

EVALUATION OF ENVIRONMENTAL CARRYING CAPACITY
AND APPLICATION OF THE SUSTAINABILITY TARGET METHOD

by

Chatpet Yossapol

TABLE OF CONTENTS

Chapter	Page
1 INTRODUCTION.....	1
1.1 Introduction.....	1
1.2 Problem Statement.....	2
1.3 Objectives and Scope.....	2
1.4 Scholarly Contributions of This Research.....	3
2 LITERATURE REVIEW.....	4
2.1 Overview.....	4
2.2 Life Cycle Impact Assessment Background.....	4
2.3 Life Cycle Impact Assessment Methods.....	9
2.3.1 Eco-Indicator 95 Distance-to-Target Method.....	9
2.3.2 Eco-Indicator 99 Damage-Oriented Method.....	11
2.3.3 Environmental Priority Strategies.....	14
2.3.4 Environmental Design of Industrial Products.....	16
2.3.5 IMPACT2002+.....	19
2.3.6 Life Cycle Impact Assessment Method Based on Endpoint Modeling.....	20
2.3.7 Summary and Opportunities for Increasing LCIA Sophistication.....	23
2.4 The Sustainability Target Method.....	28
2.4.1 The Development of the STM.....	28
2.4.2 Characteristics of the STM.....	28
2.4.3 The Importance of the Carrying Capacity to the STM.....	29
2.5 Impact Categories and Methodologies for Carrying Capacity Estimates.....	30
2.5.1 Impact Categories.....	30
2.5.2 Survey of Potential Methodologies for Carrying Capacity Estimates.....	33
2.5.3 Summary.....	37
2.6 Summary of Literature Review and Problem Statements.....	38
3 OBJECTIVES AND HYPOTHESES.....	39
3.1 Objectives.....	39
3.2 Hypotheses.....	39
3.3 Basic Principle for Practicality.....	42
3.3 Summary.....	43
4 METHOD.....	44
4.1 Less-is-Better and Only-Above-Threshold.....	44
4.2 Threshold-Oriented Carrying Capacity Evaluation Technique.....	45
4.3 Perception of Carrying Capacity Estimates.....	49
4.4 Economic Carrying Capacity and Natural Burden.....	51
4.5 Temporal and Spatial Variations of Carrying Capacity Estimates.....	51
4.6 Summary.....	54
5 GLOBAL WARMING IMPACT.....	55
5.1 Overview.....	55
5.2 Greenhouse Gas Emission and Mitigation scenarios Carrying.....	56
5.2.1 Greenhouse Gas Emission Scenarios.....	56

TABLE OF CONTENTS

(Continued)

Chapter	Page
5.2.2 Greenhouse Gas Mitigation Scenarios.....	58
5.3 Threshold Level for Carrying Capacity Estimate.....	59
5.4 Carrying Capacity Estimate.....	60
5.5 Summary.....	62
6 STRATOSPHERIC OZONE DEPLETION IMPACT.....	63
6.1 Overview.....	63
6.2 The Montreal Protocol.....	65
6.3 Threshold Level for Carrying Capacity Estimate.....	65
6.4 Carrying Capacity Estimate.....	67
6.5 Summary.....	69
7 ACIDIFICATION IMPACT.....	70
7.1 Overview.....	70
7.2 Acid Deposition Control Policies.....	71
7.2.1 International Policies and the Critical Load Approach.....	71
7.2.2 U.S. Policy.....	74
7.3 Threshold Level for Carrying Capacity Estimate.....	75
7.4 Carrying Capacity Estimate.....	76
7.4.1 Carrying Capacity Estimate.....	76
7.4.2 Region-Specific Carrying Capacities.....	77
7.4.3 Spatial-Distributions of Emissions.....	80
7.5 Summary.....	80
8 EUTROPHICATION IMPACT.....	82
8.1 Overview.....	82
8.2 Threshold Level for Carrying Capacity Estimate.....	84
8.3 Carrying Capacity Estimate.....	86
8.3.1 Carrying Capacity Estimate Using TMDL.....	86
8.3.2 Spatial-Distributions of Emissions.....	89
8.4 Summary.....	90
9 PHOTOCHEMICAL OZONE FORMATION IMPACT.....	92
9.1 Overview.....	92
9.2 Approach.....	94
9.3 Threshold Levels for Carrying Capacity Estimate.....	95
9.4 Photochemical Ozone Modeling.....	96
9.4.1 Photochemical Ozone Model.....	96
9.4.2 Description of Model and Database Used in Carrying Capacity Estimate.....	97
9.5 Carrying Capacity Estimate.....	98
9.5.1 Emission-Concentration Relationship.....	98
9.5.2 Carrying Capacity Estimate.....	101
9.5.3 Characterization of Volatile Organic Compounds.....	107
9.5.4 Natural Burden and Economic Carrying Capacity.....	111

TABLE OF CONTENTS

(Continued)

Chapter	Page
9.5.5 Spatial Distributions of Emissions.....	112
9.6 Summary	112
10 HUMAN TOXICITY IMPACT	114
10.1 Overview.....	114
10.2 Approach	115
10.3 Threshold Levels for Carrying Capacity Estimate.....	116
10.4 Environmental Transport Model.....	120
10.4.1 Environmental Transport Model	120
10.4.2 Description of Model and Database Used in Carrying Capacity Estimate	121
10.5 Carrying Capacity Estimate.....	122
10.5.1 Emission-Concentration Relationship	122
10.5.2 Carrying Capacity Estimate	123
10.5.3 Empirical Approach for Carrying Capacity Estimate	128
10.6 Summary	131
11 ECO-TOXICITY IMPACT	133
11.1 Overview.....	133
11.2 Approach.....	135
11.3 Threshold Levels for Carrying Capacity Estimate	135
11.4 Carrying Capacity Estimate	138
11.5 Summary	142
12 RESOURCE DEPLETION IMPACT.....	143
12.1 Overview.....	143
12.2 Carrying Capacity Estimation for Consumption of Fossil Fuels.....	145
12.3 Carrying Capacity Estimation for Consumption of Minerals.....	147
12.4 Carrying Capacity Estimation for Consumption of Freshwater.....	147
12.5 Summary	151
13 APPLICATION OF CARRYING CAPACITY.....	152
13.1 Overview.....	152
13.2 Case Study I: LCA for Electrical Energy Generation Sources.....	152
13.2.1 LCA for Electrical Energy Generation Sources Using the STM... ..	152
13.2.2 LCA for Electrical Energy Generation Sources Using Other LCIA Methods.....	157
13.2.3 Comparison and Discussion	159
13.3 Case Study II: LCA for Basic Material Productions	165
13.3.1 LCA for Basic Material Productions Using the STM.....	165
13.3.2 LCA for Basic Material Productions Using Other LCIA Methods	167
13.3.3 Comparison and Discussion	167
13.4 Case Study III: LCA for a Household Coffee Maker	173
13.4.1 LCA for a Household Coffee Maker Using the STM.....	173
13.4.2 LCA for Household Coffee Maker Using Other LCIA Methods... ..	179

TABLE OF CONTENTS

(Continued)

Chapter	Page
13.4.3 Comparison and Discussion	179
13.5 Carrying Capacity Estimates for Europe	184
13.5.1 Carrying Capacity Estimates.....	184
13.5.2 Comparison and Discussion	186
13.6 STM Implementation Using the Modified Target Values	190
13.6.1 U.S. Target Values Modified from EI95 Target Values.....	190
13.6.2 STM Implementations Using the Modified Target Values.....	191
13.7 Summary	193
14 SENSITIVITY AND UNCERTAINTY ANALYSIS	195
14.1 Overview.....	195
14.2 Sensitivity Analysis.....	195
14.2.1 One-Way Sensitivity Analysis.....	196
14.2.2 Ratio Sensitivity Analysis.....	201
14.2.3 Summary and Conclusion	203
14.3 Uncertainty Analysis.....	203
14.3.1 Qualitative Uncertainty Analysis.....	204
14.3.2 Summary and Conclusion	208
15 SUMMARY, DISCUSSION, AND CONCLUSIONS.....	210
15.1 Summary and Discussion.....	210
15.1.1 Carrying Capacity Estimates.....	210
15.1.2 Limitations of the Carrying Capacity Estimates	216
15.1.3 Characteristics of the STM	217
15.2 Conclusions.....	219
15.2.1 Evaluation of Environmental Carrying Capacity.....	219
15.2.2 Performance of the STM in Conjunction with the Carrying Capacity Estimates.....	210
15.3 Scholarly Contributions	211
15.4 Recommendations for Further Studies.....	212
APPENDIX A REVIEW OF ENVIRONMENTAL PERFORMANCE FRAMEWORKS AND APPROACHES.....	223
APPENDIX B THE STM METHODOLOGY.....	238
APPENDIX C CHARACTERIZATION FACTORS AND SITE FACTORS.....	242
APPENDIX D REPORTED TMDLs AND LIST OF ONLINE REFERENCES.....	266
APPENDIX E PNECs OF CHEMICALS WITH HIGH PRODUCTION VOLUME.....	278
APPENDIX F UNCERTAINTY ASSESSMENT FOR CARRYING CAPACITY ESTIMATES	283
REFERENCES	288

LIST OF TABLES

Table		Page
2.1	Summary of Weighting Techniques Used in LCIA.....	8
2.2	Importance of Impact Categories as a Percentage and Rank of Total Impact.....	8
2.3	Reduction Factors in Eco-Indicator 95.....	10
2.4	Damage Categories and Impact Categories in Eco-Indicator 99.....	13
2.5	Monetary Weighting Factors in LIME.....	21
2.6	A Comparison of Features of Six LCIA Methods.....	24
2.7	Units for Single-score indicators of Four LCIA Methods.....	25
2.8	Impact Categories Used in Other Studies and Methods.....	32
2.9	Significance of Impact Categories.....	32
2.10	Normalization Values, Reduction Factors, and Target Values EI95.....	36
2.11	EDIP's Carrying Capacity.....	36
2.12	Preliminary U.S. Carrying Capacity Modified from EI95's Target Values...	37
4.1	Summary of Advantages and Disadvantages between the Less-Is-Better Approach and the Only-Above-Threshold Approach.....	45
4.2	Risk Quotient of Sustainability in the STM.....	48
5.1	Description of the IPCC-SRES Emission Scenarios.....	57
5.2	Projected Manmade Greenhouse Gas Emissions and Predicted Temperature and Sea level rise According to IPCC Emission Scenarios.....	57
5.3	Carrying Capacity for Greenhouse Gas Emissions.....	52
6.1	Carrying Capacity for Ozone-Depleting Substance Emissions.....	69
7.1	Estimated Critical Loads for Some U.S. Eastern Lakes.....	73
7.2	Improvement of Water Resource Conditions in Acid-Sensitive Regions	75
7.3	Summary of the Carrying Capacity for Acidification Impact.....	77
7.4	Calculations of Region-Specific Factors and Region-Specific Carrying Capacities for U.S.....	79
7.5	Carrying Capacities for Acidifying Substance Emissions.....	81
8.1	Summary of the Ecoregional Nutrient Criteria.....	85
8.2	Carrying Capacity Estimates at Different Probabilities.....	88
9.1	Equivalence of 8-hour and 1-hour Ozone Design Values.....	100
9.2	Calculations of Critical VOC Emission.....	102
9.3	Calculations of Critical NO _x Emission.....	103
9.4	U.S. Carrying Capacity Estimates for VOC Emission at Different Probabilities.....	107
9.5	U.S. Carrying Capacity Estimates for NO _x Emission at Different Probabilities.....	107
9.6	Calculation of Equivalency Factor for Typical VOC and Ethylene Equivalent.....	110
9.7	U.S. Carrying Capacity for VOC Emission in Terms of C ₂ H ₄ -Equivalent...	111
9.8	U.S. Economic Carrying Capacity for VOC Emission.....	111
9.9	U.S. Economic Carrying Capacity for NO _x Emission.....	111
9.10	Carrying Capacities for Photochemical Ozone formation Impact.....	113
10.1	Summary of the Threshold Levels for 89 Toxic Chemicals.....	118
10.2	Units for Partitioning Factors.....	123
10.3	Partitioning Factors for Air and Water Emissions of 78 Chemicals.....	124

LIST OF TABLES (Continued)

Table	Page
10.4 Summary of Carrying Capacity Estimates for Human Toxicity Impact For 89 Toxic Chemicals.....	126
10.5 Average Partitioning Factors for Empirical Carrying Capacity Estimation...	230
10.6 Summary of the Threshold Levels for Some Chemicals.....	130
10.7 Carrying Capacity Estimate for Some Commonly Emitted Chemicals Using Empirical Approach.....	131
11.1 List of Priority Ecological Entities in Ecosystems.....	136
11.2 Average Partitioning Factors for Empirical Carrying Capacity Estimate....	138
11.3 Carrying Capacity Estimate for Eco-Toxicity Impact.....	139
12.1 Proposed Input-Related Impact Categories.....	143
12.2 Carrying Capacity for Consumption of Fossil Fuels.....	146
12.3 Carrying Capacity for Consumption of Selected Minerals	180
12.4 Annual Water Recharge Rate in Selected Countries	150
12.5 Locally Specific Carrying Capacity for Freshwater Consumption.....	150
13.1 STM Indicators for Electrical Energy Generation Sources	155
13.2 Eco-Indicator 95 Scores for Energy Generation Sources.....	157
13.3 Eco-Indicator 99 Scores for Energy Generation Sources.....	158
13.4 EPS Scores for Energy Generation Sources.....	158
13.5 EDIP Scores for Energy Generation Sources.....	159
13.6 Impact Categories Included in the STM and Other LCIA Implementations..	160
13.7 Primary Contributing Impact to Total Impact for Energy Generation Sources Assessed from the STM and Other LCIA Methods.....	161
13.8 Ranking in Terms of Environmental Performance of Energy Generation Sources Assessed by the STM and Other LCIA Methods.....	164
13.9 Comparison between the Rankings with All Impact Categories And the Rankings with only Five Common Impact Categories.....	164
13.10 STM Indicators for Basic Material Productions	166
13.11 Eco-Indicator 95 Scores for Basic Material Productions.....	168
13.12 Eco-Indicator 99 Scores for Basic Material Productions.....	168
13.13 EPS Scores for Basic Material Productions.....	169
13.14 EDIP Scores for Basic Material Productions.....	169
13.15 Major Contributing Impact to Total Impact for Basic Material Productions Assessed from the STM and Other LCIA Methods.....	170
13.16 Ranking in Terms of Environmental Performance of Basic Material Productions Assessed by the STM and Other LCIA Methods	173
13.17 Comparison between the Rankings with All Impact Categories and the Rankings with only Five Common Impact Categories	173
13.18 Processes In the Household Plastic Coffee Maker.....	174
13.19 Temporal and Spatial Variations of Carrying Capacity and Impact Reference Levels Used in the Evaluation of the Production of Household Coffee Maker.....	175
13.20 Variations in Carrying Capacity Estimates Used in the Third Case Study....	176
13.21 U.S. GDP and GGP.....	176
13.22 STM Indicators for the Production of the Plastic Household Coffee Maker..	176
13.23 Eco-Efficiency for the Production of the Plastic Household Coffee Maker...	177

LIST OF TABLES

(Continued)

Table	Page
13.24 Single-Score Indicators for a Unit of Household Coffee Maker Assessed By the STM and Other LCIA Methods.....	180
13.25 Environmental Impact Contribution Analysis of the Household Coffee Maker Assessed from Different LCIA Methods.....	182
13.26 Environmental Impact Contribution Analysis for Five Common Impact Categories.....	182
13.27 European-Based Carrying Capacities for Photochemical Ozone Formation..	185
13.28 European-Based Carrying Capacity Estimated Using the Technique and Approaches Developed in This Research.....	186
13.29 EDIP's Carrying Capacity.....	187
13.30 Eco-Indicator 95 Target Values.....	188
13.31 Comparison of Some European-Based Carrying Capacity Values Estimated in This Research and the Values in Other Studies.....	188
13.32 U.S. Target Values Modified from EI95 Target Values.....	190
13.33 Comparison of U.S. Target Values Modified from EI95 Target Values and U.S. Carrying Capacity Estimated in This Research.....	191
13.34 Comparison of Key Parameters from the STM Implementations Using the Target Values and the Carrying Capacity for the Case Studies.....	192
14.1 Impacts of a Marginal Change in Carrying Capacity Estimates on the Ranking between Alternatives for the Case Study of Energy Generation Sources.....	202
14.2 Impacts of a Marginal Change in Carrying Capacity Estimates on the Ranking between Alternatives for the Case Study of Basic Material Productions.....	202
14.3 Types and Sources of Uncertainty	205
14.4 Uncertainties Associated with the Carrying Capacity Evaluation for Human Toxicity Impact	207
A.1 Classification of Environmental Performance Indicators	224
A.2 Examples of Environmental Performance Indicators.....	224
A.3 Eco-Efficiency Indicators Proposed by WBCSD.....	227
A.4 Performance Indicators of the GRI	228
A.5 Examples of MPI and OPI	233
A.6 Impact Categories in Footprint Calculations	235
A.7 ISO 14040 Series.....	236
C.1 Global Warming Potentials.....	243
C.2 Ozone Depletion Potentials.....	245
C.3(a) Acidification Potentials.....	248
C.3(b) Site Factors for Characterization of Acidifying Substances	248
C.4(a) Eutrophication Potentials.....	249
C.4(b) Transport Factors for Characterization of Nutrients	249
C.5(a) MIR for VOCs for Ozone Formation Impact.....	250
C.5(b) POCP for VOCs for Ozone Formation Impact	264
C.5(c) Site Factors for Characterization of VOC and NO _x for Ozone Formation Impact.....	265

LIST OF TABLES (Continued)

Table	Page
D.1 Reported TMDLs in the Evaluation of the Critical Loads for Nitrogen and Phosphorus Emissions.....	267
D.2 List of Online Reference for TMDL Reports.....	273
E.1 Summary of PNEC Studied by OECD	279
F.1 Uncertainty Associated with the Carrying Capacity Evaluation for Global Warming Impact	284
F.2 Uncertainty Associated with the Carrying Capacity Evaluation for Stratospheric Ozone Depletion Impact.....	284
F.3 Uncertainty Associated with the Carrying Capacity Evaluation for Acidification Impact	285
F.4 Uncertainty Associated with the Carrying Capacity Evaluation for Eutrophication Impact.....	285
F.5 Uncertainty Associated with the Carrying Capacity Evaluation for Photochemical Ozone Formation Impact.....	286
F.6 Uncertainty Associated with the Carrying Capacity Evaluation for Eco-Toxicity Impact	287
F.7 Uncertainty Associated with the Carrying Capacity Evaluation for Resource Depletion Impact.....	287