w	PDI_s	PDI_s/HLV	HTP_s
Cadmium	Cancer generation	1.9e-7	3.1e-11	1.7e-4	3.8e+3	6.2e-11	3.4e-4	7.5e+3	8.2e-11	4.4e-4	9.8e+3
Benzene	Cancer generation	3.5e-5	1.6e-12	4.5e-8	1.0e+0	2.0e-11	5.8e-7	1.3e+1	3.6e-13	1.0e-8	2.3e-1
Acetaldehyde'	Cancer generation	1.6e-5	6.3e-13	3.9e-8	8.7e-1	1.2e-11	7.4e-7	1.6e+1	4.1e-14	2.5e-9	5.6e-2

Figure S.3: Concept of calculation of characterization factors (toxic chemicals)

Generally, when the harmfulness of a chemical substance is assessed, consideration is often given to two aspects – exposure efficiency and the degree of toxicity. The ratio of exposure efficiency and threshold level is used herein. That is, as the amount of exposure becomes higher and as the threshold level becomes lower, the toxicity of a substance is stronger. The methods used for assessment of exposure efficiency are fate analysis and exposure analysis. After a pollutant is emitted into the environment, human beings and the ecosystem are exposed to the pollutant after it moves through or between media, such as the air and water. The efficiency from emission to exposure is calculated by fate analysis and exposure analysis. Meanwhile, enormous information on threshold levels can be used from existing databases on chemical substances. After such calculation and data collection are performed for each substance, the characterization factors of various substances can be gained by calculating how many times the ratio of the substance subject to assessment is higher than the ratio of the reference substance.

The research to develop characterization factors began in the first half of the 1990s. This research is the most advanced among the LCIA researches, and results of the research have been used frequently. Because of this, when characterization factors were developed, after the arrangement of previous case studies, characterization factors most recommendable to LCA users in Japan were selected. Table S.2 summarizes the recommendable characterization factors and their characteristics. As shown in the table, a referential substance exists for assessment result, which indicates how many times the environmental burden of the unit quantity of another substance is larger than that of the referential substance. CO_2 and CFC-11 have been adopted as the referential substances for global warming and ozone layer destruction, respectively.

Table S.2: Characterization factors recommended in LIME2 and their characteristics

Impact category	Recommended characterization factor	Unit for assessment result	Content assessed by characterization method
Ozone layer destruction	ODP	CFC-11eq. kg	Ozone layer destruction capacity
Global warming	GWP	CO_2 eq. kg	Infrared radiation power
Acidification	DAP	SO_2 eq. kg	Quantity of protons with consideration for deposition
Urban area air pollution	UAF	SO_2 eq. kg	Reflection of weather conditions in each region in Japan
Photochemical oxidant	OECF	C_2H_4 eq. kg	Reflection of weather conditions in each region in Japan
Toxic chemicals	HTP cancer	C_6H_6 air eq. kg	Hazard ratio of carcinogenic substance
	HTP chronic disease	C_6H_6 air eq. kg	Hazard ratio of chronic illness
Biological toxicity	AETP	C_6H_6 water eq. kg	Toxicity to aquatic creatures
	TETP	C_6H_6 soil eq. kg	Toxicity to terrestrial creatures
Eutrophication	EPMC	PO_4^{3-}eq. kg	Consumption of dissolved oxygen
Indoor air contamination	TVOC	TVOCkg	Predicted intake and daily human limit value
Land use	LOF	m^3.yr	Area and period of land possession
	LTF	m^2	Area of rearranged land
Consumption of resources (mineral resources, fossil fuels, biological resources)	Consumption energy	MJ	Heat value
	1/R	Sbeq.kg	Reciprocal of recoverable reserves
Waste	WPF	m^3	Ratio of volume to area of disposal site
Noise	NPF	J/no. of vehicles. km	Energy of sound source

One characterization factor was recommended for each impact category. The following are main ways of thinking about the recommendation of characterization factors.

With regard to global environmental categories, such as global warming, ozone layer destruction, and resource consumption, because international organizations have already published general-purpose characterization factors, recommendable factors were selected from among such factors after the clarification of differences among factors.

With regard to regional environmental categories, such as acidification, eutrophication, urban area air pollution, photochemical oxidant, toxic chemicals, biological toxicity, and land use, it is necessary to use characterization factors that reflect the environmental conditions in Japan. In this research, original characterization factors were gained from the results of simulation based on the geographical conditions in Japan, and a recommendable list was selected by comparison of the results with previous case studies.

With regard to waste, although only a few international organizations have established waste as an impact category, waste is of high concern as an environmental problem in Japan. Therefore, for the purpose of LIME, waste was adopted as an impact category, and the factor that converts the volume of waste into landfill volume was newly added as a characterization factor.

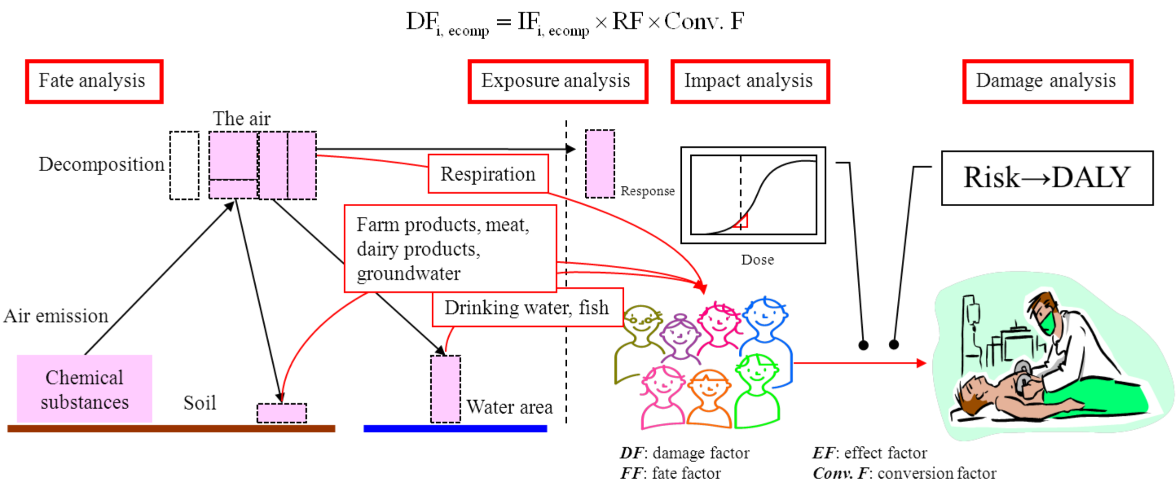
For the purpose of LIME2, indoor air contamination and noise were newly added as impact categories. With regard to noise, the characterization factor that uses energy quantity was adopted. Meanwhile, indoor air contamination was calculated based on the ratio of exposure efficiency and the daily human limited value, referring to the characterization factors of toxic chemicals. The Ministry of Health, Labour and Welfare's guideline value was adopted as the daily human limited value.

(ii) Damage assessment and the list of damage factors

Damage assessment is the step of assessing the amount of damage that can occur for each object of protection. Although it is one of the LCIA research areas that have been drawing most attention, it is a category that has few agreement items. In the development of LIME, examination was first made to define endpoints for calculation of the amount of damage, referring to discussions from the viewpoint of environmental ethics, and four items were defined as objects of protection; "human health," "social assets," "biodiversity," and "primary production." Next, damage indexes were defined to indicate the amount of damage to them from environmental changes. The Disability Adjusted Life Year (DALY), which is internationally used for health statistics, was defined as the damage index for human health. What was defined as the damage index for social assets was an economic index (in Japanese) that can comprehensively measure the impact on various components (agricultural products, forests, marine products, and resources). What was defined as that for biodiversity was the EINES that was originally defined based on the methodology of extinction risk assessment in the field of conservation ecology. Net primary production (NPP), which is widely used as an index for the richness of the ecosystem in the fields of biology and landscape architecture, was defined as the damage index for primary production.

Figure S.4 shows the flow of calculation of damage factor. The assessment of toxic chemicals is taken as an example. This figure uses the result of fate and exposure analysis gain from the calculation of characterization factors. This constructs a more consistent assessment system. In the damage assessment procedure, first an increase in the risk of illness according to an increase in the amount of exposure is analyzed. The increase in the risk is multiplied by the target population to calculate the expected number of sick persons. After that, the number is converted into Disability Adjusted Life Years (DALY). In the same way, when damage assessment is conducted for another impact category, expression of environmental impacts in the same dimension enables comparison of environmental impacts in different categories and rational integration of them.

That is, when damage factors are developed, it is necessary to quantitatively connect the occurrence of environmental burden with the amount of damage to the object of protection. When inventory was connected with the amount of damage, damage factors were established through quantitative connection of the steps up to the damage based on knowledge of natural science and integration of them (see Figure S.5).



Substance	Air emission			Water emission			Soil emission		
	Cancer generation	Chronic illness	DF	Cancer generation	Chronic illness	DF	Cancer generation	Chronic illness	DF
Cadmium	2.4e-04	2.2e-02	2.2e-02	0.0e+00	9.2e-02	9.2e-02	0.0e+00	5.0e-02	5.0e-02
Benzene	6.3e-07	6.0e-08	6.9e-07	1.9e-05	1.5e-03	1.5e-03	1.7e-07	3.0e-06	3.2e-06
Acetaldehyde	6.6e-08	-	6.6e-08	1.5e-08	-	1.5e-08	2.5e-09	-	2.5e-09

Figure S.4: Concept of calculation of damage factors (toxic chemicals; example: human health)
The figures in the table show amounts of health damage and damage factors when 1 kg of a substance is emitted.

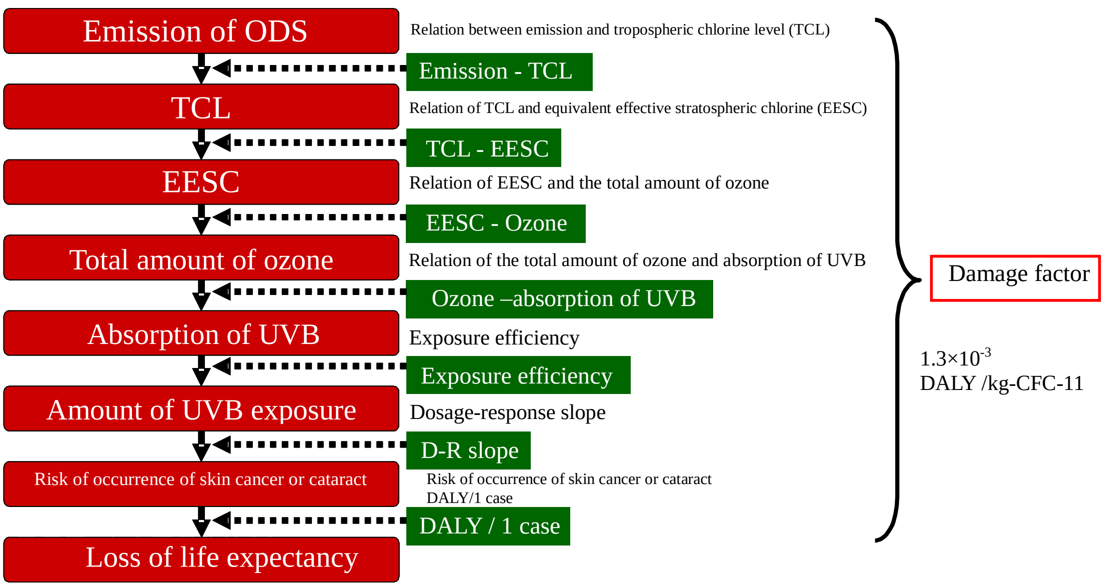


Figure S.5: Flow of calculation of damage factor

Draw a process from the inventory (in this case, ODS: Ozone Depletion Substance), which ranges from the occurrence of ODS to the quantitative connection of health damage and the aggregation of damage amounts, to the Disability Adjusted Life Year and connect the steps quantitatively based on results of environmental science research (e.g. Dose-Response relationship). The integration of them makes it possible to gain the damage factor.

In LIME, such examination was carried out in relation to all the environmentally damaging substances we dealt with. Table S.3 summarizes the category endpoints for the items for which the amount of damage was calculated in LIME. The plain parts in the figure indicate the category end points included in LIME. For example, health impacts that occur through global warming include malaria, dengue fever, and disaster. The lightly shaded parts indicate categories where impact is small or the necessity for consideration is low. On the other hand, the heavily shaded parts indicate categories where impact may be large, but assessment was not carried out during this research because calculation was difficult from the viewpoint of the latest knowledge in the respective fields. Therefore, it can be said that the development of assessment methods for such categories is a problem to be solved in the future. In this way, although it is impossible to assess all environmental impacts at present, we endeavored to secure the transparency of the scope of assessment by distinguishing the categories where the amount of damage can be measured by the current knowledge in natural science from the categories where it is difficult to do so.

Table S.3: List of category end points where the amount of damage was assessed in LIME

Column: area of protection and damage index Row: impact category	Human health DALY	Social assets Yen	Biodiversity EINES	Primary production NPP
Ozone layer destruction	*Skin cancer* *Cataract*	*Agri. production* *Wood production*		*Terrestrial ecosystem* *Aquarium ecosystem*
Global warming	**Heat stress / cold stress, malaria, dengue, disaster damage, malnutrition, hunger**	**Agri. production** **Energy consumption** **Land disappearance**		
Acidification	(Assessment in urban area air pollution)	**Wood production** **Fishery production**		**Terrestrial ecosystem**
Urban are air pollution	**Respiratory illness (12 types)**			
Photochemical oxidant	*Respiratory illness (6 types)*	*Agri. production* *Wood production*		*Terrestrial ecosystem*
Toxic chemicals (Human toxieity)	**Cancer generation (8parts), <u>Chronic Illness</u>**		(Assessment in biological toxicity)	
Biological toxicity	(Assessment in toxic substances)		**Terrestrial ecosystem** **Aquarium ecosystem**	
Eutrophication		*Fishery production*		
Indoor air pollution	**<u>* Sick House Syndrome</u>**			
Land use			**Terrestrial ecosystem**	**Terrestrial ecosystem**
Resources consumption (mineral resources, fossil fuels, living resources)		**User cost**	**Terrestrial ecosystem**	**Terrestrial ecosystem**
Waste	(Assessment of toxic waste in toxic substances, biological toxicity)	**<u>* User cost</u>**	**Terrestrial ecosystem**	**Terrestrial ecosystem**
Noise	**<u>* Sleep disorder, *Conversation disorder</u>**			

The plain parts are categories where the amount of damage was assessed. The lightly shaded parts are categories where the amount of damage is inferred to be small. The heavily shaded parts are categories where the assessment of the amount of damage is inferred to be important but assessment is difficult at present. The items with * are items newly added for LIME2. The items in **bold** face are items modified during LIME2. The *italicized* items are items cited from LIME1.

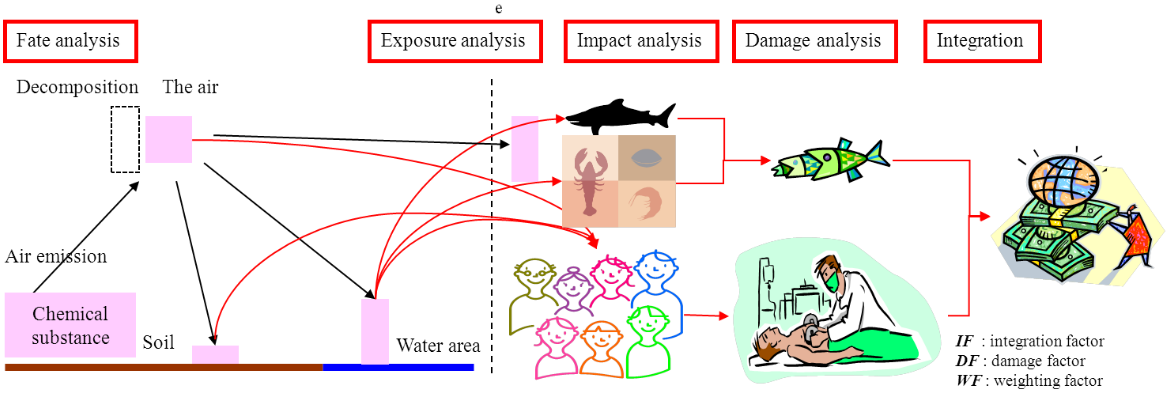
Because the development of damage factors uses more models and parameters than the development of characterization factors, there is fear that uncertainty might increase. During development of LIME2, with regard to especially important impact categories, we analyzed the uncertainty of damage factors and considered improving the uncertainty. The damage factors derived from the results of this research were reviewed by outsiders, and we considered improving the reliability as much as possible by making many improvements.

(iii) Integration and the list of integration factors

As a result of damage assessment, results of assessment of the four items to be protected can be obtained. The procedure for deriving a single index through weighing of these items is called integration. Although the integration of environmental impacts (amounts of damage) has been mainly used for LCIA so far, it has begun to be used frequently for environmental accounting, environmental efficiency, and environmental performance assessment.

Figure S.6 shows the procedure for calculating integration factors in the case of toxic chemicals. The result of damage assessment is used for the relations from the occurrence of environmental burden to the occurrence of damage to the receptor. If the environmental burden of a substance has effect on two or more endpoints, it is possible to make a single index by weighting the area of protection.

$$IF_{i,\,ecomp} = \sum_{e} \left(DF_{i,\,ecomp} \times WF_e \right)$$



Substance	Air emission					Water emission					Soil emission				
	Damage factor		Economic valuation		IF	Damage factor		Economic valuation		IF	Damage factor		Economic valuation		IF
	HH	BD	HH	BD		HH	BD	HH	BD		HH	BD	HH	BD	
Cadomium	2.2e-2	7.9e-8	2.2e+5	3.8e+5	6.0e+5	9.2e-2	2.6e-7	9.0e+5	1.2e+6	2.1e+6	5.0e-2	1.2e-7	4.9e+5	5.9e+5	1.1e+6
Benzene	6.9e-7	6.1e-13	6.7e+0	2.9e+0	9.6e+0	1.5e-3	7.5e-9	1.5e+4	3.6e+4	5.1e+4	3.2e-6	1.3e-11	3.1e+1	6.3e+1	9.3e+1
Formaldehyde	6.6e-8	7.5e-13	6.4e-1	3.6e+0	4.2e+0	1.5e-8	3.3e-10	1.5e-1	1.6e+3	1.6e+3	2.5e-9	5.0e-13	2.4e-2	2.4e+0	2.4e+0

Figure S.6: Concept of calculation of integration factors (toxic chemicals, Biological toxicity)
The figures in the table indicate the amount of damage when 1 kg of each substance is emitted, and the integration factor derived through monetary conversion.

In LIME1 and LIME2, we adopted conjoint analysis for weighting the area of protection. Conjoint analysis makes it possible to calculate the weight of the attributes (such as emissions and the highest speed) of the objects of assessment (such as an automobile) from results of a questionnaire survey of inhabitants and others. In the field of environmental economics, conjoint analysis has been drawing attention as the most advanced method for measuring the effectiveness of the elements of the environment (such as the biodiversity and recreation effect of a tideland). However, there has been no case of using conjoint analysis for LCIA. We conducted a questionnaire survey of Japanese people's opinions about environmental policy, gained weighting factors for the objects of protection through statistical analysis of the survey result, and calculated integration factors by multiplying the damage factors by the result.

To derive a weighting factor that can be used for general purposes, it is necessary to check that the analysis result is statistically significant. For this purpose, respondents are required to fully understand the contents of questionnaires. Because survey contents are comparatively difficult, it is important to send questionnaires that respondents can answer without misunderstanding. This survey was conducted after several pretests were carried out to check that the respondents could fully understand the contents. Placing importance on the establishment of a weighting factor that represents the Japanese people's views about the environment, we randomly selected respondents from throughout Japan and visited 1,000 respondents to interview them. This enabled sampling that is not slanted in terms of family structure, sex, age, or annual income. Although there are other survey methods, such as the use of telephone or the Internet, the interview survey method facilitates the understanding of questionnaires and is least likely to contain survey bias.

The results were good in both statistical significance and the explanation power of the logit model used for analysis, were high in social consensus, and made it possible to develop an integration factor that can be used for general purposes. In addition, LIME2 used the random parameter logit model and succeeded in quantitatively measuring changes in the weighing factor, with the result that the integration factor could be calculated with consideration for difference in subjective value. Table S.4 shows differences between LIME1 and LIME2 in the procedure for calculating the integration factor.

Table S.4: Main differences between LIME1 and LIME2 in the integration method

	LIME1	LIME2
Number of samples collected	400	1,000 (collection rate: 48%)
Survey method	Central location interviews	Visiting interviews
Survey area	Kanto	Nationwide
Weighting factor	Representative value	Representative value and amount of statistics
Statistical significance	Already verified	Already verified

S5 Comparison with overseas research cases

Various organizations have already developed or proposed LCIA methods. These methods can be divided into those covering the steps up to characterization and damage assessment and those covering the steps up to integration. The latter are divided into theme oriented methods and damage oriented methods. Table S.5 shows main LCIA methods proposed so far.

Table S.5: Main LCIA methods and their characteristics

Method	Country of development	Year of development/ renewal	Object of assessment			Remarks
			Characteri -zation	Damage assessment	Integration	
CML	Holland	2002 renewal	○			
EDIP	Denmark	2003 renewal	○			
TRACI	US	2003	○			
Eco-scarcity	Switzerland	2007 renewal			○	Midpoint modeling
JEPIX	Japan	2003			○	Midpoint modeling
Ecoindicator'95	Holland	1995			○	Midpoint modeling
Ecoindicator'99	Holland	2000		○	○	Endpoint modeling
EPS	Sweden	2000 renewal		○	○	Endpoint modeling
Impact2002	Switzerland	2002	○	○		
ExternE	Europe	2005 renewal			○	Endpoint modeling
LIME2	Japan	2008 renewal	○	○	○	Endpoint modeling

LCIA methods can be classified by steps, such as characterization and integration, and their characteristics differ from each other. To achieve users' various needs, it is desirable for an LCIA method to contain all the steps specified in ISO14044. In addition, because the developer's arbitrariness is high in methods based on midpoint modeling (see 1.2.1 "theme oriented method and damage oriented method"), the methods can be used for damage assessment based on knowledge of natural science and are expected to reduce bias as much as possible by minimizing the number of items to be weighted. However, methods based on endpoint modeling are considered higher-level methods.

Table S.6 shows comparison of the characteristics of LIME2 with other methods based on endpoint modeling (EPS, ExternE, Eco-indicator 99). Although all of them are the same in the framework of assessment, they differ in various points, such as substances to be assessed and impact categories. Especially important differences are described below.

(i) Types of area of protection and damage indexes

What is common is that impact on human health is included in assessment, and loss of life expectancy is used as a damage index. However, although the ecosystem is commonly included in the objects of assessment, the methods greatly differ in what part of the ecosystem should receive attention and how to express damage to the ecosystem. As a damage index, EPS uses the contribution (ratio) to the extinction of species within one year, Eco-indicator 99 uses the ratio of disappeared species (vascular plant species), and LIME uses the expected number of extinct species. That is, while LIME counts the number of species, the other methods use non-dimensional indexes, such as ratio.

The methods also differ in how to consider the impact on human society, such as resources, materials, and agricultural products. LIME has established "social assets" for the objects of protection as a concept comprehensively covering what are treated as valuable things in human society (nonliving resources, agricultural products, marine resources, forest resources). In addition to this, EPS includes cation, which is used as a buffer for soil acidification, and divides the objects of protection into "resources" and "production capacity." Eco-indicator 99 does not

Table S.6: Comparison of characteristics of environmental impact integration methods

<table>
<tr><th>Method</th><th colspan="2">EPS</th><th>ExternE</th><th colspan="2">Eco indicator 99</th><th colspan="2">LIME2</th></tr>
<tr><td>Country of development, year of publication</td><td colspan="2">Sweden (2000 revision)</td><td>EC (2005 revision)</td><td colspan="2">Holland (2000 revision)</td><td colspan="2">Japan (2008)</td></tr>
<tr><td>Endpoint modeling or midpoint modeling</td><td colspan="2">Endpoint modeling</td><td>Endpoint modeling</td><td colspan="2">Endpoint modeling</td><td colspan="2">Endpoint modeling</td></tr>
<tr><td>Environmentally damaging substances considered</td><td colspan="2">250 substances, 5 land use styles</td><td>13</td><td colspan="2">550 substances, 10 land use styles</td><td colspan="2">1,000 substances, 80 land use styles</td></tr>
<tr><td>Assessable steps</td><td colspan="2">Integration</td><td>Integration</td><td colspan="2">Damage assessment, normalization, integration</td><td colspan="2">Characterization, damage assessment, integration</td></tr>
<tr><td>Impact assessment region</td><td colspan="2">Sweden</td><td>Europe</td><td colspan="2">Europe</td><td colspan="2">Japan</td></tr>
<tr><td rowspan="5">Object of protection and damage index</td><td>Human health</td><td>YOLL, etc.</td><td rowspan="5">No definition (Consideration for damage to human health, ecosystem, materials)</td><td>Human health</td><td>DALY</td><td>Human health</td><td>DALY</td></tr>
<tr><td>Biodiversity</td><td>NEX (ratio of species extinct within a year)</td><td>Quality of ecosystem</td><td>PDF (Ratio of extinct species)</td><td>Biodiversity</td><td>EINES (expected increase in the number of extinct species)</td></tr>
<tr><td>Resources</td><td>Amount of money</td><td rowspan="3">Resources</td><td rowspan="3">Excess energy</td><td rowspan="2">Social assets</td><td rowspan="2">Yen</td></tr>
<tr><td>Production capacity</td><td>kg</td></tr>
<tr><td>Sensuousness</td><td>Not measured</td><td>Primary production</td><td>ton</td></tr>
<tr><td>Impact categories</td><td colspan="2">The above five items have been defined as impact categories.</td><td>No definition</td><td colspan="2">Resources, global warming, ozone layer destruction, carcinogenic substances, respiratory disease, biological toxicity, acidification/eutrophication, land use, radiation</td><td colspan="2">Global warming, ozone layer destruction, urban area air pollution, toxic chemicals, biological toxicity, acidification, eutrophication, photochemical oxidant, indoor air contamination, land use, mineral resources consumption, fossil fuels consumption, biological resources consumption, waste, noise</td></tr>
<tr><td>Assessment process</td><td colspan="2">Inventory → category endpoint → single index</td><td>Inventory → category endpoint → single index</td><td colspan="2">Inventory → area of protection → normalization → single index</td><td colspan="2">Inventory → characterization → category endpoint → area of protection → single index</td></tr>
<tr><td>Integration method</td><td colspan="2">With market value: market value
Without market value: citation from CVM</td><td>CVM (document)</td><td colspan="2">Panel method</td><td colspan="2">Conjoint analysis</td></tr>
<tr><td>Unit of single index</td><td colspan="2">Damage cost</td><td>Damage cost</td><td colspan="2">Nondimensional index (3 types: hierarchist, egalitarian, individualist)</td><td colspan="2">Damage cost</td></tr>
<tr><td>Number of samples for integration survey and survey method</td><td colspan="2">Only citation, no field survey</td><td>Unknown</td><td colspan="2">80 persons (collection rate: 20%), mail survey</td><td colspan="2">1,000 households (collection rate: 48%), visiting interview survey</td></tr>
<tr><td>Statistical significance of weighting factor</td><td colspan="2">Unknown</td><td>Unknown</td><td colspan="2">No verification</td><td colspan="2">Already verified</td></tr>
</table>

include agricultural products or marine resources in the objects of protection, but includes “resources,” limited to mineral resources and fossil fuels. ExternE includes construction and other “materials” in the objects of calculation, but has no clear definition of the area of protection.

LIME and EPS include the impact on primary production (plant production) in the objects of calculation, whereas Eco-indicator 99 and ExternE do not include it. In addition, although LIME defines “primary production” as an area of protection, EPS considers it a part of the “production capacity of the ecosystem.” Therefore, the two methods differ in the range of areas of protection.

(ii) Impact categories

Because EPS and ExternE have not defined impact categories such as global warming and ozone layer destruction, direct comparison of the range of impact categories is impossible. However, they are almost the same between the methods. What is different among them is that Eco-indicator 99 includes radiation, whereas LIME2 includes waste, indoor air pollution, and noise.

(iii) Method to indicate the integration result and methodology of weighting

Approaches to integration can be roughly divided into economic assessment methods (ExternE, EPS, LIME2) and a panel method (Eco-indicator 99). The integration result is expressed in amount of money (euro or yen) under the former methods, whereas it is expressed in a non-dimensional index under the latter method. The conjoint analysis adopted for LIME is characterized by the capability to estimate the weighting factor through statistical analysis and verify the significance through examination. LIME2 has devices to minimize bias, such as 1,000 nationwide interviews, and has been verified as statistically significant. In addition, it has a great advantage – disclosure of integration factors that reflect society’s environmental philosophy and can be used for general purposes.

S6 Research challenges to be handled in the future

The following challenges were clarified through the research activities for LIME development. A, B, and C indicate priority of consideration. As shown below, there are still many challenges for LCIA methods, which require continuous examination for the improvement of research level.

- Assessment of environmental impact overseas – especially in Asian countries and developing countries (priority A)
- Establishment of a list of assessment factors for each region concerning regional impact categories (priority B)
- Environmental impact assessment with consideration for the future, analytic assessment with consideration for time series (priority C)
- Application to other environment assessment methods (such as factor and

environmental efficiency and the cost-benefit analysis method) and sustainability assessment methods (such as integration assessment model) (priority B)

- Environmental impact assessment concerning consumption of water resources – especially, quantification of environmental impact of water consumption in developing countries (priority A)

- Clarification of the relation with environmental impact methods for social welfare (priority B)

- Accumulation of case studies and discussions for improvement of methods based on the results (priority A)

- Continuous renewal of assessment methods based on the latest knowledge in each field – especially, updating of assessment models of global warming (priority A)

- Quantification of uncertainty based on data and application models in all impact categories (priority C)

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