A qualitative network model for understanding regional metabolism in the context of Social–Economic–Natural Complex Ecosystem theory

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A B S T R A C T

In Social–Economic–Natural Complex Ecosystem (SENCE) theory, regional metabolism is seen as an integral part of a complex network of interconnected natural, economic and societal subsystems. Analyzing regional metabolism within this network assists observers to understand the concept in a broader context. Some qualitative tools such as simple matrix operations have been adopted to explore such networks but related research is highly fragmented. Here the emphasis is put on a qualitative network model (QNM) that integrates the existing tools into a unified analytical framework. The tools in the QNM are organized into three levels: (1) dominance analysis focuses on how to measure the performance of each component of a network; (2) consistency analysis is used to test whether the interactions between network components are contradictory to the desired development direction for regional metabolism; and (3) sustainability analysis returns three sustainability benchmarks for regional metabolism. With the aid of these tools, QNM can comprehensively explore such networks from multiple perspectives. To test the QNM construct, we conducted a case study on the regional metabolism of bio-fuels from locally grown plant crops, a hotspot in regional environmental research. In the case study we screened key components for inconsistent variables, identified the relationships between components, and rated the sustainability of the regional bio-fuel metabolism system suggested by the model. This study demonstrated that our research approach can inform bio-fuel policy making. The QNM is helpful in the understanding of regional metabolism in the broader context of SENCE theory and may be used to improve regional environmental management and policy-making.

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1. Introduction

Understanding the structures and processes within regional metabolism has frequently been a concern of regional environmental studies, and a series of methods such as material flow analysis, emergy analysis, and environmentally extended input–output models have been developed to quantify metabolic processes (Brunner and Rechberger, 2004; Chen and Chen, 2012; Ulgiati et al., 1994; Wiedmann, 2009). Meanwhile, in the human-dominated biosphere of today, regional metabolic processes are now inevitably affected by the numerous societal, economic, and policy issues in human communities (Crosskurth and Rotmans, 2005; Vitousek et al., 1997; Wang et al., 2011). Thus, relevant human factors should also be included in the quantification and analysis of regional metabolism. Some theories have attempted to systematically integrate human factors into ecological and environmental science, and thus improve our understanding of environmental issues, including regional metabolism (Holling, 2001; Liu et al., 2007; Wang et al., 2011). Social–Economic–Natural Complex Ecosystem (SENCE) analysis is characterized by the integration of human activities and natural ecosystems, and has been widely applied in regional environmental studies in China (Ma and Wang, 1984; Wang et al., 2011). In SENCE theory, regional metabolism is seen as an integral part of a complex network constructed of multiple factors from the domains of nature, economics and society (Gentleman, 2009; Wang et al., 2011). Analyzing regional metabolism within this larger network gives a broader perspective to our understanding of this issue.

Numerous models can be used to analyze such multiple factor networks. There are two distinct tendencies in the mathematical description of these networks. The more popular one is to emphasize the accuracy of description, such as in system simulation and system dynamics models (Jørgensen and Bendoricchio, 2001; Meadows, 2008). However, significant challenges remain because of lack of valid accurate data, contradictory information from different sources, and the enormous amount of modeling work required for understanding (Verghese and Hes, 2007; Vester, 2007; Williams, 2011). For example, quantification is inherently unsuitable for some socio-economic factors involving regional metabolism.

Another modeling strategy is focused on quick system-level information mining rather than on performing excessive work to determine quantitative values for all local factors, and includes a group of qualitative or semi-quantitative methods. Such methods demonstrate strong
robustness, especially when the quantitative models are constrained by certain conditions (Bredeweg et al., 2009; Sale et al., 2002; Zitek et al., 2009). The Qualitative Differential Equation method is mainly used to find common network patterns between seemingly unrelated cases from different sources (Petschel-Held and Lüdeke, 2001; Petschel-Held et al., 1999). For example, in the case of global environmental change it can be used to summarize a common sequence of regional environmental degradation from a large number of local cases (Eisenack and Petschel-Held, 2002).

Another set of qualitative or semi-quantitative methods transforms the network of relevant factors into matrices, and explores the network system using simple matrix operations (Vester, 2007; Vester and Hesler, 1980; Wiek et al., 2008). These methods provide some performance evaluations of factors in the network system through row and column operations, and in an assessment of sustainability through testing whether the revealed network structure is contradictory to the desired direction of system development (Cole et al., 2007; Grosskurth and Rotmans, 2007; Vester, 2007). Compared with other methods, this set of tools has broader application because it is easier to understand and use (Cole et al., 2007; Ulrich, 2005). However, such methods are discussed in a fragmented way in the literature and lack a unified methodological framework, which hinders their application. The present study aims to improve this situation by the application of these models to regional metabolism analysis.

The study focuses on the development of a standardized model that integrates existing tools into a unified analytical framework. In this study, networks, regional metabolism and relevant factors are collectively referred to as qualitative network systems (QNS). In addition to the existing tools discussed in the literature, some new tools are developed to explore QNS more fully and comprehensively. The QNS and associated tools are collectively defined as a qualitative network model (QNM).

In Section 2, the QNM methodology is described, while Section 3 reports on a case study that applies QNM to regional metabolism analysis by focusing on bio-fuels, a hotspot in regional environmental research. Section 4 briefly presents the results of this case study and, finally, the paper discusses the results and concludes on the value of the QNM method in Section 5.

2. Methodology

2.1. Qualitative network systems (QNS)

QNS is a simplified standardized descriptive form for networks constructed from the components of regional metabolism. Normally, there always exists a set of variables for characterizing individual factors (including factors that describe metabolism itself). Here the variables are expressed as $X_i$ $(i = 1, 2, \ldots, n)$, and are linked by directed causal relations. Likewise, $a_{ij}$ is used to represent the impact of variable $X_j$ on $X_i$. Then the directed relations $\{a_{ij}, i, j = 1, 2, \ldots, n\}$ form a relation network described as a Causal Loop diagram. Together, the variable set $\{X_i, i = 1, 2, \ldots, n\}$ and the relation set $\{a_{ij}, i, j = 1, 2, \ldots, n\}$ form an abstract symbol system, i.e., the QNS, as shown in Fig. 1. The QNS contains the main information about the interaction between regional metabolism and other relevant factors, so compiling regional metabolism issues into the form of a standardized QNS facilitates in-depth analysis of this facet of regional environments.

The topological structure of the QNS is a digraph, which can be equivalently expressed in the form of a matrix. The rows and columns of the matrix correspond to all of the variables in order. For example, the matrix element at the intersection of the i-th row and j-th column is the relation $a_{ij}$, whose value is determined based on the strength of the relationship. This forms an impact matrix that is denoted as:

$$A = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix}.$$  \hspace{1cm} (1)
Water security measures. Changes toward the desired direction, it will in protection and bio-energy crop cultivation. Still, it is generally bene relations are the focus of future policy interventions. Some relations are inconsistent and drive this in an undesirable direction. These inconsistent variables indicate abnormal states of regional metabolism and need to be monitored specifically.

2.3.2 Consistency of relations

Here the consistency of relations benchmarks is used to test whether each relation is contradictory to the goal of system development. The system development goal can be denoted as the desired direction of change for all variables \( \{ \text{Sign}(X_i), i = 1, 2, \ldots, n \} \). We took the relation \( a_{ij} \) as an example. \( \text{Sign}(+ \text{ or } -) \) can be denoted as \( \text{Sign}(a_{ij}) \) corresponding to the two variables \( X_i \) and \( X_j \). If \( \text{Sign}(a_{ij}) \) can be represented by the equation \( \text{Sign}(a_{ij}) = \text{Sign}(X_i) \times \text{Sign}(X_j) \), then the relation is consistent; otherwise, the relation is inconsistent. If the value assigned to relation \( a_{ij} \) is taken as the weight, then its consistency can be calculated using the following formula:

\[
CV_j = \text{Sign}(X_j) \times \sum_i a_{ij}.
\]

If \( CV_j < 0 \), the behavior of \( X_j \) is inconsistent and likely to deviate from the desired direction. The inconsistent variables indicate abnormal states of regional metabolism and need to be monitored specifically.

2.4. Sustainability analysis

2.4.1. Behavior sustainability

The behavior of QNS can be interpreted as the total behavior of all variables. When there are more variables showing consistency than inconsistency, then the target system’s behavior will deviate toward the desired direction, meaning that the system will naturally become more sustainable. In addition, the importance of each variable is generally different to that of the other variables. For example, the environmental variables of more public concern, or those associated with serious consequences, should have higher priority than other variables. Here, the weight coefficient \( w_j (j = 1, 2, \ldots, n; w_j > 0 \) and \( \sum_j w_j = 1 \) is introduced to characterize differences in the importance of the variables. For single variable \( X_j \), consistency can be calculated using the formula \( CV_j = \text{Sign}(X_j) \times \sum_i a_{ij} \). Then the behavior sustainability of QNS is calculated as follows:

\[
S_{\text{behavior}} = \frac{\sum_j \text{Sign}(X_j) \times w_j \times a_{ij}}{\sum_j w_j \times |a_{ij}|} = \frac{\sum_j \text{Sign}(X_j) \times w_j \times a_{ij}}{\sum_j w_j \times |a_{ij}|}
\]

where \( S_{\text{behavior}} = [0, 1] \) and \(|\cdot|\) is the absolute value operator.

2.4.2. Structure sustainability

The structure sustainability of QNS can be interpreted as a comprehensive evaluation of the degree of consistency among all relations. When more relations show high consistency, the system will have a stronger internal driving force towards the desired direction, and the system structure is considered to be more sustainable. For the single relation \( a_{ij} \), consistency can be calculated using the following formula:

\[
CR_{ij} = \text{Sign}(X_i) \times \text{Sign}(X_j) \times a_{ij}.
\]

An inconsistency in the relation means that when the active variable changes toward the desired direction, it will influence the passive variable and drive this in an undesirable direction. These inconsistent relations are the focus of future policy interventions. Some relations are bound to be inconsistent, such as a contradiction between habitat protection and bio-energy crop cultivation. Still, it is generally beneficial to alleviate such contradictions by implementing a series of intervention measures.
2.4.3. Integrated sustainability

In some cases further integration of the structure and behavior of the system is needed to obtain more integrated indicators to assess sustainability. Here, we recommend the geometric averaging operator:

\[ S = \sqrt{S_{\text{behavior}} \cdot S_{\text{structure}}}. \]  

It is necessary to point out that the purpose of integrated evaluation is to help model users to understand the overall status of the system more directly rather than to provide a specific solution. The specific solution can be developed in the light of single variables and of relation analysis.

So far we have defined the dominance analysis, consistency analysis, and sustainability analysis tools used to explore QNS, which is a simplified standard description form for networks constructed of the components of regional metabolism and other relevant factors. These tools are listed together in Table 1.

3. The case study

3.1. Case study description

The cultivation, production and consumption of bio-fuel crops are becoming an increasingly important component of regional metabolism (Gasparatos et al., 2013). Bio-fuels are believed to be an effective way of strengthening energy security, reducing greenhouse gas emissions, and promoting rural development (Sexton et al., 2009). Therefore, the bio-fuel industry is supported by policy makers and a number of environmental protection organizations (Koizumi, 2013). However, bio-fuel production requires large plantations of energy crops, which results in a series of regional impacts. If the cultivation of energy crops occupies arable land suitable for food production the original ecosystem structure maybe damaged, and water demand for energy crop cultivation is also not negligible. Numerous studies have indicated that large-scale production of bio-fuels inevitably results in a series of side effects such as irreversible changes in land use, environmental damage, and threats to food security (Börjesson and Tufvesson, 2011; Schaffel and La Rovere, 2010). In short, there are intricate and contradicted interactions between regional metabolism patterns based on bio-fuels and the above factors.

Therefore, in SENCE theory, the regional metabolism of bio-fuels should be seen as an integral part of a larger network consisting of the metabolism pattern itself and other relevant factors. The QNM proposed in this study is suitable for analyzing the interactions between bio-fuels and relevant factors. The results are expected to be helpful for understanding the regional metabolism of bio-fuels in a broader context. A discussion group was organized by the authors and coworkers in an attempt to analyze bio-fuel issues with the aid of the QNM. There were seven members in the discussion group, whose professional backgrounds were in ecology, environmental science, environmental policy, mathematical models and regional planning. The multi-disciplinary background of the discussion group members was beneficial in overcoming errors owing to blind spots in the personal knowledge of the authors.

3.2. Analytical procedures

We selected 10 variables that are most relevant to bio-fuels from the social-economic-natural domains. It is noted that the bio-fuels we mention here refer especially to fuels extracted from local crops, not from other sources (kitchen waste recycling, for example). As a result, factors closely related to energy crop cultivation such as land use change, food security, and water security were fully considered in variable selection. Then, we defined direct interactions among these variables as the relation set. Detailed information on the selected variables and relations is shown in Fig. 2. Additionally, we assumed that the desired direction of change in each variable is based on daily experience (Fig. 2).

Table 1

Analysis tools for exploring qualitative network systems (QNS).

| Type                  | Name                        | Formula                                      |
|-----------------------|-----------------------------|----------------------------------------------|
| Dominance analysis    | Variable activity           | \( A_S = \sum_{i} |a_{ij}| \)                                     |
|                       | Variable passiveness        | \( P_S = \sum_{i} |a_{ij}| \)                                     |
|                       | Variable vitality           | \( P = A_S \cdot P_S \)                                    |
|                       | Variable sensibility        | \( Q = A_S / P_S \)                                    |
| Consistency analysis  | Variable consistency        | \( C_V = \text{Sign}(X_S) \cdot \sum_{j} a_{ij} \)       |
|                       | Relation consistency        | \( C_R = \text{Sign}(X_S) \cdot \text{Sign}(X_B) \cdot \alpha \) |
| Sustainability analysis | Behavior sustainability    | \( S_{\text{behavior}} = \frac{(\sum_{i}c_{ij} \cdot (\sum_{j}a_{ij} + \alpha_{ij}))}{(\sum_{j}a_{ij} + \alpha_{ij})} \) |
|                       | Structure sustainability    | \( S_{\text{structure}} = \frac{(\sum_{i}c_{ij} \cdot \text{Sign}(X_S) \cdot \text{Sign}(X_B) \cdot \alpha_{ij})}{(\sum_{j}a_{ij})} \) |
|                       | Integrated sustainability   | \( S = \sqrt{S_{\text{behavior}} \cdot S_{\text{structure}}} \) |
values less than 1: greenhouse gas mitigation, natural ecosystem integrity, and food security. These results indicated that those three variables have buffering effects on the system.

There are three negative integers in the column for the indicator of variable consistency, $CV$, suggesting that potential changes in these three variables contradict their desired directions (Table 3). These inconsistencies remind users that it is necessary to specifically monitor the dynamic behaviors of the three variables. The last column of Table 3 lists all those relations that show inconsistencies. In all of the 24 relations that are valid in the QNS, six are inconsistent. That is, inconsistent relations account for 25% of the total relations identified. There are four inconsistent relations involving the ninth variable, subsidies and taxes, and indicating that the dynamic of the system as a whole is highly sensitive to the value assigned to this variable. This variable stands for a common policy, and is one of the major avenues for government regulation of the bio-fuel industry. This means that when formulating bio-fuel policy, the government needs to be especially cautious when balancing inconsistent relations, because this may cause the system to deviate from the expected trajectory. The remaining two inconsistent relations are both associated with the first variable, bio-fuel output, again indicating the importance of this variable.

On the basis of consistency analysis, the model returned an overall evaluation result for the QNS of regional bio-fuel metabolism. The behavior sustainability indicator ($S_{behavior}$), structure sustainability indicator ($S_{structure}$), and integrated sustainability indicator ($S$), scored 0.73, 0.64 and 0.68 respectively. These scores show that the sustainability performance of regional bio-fuel metabolism is at an intermediate level.

5. Discussion

The results from the model improved our understanding of regional metabolism in the broader context of SENCE theory. The analysis of the dominance of variables can help users target fewer key factors and untangle some of the social–economic–natural factors involved with regional metabolism. For example, attention should be given to the buffer variables in policy-making to avoid the emergence of unexpected rebound effects. Similarly, the inconsistent variables and their relationships should be carefully investigated, because they imply clues for formulating appropriate intervention policy (Grosskurth and Rotmans, 2007). Taking the impact of bio-fuel output on water security as an example, the inconsistency of this relation could be eliminated by implementing a cautious industrial layout and high-efficiency water-saving technologies (Sexton et al., 2009). Nevertheless, some inconsistent relations cannot be eliminated, though the resulting negative impacts can be reduced to a controllable level by implementing appropriate intervention measures. Furthermore, the sustainability scores can directly show the overall degree of consistency between patterns of regional metabolism and the factors impacting on these. With the aid of QNM, regional metabolism can be further understood in a broader policy context.

Finally, we provide a supplementary discussion on the QNM methodology, including its main advantages and limitations:

Advantages. The QNM provides an alternative method when quantitative methods are constrained by insufficient quantitative data or excessive qualitative information. Because the QNM is based on qualitative theory and systems thinking, it has the inherent ability to integrate diverse information from the natural and social sciences. The structure and results of the model are in a semi-quantitative or qualitative form, and can be easily understood by policy makers. Users can then focus on understanding the object of study rather than the model thus improving efficiency. These advantages make the QNM suitable for adaptive management, which is believed to be the optimal way to manage natural resources and ecosystems (Allen et al., 2011; Martinez et al., 2008; Westgate et al., 2013). The QNM can also provide other benefits such as increased efficiency for policy makers.

Limitations. The QNM also has some limitations. The model assumes the relationship network to be static and assigns it fixed strength values, thereby ignoring the system's dynamic nature. The construction process for the QNS also needs to integrate a large amount of information from different sources. This may cause an additional burden to users without good support tools. Another limitation of the model is that it only performs simple matrix calculations for the first order analysis, and cannot produce dynamic simulations for observing the system’s long-term trends. In addition, a lack of specialized software support tools affects the practical application of the model. In this case study of bio-fuels and regional metabolism, we completed the model calculations manually and by computer and felt slightly inconvenienced. Therefore, QNM is still at a preliminary stage and requires further development.

In summary, the QNM is helpful in improving our understanding of regional metabolism in the broader context of SENCE theory. Our case

### Table 2

Matrix of the qualitative network system (QNS) of regional bio-fuel metabolism.

| Variables                  | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|----------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1. Bio-fuel output         | 1   | 3   | 2   | −2  | −1  |     |     |     |     |     |
| 2. Energy security         |     |     |     |     |     |     |     |     |     |     |
| 3. Land use change         | −1  | −3  | −2  |     |     |     |     |     |     |     |
| 4. Greenhouse gas mitigation|     |     |     |     |     |     |     |     |     |     |
| 5. Water security          | 1   | 1   | 1   |     |     |     |     |     |     |     |
| 6. Natural ecosystem integrity |     |     |     |     |     |     |     |     |     |     |
| 7. Food security           | −1  |     |     |     |     |     |     |     |     |     |
| 8. Rural development       | 1   |     |     |     |     |     |     |     |     |     |
| 9. Subsidies and taxes     |     |     |     |     |     |     |     |     |     |     |
| 10. Production efficiency  | 2   |     |     |     |     |     |     |     |     | −1  |

### Table 3

Dominance and consistency analysis results from the qualitative network system (QNS) of regional bio-fuel metabolism.

| Variables                  | Variable activeness (AS) | Variable passiveness (PS) | Variable vitality (P) | Variable sensibility (Q) | Variable consistency (CV) | Inconsistent relations |
|----------------------------|--------------------------|----------------------------|-----------------------|--------------------------|----------------------------|------------------------|
| 1. Bio-fuel output         | 8                         | 7                          | 56                    | 1.14                     | 7                          | (9, 1)                 |
| 2. Energy security         | 1                         | 1                          | 1                     | 1.00                     | 1                          | (1, 3)                 |
| 3. Land use change         | 6                         | 4                          | 24                    | 1.50                     | −2                         | (1, 5)                 |
| 4. Greenhouse gas mitigation| 2                         | 3                          | 6                     | 0.67                     | 1                          | (9, 8)                 |
| 5. Water security          | 3                         | 2                          | 6                     | 1.50                     | −2                         | (4, 9)                 |
| 6. Natural ecosystem integrity | 2                         | 4                          | 8                     | 0.50                     | −2                         | (9, 10)                |
| 7. Food security           | 2                         | 5                          | 10                    | 0.40                     | 1                          |                        |
| 8. Rural development       | 3                         | 3                          | 9                     | 1.00                     | 3                          |                        |
| 9. Subsidies and taxes     | 6                         | 4                          | 24                    | 1.50                     | 0                          |                        |
| 10. Production efficiency  | 3                         | 3                          | 9                     | 1.00                     | 3                          |                        |

Note: "*" In the last column, (i, j) indicates that relation $a_{ij}$ is inconsistent with the goal of system development; i, j are the serial numbers for the variables in the first column; for instance, (9, 1) indicates the impact of the ninth variable, subsidies and taxes, on the first variable, bio-fuel output.
study showed its potential applicability and advantages in regional environmental management and policy-making.

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References

Allen, C.R., Fontaine, J.J., Pope, K.L., Garretstani, A.S., 2011. Adaptive management for a turbulent future. J. Environ. Manag. 92, 1339–1345.
Börjesson, P., Tufvesson, L.M., 2011. Agricultural crop-based biofuels resource efficiency and environmental performance including direct land use changes. J. Clean. Prod. 19, 108–120.
Bredeweg, B., Linnebank, F., Bouwer, A., Liem, J., 2009. Garp3. Börjesson, P., Tufvesson, L.M., 2011. Agricultural crop-based biofuels resource efficiency and environmental performance including direct land use changes. J. Clean. Prod. 19, 108–120.
Bredeweg, B., Linnebank, F., Bouwer, A., Liem, J., 2009. Garp3 — workbench for qualitative modelling and simulation. Ecol. Inf. 4, 263–281.
Brunner, P.H., Rechberger, H., 2004. Network environ perspective for urban metabolism and carbon emissions: a case study of Vienna, Austria. Environ. Sci. Technol. 46, 4498–4506.
Cole, A., Allen, W., Kilvington, M., Fenemor, A., Bowden, B., 2007. Participatory modelling with an influence matrix and the calculation of whole-of-system sustainability values. Int. J. Life Cycle Assess. 9, 337–338.
Chen, S., Chen, B., 2012. Graph theoretical analysis of qualitative models in sustainability science. Working Papers of 16th Workshop on Qualitative Reasoning, pp. 53–60.
Gasparatos, A., Stromberg, P., Takeuchi, K., 2013. Sustainability impacts of first-generation biofuels. Anim. Front. 3, 12–26.
Gentleman, D.J., 2009. Jacques Buffle: complex insight and environmental solutions. Environ. Sci. Technol. 43, 7165–7169.
Grosskurth, J., Rotmans, J., 2005. The scene model: getting a grip on sustainable development in policy making. Environ. Dev. Sustain. 7, 135–151.
Grosskurth, J., Rotmans, J., 2007. Qualitative system sustainability index: a new type of sustainability indicator. In: Huk, T., Moldan, B., Dahl, A.L. (Eds.), Sustainability Indicators: A Scientific Assessment. Island Press, Washington, USA, pp. 177–187.
Holling, C.S., 2001. Understanding the complexity of economic, ecological, and social systems. Ecosystems 4, 390–405.
Jørgensen, S.E., Bendoricchio, G., 2001. Fundamentals of Ecological Modelling. Access Online via Elsevier.
Koizumi, T., 2013. The Japanese biofuel program — developments and perspectives. J. Clean. Prod. 40, 57–61.
Liu, J., Dietz, T., Carpenter, S.R., Alberti, M., Folke, C., Moran, E., Pell, A.N., Deadman, P., Kratz, T., Lubchenco, J., Ostrom, E., Ouyang, Z., Provencher, W., Redman, C.L., Schneider, S.H., Taylor, W.W., 2007. Complexity of coupled human and natural systems. Science 317, 1513–1516.
Ma, S., Wang, R., 1984. The social-economic-natural complex ecosystem. Acta Ecol. Sin. 4, 1–9 (In Chinese).
Martinez, E., Tadzait, T., Tovar, E., 2008. Participative democracy and local environmental issues. Ecol. Econ. 68, 68–79.
Meadows, D., 2008. Thinking in Systems: A Primer. Chelsea Green Publishing.
Petschel-Held, G., Lüdeke, M.B., 2001. Integration of case studies on global change by means of qualitative differential equations. Integr. Assess. 2, 123–138.
Petschel-Held, G., Block, A., Cassel-Gintz, M., Kropp, J., Lüdeke, M.K.B., Moldenhauer, O., Reusswig, F., Schellnhuber, H.J., 1999. Syndromes of global change: a qualitative modelling approach to assist global environmental management. Environ. Model. Assess. 4, 295–314.
Sale, J.M., Loehle, L., Brazil, K., 2002. Revisiting the quantitative-qualitative debate: implications for mixed-methods research. Qual. Quant. 36, 43–53.
Schaffel, S.B., La Rovere, E.L., 2010. The quest for eco-social efficiency in biofuels production in Brazil. J. Clean. Prod. 18, 1663–1670.
Sexton, S.E., Rajagopal, D., Hochman, G., Zilberman, D.D., Roland-Holst, D., 2009. Biofuel policy must evaluate environmental, food security and energy goals to maximize net benefits. Calif. Agric. 63, 191–198.
Ulgiati, S., Odum, H.T., Bastianoni, S., 1994. Emergy use, environmental loading and sustainability an emergy analysis of Italy. Ecol. Model. 73, 215–268.
Ulrich, W., 2005. Can nature teach us good research practice? A critical look at Frederic Vester’s bio-cybernetic systems approach. J. Res. Pract. 1 (Article R2).
Verghese, K., Hes, D., 2007. Qualitative and quantitative tool development to support environmentally responsible decisions. J. Clean. Prod. 15, 814–818.
Vester, F., 2007. The Art of Interconnected Thinking: Tools and Concepts for a New Approach to Tackling Complexity. MCB Verlag GmbH, Munich, Germany.
Vester, F., Hesler, A.V., 1980. Sensitivity Model. Regionale Planungsgemeinschaft Untermain, Frankfurt am Main, Germany.
Vitousek, P.M., Mooney, H.A., Lubchenco, J., Melillo, J.M., 1997. Human domination of earth’s ecosystems. Science 277, 494–499.
Wang, R., Li, F., Hu, D., Lanny Li, B., 2011. Understanding eco-complexity: social-economic-natural complex ecosystem approach. Ecol. Complex. 8, 15–29.
Westgate, M.J., Likens, G.E., Lindemayer, D.B., 2013. Adaptive management of biological systems: a review. Biol. Conserv. 158, 128–139.
Wiedmann, T., 2009. A review of recent multi-region input–output models used for consumption-based emission and resource accounting. Ecol. Econ. 69, 211–222.
Wiek, A., Lang, D.J., Siegrist, M., 2008. Qualitative system analysis as a means for sustainable governance of emerging technologies: the case of nanotechnology. J. Clean. Prod. 16, 988–999.
Williams, B.K., 2011. Adaptive management of natural resources – framework and issues. J. Environ. Manag. 92, 1346–1353.