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Review

Environmental accounting: In between raw data and information use for management practices

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A B S T R A C T

Scholars in environmental accounting have developed many methods, capable to transform raw environmental and socio-economic data into useful information, both to protect natural ecosystems and to define the most appropriate policy and planning options to meet the existing sustainable development goals. Due to the high number of existing research challenges and needs, Beijing Normal University organized a World Summit on Environmental Accounting and Management on "Designing A Prosperous and Sustainable Future", which was held in Beijing on July 4–6, 2016. The main topic of the conference was the inclusion of system-wide effects into on-site environmental impacts, considering an integrated environmental accounting and management framework. The outcomes of this international summit, partially represented by the papers published in this Special Volume, provide an opportunity to assess the most recent progresses in biophysical and socioeconomic accounting, as well as in modelling the impacts of anthropogenic activities on environmental and socioeconomic systems. This SV includes cutting-edge papers, that focused on promoting the theories, ideas and practices involved in ecological accounting and management. All the works are aimed to develop broader perspectives, which can be applied to ecosystem protection, as well as on planning and policy-making in view of a transition toward more sustainable and equitable societies, as indicated through the Sustainable Development Goals.

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1. Introduction

At the end of 19th Century, the development of several new branches of sciences supported the birth of a new vision of the world. Thermodynamics and statistical mechanics, chemistry (with the year 1860 conference in Karlsruhe) and ecology were among the key emerging disciplines, which enabled the disclosure of new narratives about our planet and the biosphere. Close to the Second World War, interdisciplinary enquiries tried, for the first time, to find deeper connections among chemistry, physics and biology. This is the case of the book "What is life?" by E. Schrodinger (1944). The same attention was given to the intersections between physics and social sciences, as suggested in the posthumous paper, published in year 1942, by the Italian physicist Ettore Majorana (Majorana and Mantegna, 2006). The focus on resources limitation, pollution and the environment developed a few decades later. The publication of "Silent Spring" (Carson, 1962), "Patient Earth" (Harte and Socolow, 1971) and "The limits to Growth" (Meadows et al., 1972) were among the signs of such a shift of attention. Systems ecology views, with the outstanding works by H. T. Odum (1924–2002), created a fertile background for further research, trying to develop a holistic view, in order to integrate the biophysical and socio-economic dimensions of human society. New interdisciplinary integration attempts, which are of interest for environmental accounting, were represented by ecophysics and evolutionary physics. In particular, starting from the 1970s, the study of physical conditions for life stability on planets were studied. In particular, they were developed on the basis of non-equilibrium thermodynamics and quantum mechanics, considering planet-star relations (e.g.: Sertorio, 1991; Sertorio and Renda, 2009). Then, allometric scaling laws for different living species were connected to the stability of different living species, also considering the differences among them, with a specific focus on humans (e.g.: Gorshkov, 1995). The interactions among humans, technologies and the environment, as well as economy, was discussed from a physical perspective (e.g.: Casazza, 2012; Sertorio and Renda, 2018), as well as from a socio-ecological perspective (e.g.: Odum, 2007; Singh et al., 2012; Lockie et al., 2014; Park and Guille-Escuret, 2017). Finally, the ecosystem dynamics was rediscussed, introducing the use of goal functions (also called orientors) instead of state functions (Tiezzi, 2006).

Three main facts are evident: Since the 1950s, humans have been the main cause of global environmental transformation, crossing the existing planetary boundaries, which constitute a safe space for humanity (Steffen et al., 2015); Biophysical and socio-economical processes cannot be understood and described separately, due to their mutual influences; Maintaining a "business-as-usual" style, ecosystem services and the biosphere will continue to decline (Crutzen and Stoermer, 2000; Crutzen, 2002; Palmer et al., 2004; Steffen et al., 2007; Lewis and Maslin, 2015; Drutschinin et al., 2015). Consequently, evidence-based policies and actions should be adequately developed.

The present situation stimulated a growing convergence between Earth systems analysis (Schellnhuber et al., 2004) and sustainability scientists (Kates et al., 2001). In parallel, the quest for solutions stimulated the development of cleaner productions, circular economy, as well as newly emerging disciplines, like biomimicry. However, despite the huge amount of work already done, Folke et al. (2011) argued that it would be necessary to further integrate natural and social dimensions through new perspectives. Any narrative in this context requires a knowledge, which is generated by the elaboration of quantitative and qualitative field data. This is why socio-economic systems dynamics should be supported, first, by statistically reliable data, that can be used in numerical simulation, as well as for supporting appropriate decision making options.

In between data and narrative, which transform data into useful information, environmental accounting plays a crucial role. Broadly paralleling anatomy and physiology, environmental accounting can unveil the structures and functions of processes and society at different levels. This is why the word 'metabolism', which unveils the co-existence of concept assumes the multi-dimensional nature of accounting process, is often used (Lomas and Giampietro, 2017). Many different approaches, with respect to environmental accounting and management, came into light since the 1990s. They often developed as separate methods, having different conceptualizations behind them.

Environmental accounting conceptualizations and narratives are not separate. This is why, for example, in the case of LCA, the system characteristics, as well as impact categories, accounting methods, data quality requirements and report phase are defined during the scoping phase (EU-JRC, 2010). This is particularly true in the case of sustainability, where different interpretations co-exist (Patterson et al., 2017). In particular, ecological interpretations (e.g.: Grimm et al., 2005; Schlüer et al., 2014; Rounsevell et al., 2012) evolved from the idea of steady state (now disputed), to thresholds (as in the case of planetary boundaries) and carrying capacity, showing the connections of ecological and socio-economic processes, which are embedded in a global bio-physical system. In parallel, economic interpretations (e.g.: Coscieme et al., 2013; Filatova et al., 2013; Hinkel et al., 2014) tried to modify the vision of environmental costs as externalities with respect to economic activities. This allows to approach to the principle of intergenerational equity, integrating economic well-being with the preservation of the environment. Thermodynamic and ecological-economic interpretations (e.g.: Jørgensen et al., 2016; Wallace, 2016) described the socio-ecological dynamics on the basis of existing bio-physical constrains and on the use of statistical mechanics and thermodynamic language. The role of citizens, policymakers and experts was discussed, considering the necessity of integrating all the existing views for developing sustainable public policies (Bäckstrand, 2003; Barr, 2016). In parallel, environmental accounting techniques were developed to include spatial representation of biophysical flows and resources use to identify appropriate planning options (e.g.: Zhang et al., 2007; Pulselli, 2010; Borriello, 2013).

The importance, in environmental accounting practices, of having a shared methodological and conceptual framework is a known fact. However, some limitations are still relevant in the development of accounting methods and practices. In particular: The links between local and global levels are often missed; Information flows are often neglected, even if they contribute to shaping the behavior of bio-system at all scales, is usually neglected (Young et al., 2006; Brown and Ulgiati, 2010; Pretty, 2011; UN-FCCC, 2015; Nielsen, 2016). Consequently, environmental accounting and management tools need to address these challenges: (1) use a multicriteria, multiscale, multipurpose framework, capable to integrate hierarchies, as well as the local and global visions; (2) adapt an assessed metrological approach for environmental accounting purposes; (3) integrate information into metabolic dynamics.

Beijing Normal University organized a World Summit on Environmental Accounting and Management, which was held in Beijing on July 4–6, 2016, on “Designing A Prosperous and Sustainable Future”. The main purpose was to discuss about the integration of system-wide effects into on-site environmental impacts, within the framework of environmental accounting and management. This international summit aimed to provide an opportunity to academic and decision-making professionals to discuss recent progress in biophysical and socioeconomic accounting as well as in modelling the impacts of anthropogenic activities on environmental and socioeconomic systems). Among the outcomes, this Special Volume (SV) of the Journal of Cleaner Production (JCLP) is now published.

This paper has the purpose of giving a framework to the collected results, which include cutting-edge papers focused on promoting the theories, ideas and practices involved in ecological accounting and management. Moreover, results are discussed to identify the future challenges, which will support a better integration of the process, which starts from field data collection and develops into useful narratives for accelerating the transition to sustainable (and socially equitable) post fossil-carbon societies.

2. Objectives of this special volume

Table 1 lists the Environmental Accounting and Management methods, which are proposed in this SV, in terms of four criteria: (1) the method's Purpose, (2) Key concepts; (3) Analytical methods used for measuring indirect effects; (4) Corresponding papers. Each of them will be presented later in this work using these and other criteria. In particular, the main findings will be defined, showing the research topics, that need urgent attention in near future.

3. Present knowledge and challenges for environmental accounting

The global scientific production on environmental accounting, limitedly to research and review papers, counts up to 371 works, according to Web of Science (WOS), starting from year 1991, and

Table 1
Structure of SV and comparison of the environmental accounting and management methods.

Environmental Accounting and Management Methods	Method's Purpose	Key Concepts	Analytical Methods Used for Measuring Indirect Effects	Corresponding Papers
Environmental flow analysis	Environmental flow accounting and identify the main influencing factor	Flow analysis; node analysis	Flow diagrams depict and quantify flows of environmental factors	Zheng et al. (2017); Song et al. (2017); Liu et al. (2017); Hou et al. (2017);; Yan et al. (2017); Yin et al. (2018); Chang et al. (2017); Yin et al. (2018)
Emergy Analysis	Holistic appreciation of the Sustainability of Coupled Economic and Ecological systems	Emergy, Transformity, Maximum Power Principle	Flow diagrams depict and quantify flows of energy, mass and information in systems. From these data, ‘indirect’ emergy inputs are calculated in the transformity metric.	Huang et al. (2017); Corcelli et al. (2017); Yang et al. (2017); Zhang et al. (2017a); Spagnolo et al. (2018); Zhao et al. (2017)
Energy Analysis/ Exergy Analysis	Quantifies Direct and Indirect Energy Inputs of Economic Production	Embodied Energy, Net Energy, Embodied Exergy	Two main methods: (1) Process Method, (2) Input- Output Analysis	Yang and Shi (2017); Aghbashlo et al. (2018); Han et al. (2018); Munguia et al. (2017); Zhang et al. (2017b); Lun et al. (2017)
Carbon Footprinting	Quantifies the Effects of Human Activity on Global Warming	Global Warming Equivalents	Two approaches: (1) Mainly Process Method, (2) Some Input- Output Analysis	Wang and Lin (2017); Tang et al. (2017); Zhang et al. (2017c)
Ecological Network Analysis	Environmental Consequences (resources used, pollutants produced) of Economic Production	Ecological Network Analysis; Structure Analysis; Utility Analysis	Ecological Multiplier (eg, direct and indirect water per $ output of a sector)	Qiao et al. (2017); Su et al. (2017); Zhang et al. (2018a, b)
Life Cycle Assessment	Environmental Consequences of making a product	“Cradle-to-Grave” Environmental impact	Two approaches: (1) Mainly ‘Process Method’, (2) Some use of the ‘Hybrid Method’ that combines the Process Method with I-O Analysis	Chang et al. (2017); Yao et al. (2018); Yang et al. (2018)
Environmental Inventory Analysis	Environmental Inventory establishment	Two approaches: (1) Mainly Process Method, (2) Some Input- Output Analysis	Standards defined by the Global Footprint Network	Li et al. (2017a, b, c); Fei et al. (2017); Yin and Xu (2018); Guo et al. (2017); Zhang et al. (2018c); Jiao et al. (2017); Tang et al. (2017)
Multi-criteria Optimization and Management	Resolve problems of system uncertainties and difficulties of trade-offs between the system economy as well as system stability	Interval stochastic chance-constrained robust programming	Simulate the spatial distribution and temporal change of pollution	Chifari et al. (2017); Wang et al. (2017); Li et al. (2017); Qiu et al. (2017).; Ding et al. (2017a); Xu et al. (2018); He et al. (2018); Ding et al. (2017b); Wang et al. (2018); Zhang et al. (2018d); Cai et al. (2018)

Table 2
Top 15 WOS categories and Sc subject areas, adding also the number of papers associated to each category or subject area.

WOS Category	Paper count (WOS)	Scopus subject area	Paper count (Scopus)
Environmental Sciences	161	Business, Management and Accounting	372
Environmental Studies	84	Environmental Science	356
Ecology	77	Economics, Econometrics and Finance	243
Economics	67	Social Sciences	211
Engineering Environmental	65	Energy	89
Business Finance	60	Engineering	86
Green Sustainable Science Technology	59	Agricultural and Biological Sciences	73
Management	26	Decision Sciences	68
Business	21	Earth and Planetary Sciences	33
Energy Fuels	12	Arts and Humanities	11
Biodiversity Conservation	11	Medicine	11
Ethics	9	Chemical Engineering	9
Planning Development	8	Biochemistry, Genetics and Molecular Biology	8
Forestry	7	Mathematics	5
Agriculture Multidisciplinary	5	Chemistry	4

781 works, according to Scopus (Sc), going back to year 1976. Table 2 displays the top 15 WOS categories and Sc subject areas, including also the number of papers associated to each category or subject area.

Table 3 illustrates the top 15 source titles according to WOS and Sc, together with the number of papers published in each journal. Finally, Table 4 lists the top 15 Countries, whose Authors published a work in the field of environmental accounting, combined with the number of published papers associated to each listed Country. Data are given both from WOS and Sc.

Contrasting to the statement by Russell et al. (2017), who declared that “there is little or no environment in environmental accounting, and certainly no ecology”, environmental studies, environmental sciences and ecology represent the three top categories of published papers in environmental accounting. The areas of “Business, Management and Accounting”, as well as “Social sciences” should be added too, according to Scopus classification. USA, Italy and England represent the three top producing Countries in this field. Top journal titles include: Journal of Cleaner Production; Ecological Economics; Ecological Modelling; Social and Environmental Accountability Journal.

The integration of biophysical and socioeconomic variables across different accounting methods represents one of the major challenges for the future of this discipline. In year 2014, The System of Environmental-Economic Accounting (SEEA) (seea.un.org) Central Framework (European Commission, Organisation for Economic Co-operation and Development, United Nations and World Bank, 2014) was published for the first time. Using SEEA as a starting point, Banerjee et al. (2016) suggested to include its use into economic Computable General Equilibrium (CGE) models, indicating implicitly, in the last part of their work, some important factors in the application of any accounting method: the need of enhanced analytical power; the need of avoiding strong assumption in the integration of economic-environmental inputs; need of timeliness in developing appropriate advices for evidence-based policies.

This is not the only case of integration between the two

Table 4
Top 15 Countries, whose Authors published a paper about environmental accounting. Authors' Countries are ranked against the number of published papers according to WOS and Sc.

Authors' Countriy	Paper count (WOS)	Authors' Countriy	Paper count (Scopus)
USA	88	USA	148
Italy	66	England	123
England	39	Italy	94
Australia	36	Australia	93
Germany	24	Spain	46
Spain	24	Brazil	37
Brazil	21	New Zealand	34
Peoples R China	21	Canada	31
Canada	20	Peoples R China	30
New Zealand	17	Germany	29
Scotland	16	France	18
Netherlands	15	Netherlands	18
Sweden	12	Japan	17
France	11	South Africa	17
Norway	11	Sweden	17

Table 3
Top 15 source titles according to WOS and Sc, and number of papers published in each journal.

Journal	Paper count (WOS)	Journal	Paper count (Scopus)
Journal of Cleaner Production	37	Social and Environmental Accountability Journal	54
Ecological Economics	34	Ecological Economics	38
Ecological Modelling	27	Journal of Cleaner Production	38
Accounting Auditing Accountability Journal	20	Critical Perspectives on Accounting	30
Journal of Industrial Ecology	10	Accounting Auditing and Accountability Journal	27
Critical Perspectives on Accounting	9	Ecological Modelling	26
Ecological Indicators	9	Accounting Forum	19
Environmental Resource Economics	9	Accounting Auditing Accountability Journal	12
Accounting Organizations and Society	8	Business Strategy and The Environment	12
Journal of Business Ethics	8	Sustainability Accounting Management and Policy Journal	12
Journal of Environmental Management	8	Ecological Indicators	11
Sustainability Accounting Management and Policy Journal	8	Environmental and Resource Economics	11
Environmental Management	6	Journal of Industrial Ecology	11
Sustainability	5	Accounting Organizations and Society	9
Agriculture Ecosystems Environment	4	Journal of Environmental Accounting and Management	9

dimensions of human socio-ecological systems (here, 'human' is specified, since socio-ecology also focuses on other social animals and, particularly, primates). In fact, paralleling Life Cycle Assessment (LCA), Social Life Cycle Assessment (S-LCA) focuses on the social dimension of sustainability. S-LCA has been developed since 2004 with the aim to integrate social criteria into LCA.

With respect to other approaches, H.T. Odum and followers were able to develop an accounting approach, known under the name of "emergy accounting", which uses a unified metrological approach (the use of solar equivalent joules, [sej]) to quantify both biophysical and socio-economic variables. Moreover, an updated version of emergy datasets at Country level, known as National Environmental Accounting Database (NEAD), is now available online (www.emergy-nead.com/home). The improvements contained in NEAD version 2 are described through a paper by Pan et al. (2017). Quite interestingly, WOS detects 938 papers (research or reviews, starting from 1991) about emergy, while Scopus records (starting earlier, in 1960), are 1161. However, adding "environmental accounting", as well as the connector "AND", to see how many papers about emergy were classified as environmental accounting papers, only 95 (WOS) (i.e.: 10%) and 89 (Scopus) papers (i.e.: 7%) were found. This partially explains the statement by Russell et al. (2017). Moreover, this result indicates that the apparent fragmentation of research products might be also related to the difficulties in detecting the available material through bibliographical researches.

Similar results are obtained in the case of another method: The Multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM). MuSIASEM theoretical foundations were recently detailed in a paper by Giampietro et al. (2009). WOS detects 37 papers focused on this method, while Scopus finds 35 papers about MuSIASEM. Instead, adding the words "environmental accounting", as done in the case of emergy, only 1 paper appears, both in the case of WOS and in the case of Scopus. Thus, the results shown in Tables 2–4 are defective in numbers, due to potential matching errors in the classification processes.

With respect to sustainability and its goals, which were described in the United Nations global sustainable development agenda (UN, 2015), Bebbington and Unerman (2018) individuated three challenges for the future: a better use of accounting technologies, used to collect and analyze available data, which should be available in a coherent form; a better integration on the three pillars of sustainability; the need re-examining the available theoretical frameworks and methods under the light of Sustainable Development Goals (SDGs); the need of engaging with new fields of interdisciplinary investigation and theorization, integrating different scientific domains. Another paper by Bebbington et al. (2017) unveiled two other challenges within the same framework: the inclusion of more holistic visions into accounting process; the need of conceptualizing 'engagement', to transform data into appropriate narratives for sustainability.

The importance of measuring is, then, stressed in a paper by Lindenmayer et al. (2015). In particular, the following steps are recommended: take a survey of existing monitoring programs and their outcomes; define the ecosystem targets of environmental monitoring; develop appropriate conceptual models, which also include the use of systematic syntheses, which are necessary to improve the transparency of results; find and measure the environmental variables, which drive each ecosystem's dynamics and which should be monitored. The component related to data (characteristics and quality) is crucial to improve the overall level of environmental and social accounting inputs. Big data, data openness and transparency are also relevant topics nowadays (Song et al., 2017). Due to the multi-dimensional nature of environmental and social processes, a paradigm shift would be relevant with respect to data acquisition. Some contaminations might derive from environmental forensics, where the concept of 'scene analysis', the use of hierarchical monitoring techniques and the spatio-temporal data representation are parts of the developed expertise within this domain (Agosto et al., 2008; Wolff and Ashe, 2009; Lega and Persechino, 2014; Errico et al., 2014; Gargiulo et al., 2016; Lega and Teta, 2016; Di Fiore et al., 2017).

Environmental accounting is the practice which transforms raw data into information. Consequently, the choice of a narrative, which depends on the definition of goals and scope, is crucial. A recent book by Curran (2017) focalized on the interconnection between the first and the interpretation phases with respect to LCA. With this respect, strategic rationality is relevant to integrate the biophysical and socio-economic narratives through appropriate belief systems, while participative processes should be enhanced to facilitate organizational learning (Heggen et al., 2018). However, strategic rationality is not the only way to develop narratives. In fact, aesthetic rationality, a value-oriented rationality that serves to encourage sustainable behavior in organizations (Shrivastava et al., 2017), can also be applied. In order to "move beyond this binary logic" and to "capture the emotionally charged, value-laden processes" (Poldner et al., 2017), aesthetic practices can improve the knowledge translation of the outcomes derived from accounting processes into empowering actions toward sustainability (Shrivastava, 2014; Casazza et al., 2017; Crichton and Shrivastava, 2017; Shrivastava and Guimarães-Costa, 2017; Shrivastava and Persson, 2018). Derived from this analysis, a list of challenges and research needs is given in Table 5.

Table 5
List of challenges and needs to improve the use of environmental accounting, as a component in between raw data acquisition and information use for management purposes.

Challenges	Desired actions and needs
Multi-dimensional integration	Better integration of biophysical and socio-economic dimensions; Improvement of data entry for existing published papers in official databases (specifically: WOS and Scopus); engagement with new fields of interdisciplinary investigation and theorization, integrating different scientific domains; Re-examination of available theoretical frameworks and methods under the light of Sustainable Development Goals (SDGs); Better integration, based on the three pillars of sustainability
Data acquisition and management	Survey of existing monitoring programs; define ecosystem targets of environmental monitoring; find and measure the environmental variables, which drive each ecosystem's dynamics; conceptual shift from existing measures to hierarchical and multi-dimensional scene analysis; big data management, data openness and transparency
Analytical processes	Develop appropriate conceptual analytical and synthesis models to improve the transparency of results; Avoid strong assumptions in the integration of economic-environmental inputs; Coherent form of analytical process outcome; the need of engaging with new fields of interdisciplinary investigation and theorization, integrating different scientific domains.; the inclusion of more holistic visions into accounting process;
Synthesis and narratives	Timeliness in developing appropriate advices for evidence-based policies; 'Engagement' conceptualization, to transform data into appropriate narratives for sustainability; Integration of strategic rationality into biophysical and socio-economic narratives through appropriate belief system; Use of aesthetic rationality, aesthetic inquiry and creativity to support knowledge-translation processes (i.e.: from numbers to motivations and attitudes) and to empower communities toward sustainability

4. Papers published in the special volume

Applying the classification of Table 1 and considering the major research challenges (Table 5), published papers are introduced in the following sub-sections and, then, a general discussion is given in the last part of section 4.

4.1. Environmental flows analysis

Environmental flows describe the quantity, timing, and quality of environmental elements flows required to sustain ecosystems, as well as the human livelihoods and wellbeing, that depend on these ecosystems. Eight published papers deal with this approach.

Zheng et al. (2017) focused on a target ecosystem, studying the drivers of precipitation patterns and dynamics. In particular, they explored the atmospheric precipitation spatiotemporal variations and the causes behind them in the Pearl River basin (China). Mann-Kendall statistical test, Sen's slope and inverse distance weighted (IDW) interpolation methods, as well as the correlations between precipitation concentration index and elevation are used to detect the existing spatio-temporal patterns. Finally, the random forest algorithm (RF) is applied to identify the contributions of seven associated circulation influencing factors on the CI. Taking China and Japan as cases, Cheng et al. (2017) analyzed the industrial sectoral drivers of air-pollutant emission (in particular, SO_2 and NO_x), integrating the biophysical dimension (emission data) with the economic one. Results, then, are used to develop evidence-based strategies for further abating the existing emissions.

Song et al. (2018) worked at the integration of economic and ecologic perspectives, focusing on payments for Ecosystem Services (ES). The authors proposed a new multi-scale accounting framework, which was tested at provincial and urban levels in China, based on year 2010 data, demonstrating its validity to deal with cross-regional payment issues as well as in providing a good management instrument for decision-makers. Also Yan et al. (2017) worked on a new conceptual framework, i.e. a new Tendency-Pattern-Service (TPS) one. However, they applied it to analyze the spatio-temporal drivers of landscape evolution in order to inform the management policies, using Taking Baiyangdian Lake as a case study. The same area was chosen as target for the study by Tang et al. (2018), who applied a two-dimensional hydrodynamic and water quality model to study the distribution of pollutants and determine the drivers of water quality variability, as well as to simulate different scenarios depending on different measured environmental conditions. Yin et al. (2018) applied stochastic linear programming to assess different scenarios of scenarios of riverine flows, where a hydroelectric power plant is located, and electricity prices variability, in order to evaluate the combined effects of compensations to hydropower producers, while guaranteeing the protection of the river, through maintaining the minimum environmental flows. Consequently, this study applies a combined biophysical and economic approach to a topic relevant for policy-makers (i.e.: hydroelectric power production and pricing).

An urban scale model of water metabolism was developed by Liu et al. (2017). In particular, they represented the connectivity between landscape patterns and eco-metabolic processes, using simple geometrical concepts (points, lines and areas). Then, the model provided a new tool for urban planners to improve landscape connectivity and develop better infrastructure layouts within urban ecosystem to build sustainable cities. Instead, a process-scale study was developed by Hou et al. (2017), in order to evaluate the toxicity and inhibition efficiency of lignocellulose-derived compounds on two kinds of bacteria used in the production of bioethanol. In this case, a Quantitative Structure-Activity Relationship method was applied.

4.2. Emergy analysis

Emergy is an important environmental accounting method, whose theoretical and conceptual bases are grounded in thermodynamics, general system theory and systems ecology. Five papers within the SV are published, using this method.

The first group of papers deal with an assessment of different technological processes. Spagnolo et al. (2018) focused on the sustainability of historically-relevant colored-glass production process in the island of Murano, close to Venice (Italy). Newly derived Unit Emergy Values (UEVs), not previously available in the literature, for some chemicals used for artistic glass production (i.e.: potassium nitrate; potassium chloride; sodium tetraborate decahydrate; minium; sodium nitrate; calcium fluoride) are available in the paper. The importance of this paper is that environmental accounting is applied to an artistic production, which is economically relevant. Moreover, the environmental impacts on ecosystem services are also considered to develop informed policies aimed at preserving this multi-centennial production, as well as the environmental quality of the area of Venice lagoon. Another important aspect of production processes, i.e.: end of life, is considered for the first time in the paper by Corcelli et al. (2017), dealing with the treatment of crystalline silicon PV panels. The authors also explored the implications of methodological assumptions, showing that PV panel treatment can generate large environmental benefits. Based on emergy analysis, Yang et al. (2017) focused on the sustainability of a decentralized sewage treatment plant located in Qingdao, China. This work is relevant both for its integration between the biophysical and economic dimensions and for its application to wastewater treatment, also considering the applicability of the studied plant in remote areas or developing countries.

Different development strategies at regional scale were analyzed by Zhang et al. (2018a), who used an improved cellular automata (CA) model specifically built for this research. The focus of the study was the sustainability of land resources management options, which has a great relevance in terms of ecological security and sustainability, as well as for policy-making and planning. Instead, analyzing trade data at international level, i.e. those of China with South Africa, Sudan, Algeria, Nigeria, Egypt and Morocco, Huang et al. (2017) quantified the exchange of natural capital and ecosystem services among partners (including resources that support know-how and technology exchange), identifying also the possible benefits and compensation measures, that may increase trade balance and equity. This study, besides developing a complementary tool to economic evaluation, enabled a more comprehensive understanding of trade beyond the monetary terms.

4.3. Energy/exergy analysis

Energy flows accounting enables to understand the dynamics of Countries' development stages and living standards of communities, mainly based on the first law thermodynamics. In parallel, exergy accounting is applied to identify the major sources of loss and areas for improving the performance of the system based on the second law thermodynamics. Six papers, published in this SV, deal with these topics.

The first three processes deal with the analysis of processes. Aghbashlo et al. (2018) applied standard exergy and extended exergy accounting (EEA) approaches to evaluate the performance of a wind power plant located in the northern region of Iran. Overall, the EEA theory was found to be much more accurate to measure the sustainability and productivity of wind-driven power plants compared with the standard exergy analysis. The developed EEA-based thermodynamic framework concept could be employed for decision making on the implementation of renewable energy plants under different climate conditions, such as in the case of wind driven power plants with respect to their sustainability and productivity aspects. Zhang et al. (2017a) assessed water consumption of coal-fired power plants (CPPs) in China, considering four different technological cooling options: closed-cycle cooling; once-through cooling; air cooling; seawater cooling. The results, being relevant for energy and water policies, imply that the development of CPPs needs to explicitly consider their impacts on regional water resources. Integrating the economic and biophysical dimensions, Han et al. (2018) investigated the roles of industrial organizing levels, considering economic and natural resource endowments in the development of ecological economic efficiency. Data are referred to China. An original assessing method for industrial organizing levels was developed for this study, focused on ecological economic efficiency as a function of resource usage and pollution emission efficiencies. This relationship was defined by the artificial neural network based regression method.

Concerning of energy efficiency, Munguia et al. (2018) analyzed the data associated to an UNEP energy efficiency program, developing specific auditing instruments to acquire first-hand information about Mexican make-up artists (known as maquiladoras, in Spanish). These tools showed their efficacy in supporting the identification of best managerial options both from the economic side and from an energy efficiency perspective. Thus, this work novelty is primarily related to new methods for mixed energy and economic data gathering.

Yang and Shi (2017) simulated two future urbanization scenarios in China, based on linear and logistic growth models. The authors developed a forecast of long-term (2020–2030) energy consumption of urban and rural residents in three economic sectors: transport, construction, and residential. Quite obviously, considering that the study is applied to China, the policy and environmental impacts of these forecasts are relevant for energy, emissions and climate change impacts and sustainability. Tree growth models and carbon stock models were applied by Lun et al. (2017) to discuss carbon dynamics of living trees. Consequently, carbon budgets of forest litter and soil were estimated by balancing its carbon inputs and carbon emissions (using the YASSO model). These models are important both in understanding the relevance of forests within the context of Ecosystem Services (ESs) and for developing appropriate planning actions in the forestry sector.

4.4. Carbon footprint

Trying to define ‘carbon footprint’ on the basis of previous literature definitions, Wiedmann and Minx (2008) defined ‘carbon footprint’ on the basis of previous literature definitions: “The carbon footprint is a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product”. Two papers deal with this accounting method.

Wang and Lin (2017) applied VAR and STIRPAT models, integrating economic, energy and environmental factors, to investigate the major influencing components with respect to CO_2 emissions in China’s commercial sector over the period 1980–2014. These findings have important implications for policy-makers to enact CO_2 emission reduction policies. The Chinese industrial structure was analyzed by Zhang et al. (2018b). The authors proposed a dynamic factorization model to compare the effects of industrial structure on the reduction of carbon emissions during the five Five-Year Plan (FYP) periods. Results show that the impact varies with the ratio of sectors within the economic structure. These findings are again significant for the government in formulating environment and economy policy and planning.

4.5. Ecological Network Analysis

As written by Platt et al. (1981), in order to understand the relations among aggregated compartments of an ecosystem, networks of flows can be used. This is why several analytical tools were assembled, to form what is known today under the name of Ecological Network Analysis (ENA) (Ulanowicz, 2004). Four papers in this SV deal with ENA.

Qiao et al. (2017) developed a descriptive model of urban ventilation network, aimed at exploring the relation among urban morphology, building height and urban ventilation conditions. Test data were extracted using Landsat Thematic Mapper. The joint use of remote sensing techniques and this model allows to improve the urban design. This is important, if the impacts of winds are considered with respect to pollutants transport dynamics.

Different aspects of trade networks are considered in the other three papers. Su et al. (2017) simulated and compared the energy supply security among different cities in China, based on years 1997–2012 data. Implications for primary sources of energy production were also derived, supporting meaningful indications to policy-makers. Zhang et al. (2017b) modelled the carbon metabolism of global trade system. Considering both the direct and indirect CO_2 flows and their temporal variability, this research revealed the important role of indirect flows in this dynamical representation, providing an empirical basis for adjusting and optimizing global trade network flows. Finally, Zhang et al. (2018c) second paper on the same topic, specifically focused on temporal variability of CO_2 flows during the same study period.

4.6. Life Cycle Assessment

Life Cycle Assessment (LCA) considers all the environmental implications, including the impacts throughout the whole life cycle of a product, starting from raw materials to its end-of-life, which includes recycling and final disposal (ISO, 2006). Three papers in this SV deal with LCA. This section provides insights about LCA applications to the energy sector.

Chang et al. (2017) applied LCA to estimate the energy consumption and emissions of geothermal heat pump (GHP). The study considered a university building in China as specific case. In the analysis, a hybrid Life Cycle Inventory (LCI) modelling approach was used with the aim of providing indication of possible design and operational improvements. LCI was also applied by Yang et al. (2018) to evaluate a new Chinese offshore wind power project. Yao et al. (2018) analyzed the life cycle of methanol as fuel, providing a description of costs and benefits of increasing methanol use in China.

4.7. Environmental Inventory Analysis

The analysis of environmental inventories, which archive multiple environmental measures, is applied to assess man-environment relations. Data outcomes, then, are reviewed and can be used for planning, environmental decision-making and also conflict resolution. The availability and quality of data are crucial for environmental accounting. Following, seven papers focused on inventories analysis are collected, as an example of different case studies.

The authors of a first group of five papers worked on inventory data analysis. Li et al. (2017a) analyzed the inventory of $PM_{2.5}$ concentrations Beijing, assessing the impacts of aerosol pollution on public health, as well as the associated economic losses as a function of willingness to pay. Zhang et al. (2017a,b,c) modelled the origin and contributions of different sources and emission categories to the PM2.5 concentration in the central six districts of

Beijing during year 2014. Yin and Xu (2018) studied the comparative differences of meteorological influences on PM10/PM2.5-bound PAHs distributions, as well as their potential sources and health risks. Jiao et al. (2017) identified the drivers of changes in different sectorial industrial SO_2 emissions. Li et al. (2017b) developed a model, based on data analysis and quality evaluation, to assess the environmental effectiveness of the recently strengthened air pollution regulations in China.

A second group, constituted by two papers, worked on inventory building and data quality assessment. Li et al. (2017c) developed a complete and transparent GHG inventory of Beijing to support governmental officials in identifying their priorities for reducing GHG emissions. The authors investigated and calculated emission sources defined by the, assessing also the accuracy of data. Guo et al. (2017) conducted a meta-analysis on a 35 years database of CH_4 emission related to rice production in China, showing that more field experiments should be conducted to improve the quality of available data.

Another paper, written by Fei et al. (2017), developed a method for inventory spatial data representation through GIS. The obtained results were used to define a more accurate database land use change patterns. Finally, Tang et al. (2017) established a model for data optimization, combining it with input-output analysis and multi-objective programming. Through this mixed approach, they analyzed the maximum volume of embodied emissions reduction as a function of costs.

4.8. *Multi-criteria Optimization and Management*

Multi- criteria optimization methods ae applied to decision making through the mathematical optimization of problems involving more objective functions, which should be optimized simultaneously. The total number of papers included in this group is eleven.

The majority of papers (i.e.: twelve) contained in this SV apply multicriteria optimization to water management issues, which is also relevant with respect to SDGs. Wang et al. (2017) established a System Dynamics (SD) model for the water resources carrying capacity (WRCC) in Beijing city. Within the model, population, economy, water supply and demand, as well as environmental water-related pressures trends were considered. Li et al. (2017d) investigated the pros and cons of installing a sewage outfall on the Luoyuan Bay sea area. The work was based on a Multi-Criteria Decision-Making (MCDM) tool, where nine indicators, divided in two broad areas (marine environment and built infrastructure), were analyzed accordingly. Ding et al. (2017a) developed a stochastic model analyzing different management options for flood diversion management under multiple uncertainties. The paper by Xu et al. (2018), which is based on water footprint accounting, set up an optimal water allocation model for different industrial sectors. Zhang et al. (2018d) presented a real-time control (RTC) simulator applied to the management of stormwater storage tanks. He et al. (2018) discussed a framework for performing parameter uncertainty analysis in the management of hydropower generation. Results, then, were applied to Nuozhadu hydropower station, Lancang River (Southern China). The paper by Ding et al. (2017b) dealt with the prediction of water pollution diffusion, considering the spatial and temporal evolution of pollutants concentration. The study was applied to understand the potential accident risks for Heshangshan drinking water source area. Cai et al. (2018) analyzed the construction costs and environmental benefits of four alternative Low Impact Development (LID) technologies applied to urban stormwater management. The model included the analysis of environmental and economic variables, whose uncertainties were also discussed.

Other environmental management problems were discussed by the remaining three papers within this group. Chifari et al. (2017) approached to the problem of solid waste management in the metropolitan area of Napoli (Italy) using metabolic network theory and multiscale integrated analysis of societal and ecosystem metabolism (MuSIASEM). Consequently, they addressed the following problems: (i) metropolitan self-sufficiency of urban waste final disposal; (ii) recycling; (iii) environmental and economic impacts.

Finally, two papers deal with the topic of land use. The first one, by Qiu et al. (2017) used two multi-criteria analysis approaches to compare the suitability of land use to livestock production in the metropolitan area of Hangzhou (China). The second one, by Wang et al. (2018), analyzed Dongying city ecosystem services variability as a function of land-use/land-cover change (LUCC).

5. Discussion

Considering the 45 papers published in this SV, the number of works dealing with each challenge, as well as the corresponding research needs identified in section 3, are summarized in Table 6.

Table 6
Number of papers dealing with the research needs associated to four challenges. The challenges were identified through a bibliographical analysis about environmental accounting and management (see section 2 of this paper).

Challenge	Research needs	Number of papers
Multi-dimensional integration	Biophysical and socio-economic data	19
	Bibliographical database entry improvement	0
	New fields of interdisciplinary investigation	5
	New theoretical framework	5
Data management	Define the target ecosystem	5
	Assess the existing available databases	10
	Multi-dimensional hierarchical monitoring (scene analysis)	7
	Measure the drivers of observed (ecosystem) dynamics	12
	Big data, data quality, data openness and transparency	0
Environmental accounting	Link with SDGs	20
	Analytical model development	42
	Synthesis model development	2
	Interdisciplinary investigation of new domains	12
	Holistic vision in accounting process	12
	Assumptions in integrating socio-economic and biophysical data	5
Scoping and narratives	Advices for evidence-based policies	41
	Business strategic thinking	6
	Aesthetic thinking and creativity	0

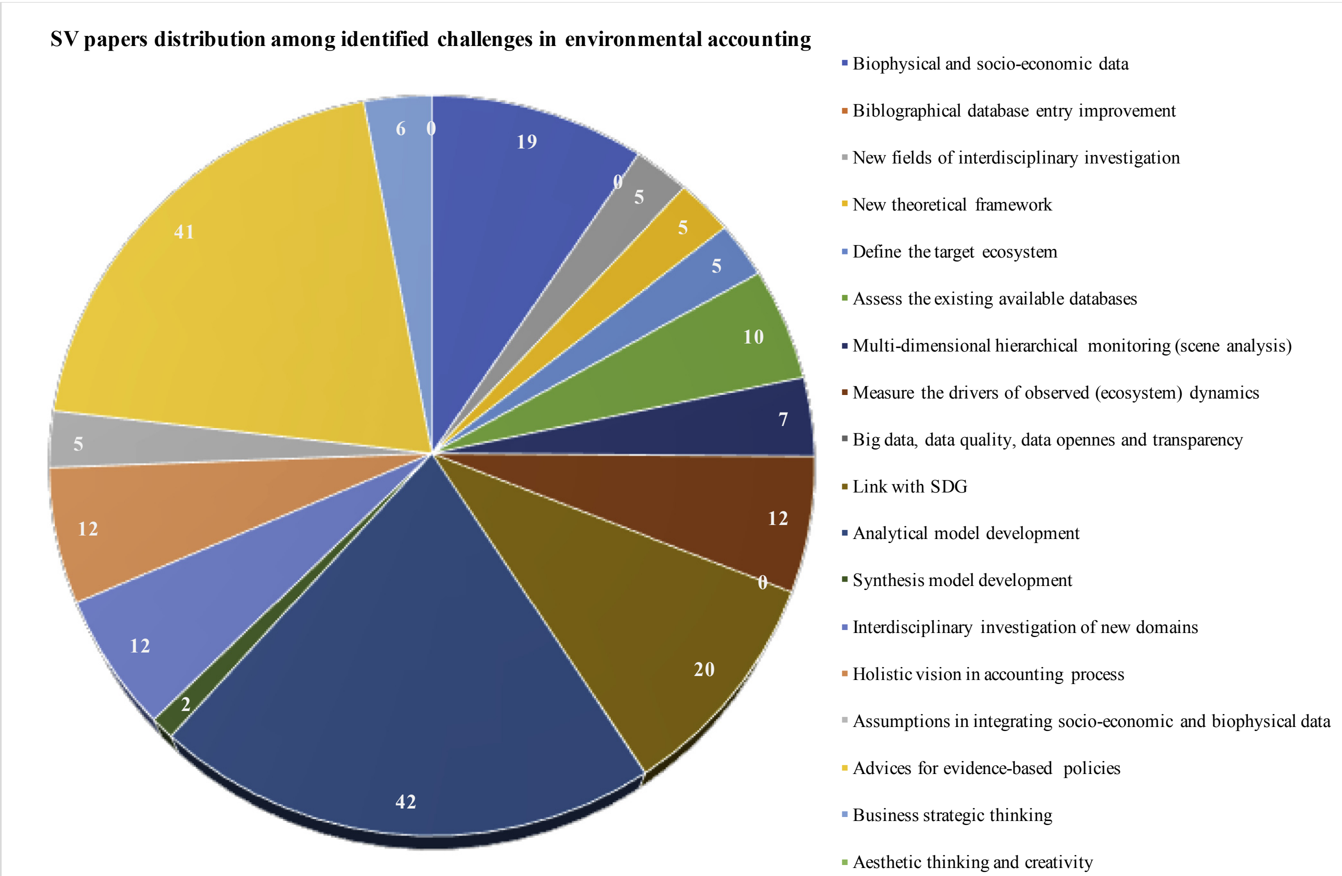

Fig. 1. Graphical representation of papers' number subdivision (white numbers inside the pie chart) with respect to different identified research needs (as shown in the legend).

Fig. 1 graphically represents the papers number subdivision with respect to different identified research needs. It is possible to see that most of the published works deal with the development of analytical models, especially if applied to supporting evidence-based policies. This means that the majority of works focus more on supporting public policies than private enterprises development. A second emerging evidence, is that the papers contained in this volume pay attention to SDGs. The multi-disciplinary nature of indicators (i.e.: biophysical and socio-economic) reflects an ongoing evolution of environmental accounting. However, new fields of theoretical or experimental investigation are presently lacking.

Two factors received lower attention. The first is the importance of data. In particular, the world of big data, which recently received a special attention within a special volume of "Journal of Cleaner Production", was not considered. With this respect, as evidenced also by the bibliographical analysis, the number and openness of existing available databases should be assessed. Data transparency and quality should be other relevant topics, since the quality of outcomes strongly depends on models' inputs. The second point, which received lower attention is the narrative. Methods for appropriate synthesis and communication of results, which are related both with scoping and with the final phases of accounting process, should be further investigated. Researchers have already demonstrated that the narrative of results could be also strengthened an aesthetic rational approach and through the use of creativity, as claimed in several recent studies.

A separate relevant topic, which was not discussed, is the importance of bibliographical databases, which enable researchers to compare different case studies and methods. The fragmented classification of existing works, as seen in section 3, generated a loss of hundreds of papers with respect to the topic of environmental accounting (this paper considered emergy accounting and MuSIASEM as examples). Academia and scientific societies interested in environmental accounting should co-work with reference database (such as WOS and Scopus) managers to re-check the existing records. Meanwhile, authors too should care about their manuscript classification, since many journals allow to identify the topics during the submission process.

The integration of multiple dimensions of environmental accounting can provide a solid basis for supporting policy makers in their actions of defining targets and actions for a transition toward a more sustainable behavior of human societies (Franzese et al., 2014). The variety of case studies discussed in the published papers demonstrate the wide-range applicability of environmental accounting to management problems. In particular, it is possible to identify four broad areas of application: ecosystem conservation; planning (e.g.: urban planning); public policies; corporations and enterprises management. As written by Lindenmayer (2017), environmental accounting can overcome the problem of poor decisions, avoiding the risk of resource mismanagement and potential collapse of impacted ecosystems. For such a purpose, in order to support the preservation of ecosystem services, natural capital and ecosystem services can be quantified in several ways (Hein et al., 2016). The application of alternative scenarios, in parallel, can support the definition of more appropriate planning strategies both for natural ecosystems and human activities (Zucaro et al., 2013; Picone et al., 2017). Environmental accounting can support different stages of policy-making. In particular, Vardon et al. (2016) identified three steps: (1) Development of agenda, where issues are identified through accounting; (2) Implementation and evaluation phases, where accounting identifies critical areas and success of actions taken; (3) Policy responses to foreseen environmental scenarios, where accounting can identify and forecast potential trajectories and future impacts. In parallel, environmental accounting can support a transition from accounting to accountability. This fact is particularly relevant in the case of enterprises, which should include environmental conservation among the goals, supporting the structural transformation of existing economies (Saremi and Nezhad, 2014). With this respect, scholarly perspectives indicate three reasons for choosing this option: the reduction of a company's socio-political risk; the increase of community acceptance; a higher engagement with stakeholders, which can support also cleaner consumption (Holdaway, 2016).

6. Conclusions

The integration of environmental accounting and management tools and methods is of paramount importance both to define the best available cleaner production options and to support policy-makers for accelerating the transition to equitable post fossil-carbon societies. Under this framework, this SV contains articles that focused on methods, technologies and management policies. Overall, the papers in this SV can be classified into eight subjects, including: (a) Environmental flow analysis; (b) Emergy Analysis; (c) Energy Analysis/Exergy Analysis; (d) Carbon Footprint; (e) Ecological Network Analysis; (f) Life Cycle Assessment; (g) Environmental Inventory Analysis; (h) Multi-criteria Optimization and Management. The paper topics and contents reflect the present research challenges in this field, according to the latest available literature analyses. Many of the works reflect the interests for sustainability and SDGs. Moreover, the application of findings to management solutions is especially directed toward policy-makers. However, a greater attention should be payed to private companies too.

Multi-dimensional and fractal models, which reflect the existing hierarchy of Socio-Ecological Systems (SES), worth to be further investigated. In particular, agents and interactions should reflect the real nature of SES: open; dissipative; non-linear. The validity of many physical principles, such as the least action one, should be also considered.

General methods, which are capable to fully represent the whole hierarchy of human energy, as well as the huge variety human means of interaction, represent a potential future integrated approach to the axiomatization of sustainability study. This is, in our opinion, the most promising fact, which will require many efforts. In fact, the ability of describing and, possibly, forecasting the transformations of human sustainability as a coherent structure would allow more efficient decision-making processes, from which, in turn, better results in supporting the transition toward a more sustainable socio-ecological lifestyle could be obtained.

Accounting methods should be integrated with the new reality of big data. However, this would require further researches and discussions among peers, since data quality, openness and transparency are crucial for improving the quality of results too. Meanwhile, the development of appropriate narratives, which stems from a growing attention to the preliminary phases of accounting, such as scoping in LCA, is worth of attention, together with an improvement of synthesis and communication phases, which represent the end of accounting process.

The latest environmental accounting methods used in this SV suggest that opportunities exist for many fields, for both environmental, business and regulation reasons, to become more active and adventurous in environmental accounting and management, and that the pressures on them to do so will increase. However, any method need to be realistic and cost-effective. Thus, this discipline will likely evolve through incremental changes to existing activities, rather than through the introduction of completely new processes. Several topics, which are summarized below, will likely become relevant in the near future:

- Multi-scale Environmental Accounting Frameworks
- Understanding and managing environmental costs
- Integrating environment into decisions with long-term implications on capital expenditure and environmental support capability evaluation
- Understanding and managing life-cycle costs
- Tool-based decision making support for complex environmental systems
- Linking data held by different environmental and business functions.

Environmental accounting and management could also go beyond environmental economics. A central objective is to be a significant driver of action and regulation, through demonstrating the long-term implications of sustainability and creating a vision of how this can be achieved. As already stressed before, research should point to what was defined a “narrative” role of making sense of a complex world (McAuley et al., 1997), as well as a “logico-scientific” role of developing an accurate representation of reality.

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