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Lake-wetland ecosystem services modeling and valuation: Progress, gaps and future directions

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ABSTRACT

Lake-wetland ecosystems provide valuable ecosystem services (ES), but lake-wetland ecosystems have suffered great loss from rapid urban expansion and other land use changes. Despite great efforts in increasing our understanding about ES produced by lake-wetlands, significant challenges (e.g., data, information, and implementation) still remain. This paper provides a thorough review of the progress in lake-wetland ES research. It addresses the pressing management needs for reliable biophysical models and economic valuation methods that quantify the trade-offs, across different spatial–temporal scales, and that can assess the effectiveness of alternative wetland management scenarios. The review identified significant gaps, namely, the need to identify data sources for more robust quantitative analyses of the link between ecosystem characteristics and final ES; the lack of information that can be used for generating evidence of trade-offs to compare alternative management actions; and the inadequate attention to incorporating information on potential trade-offs into wetland management. We conclude with lessons for future research including: (i) wetland ES monitoring programs to collect observed data on ES indicators and ecosystem characteristic metrics; (ii) integrated ES assessment models to track ES trends and evaluate ES trade-offs across temporal-spatial scale; and (iii) financial incentives to compensate ES suppliers for conservation to guarantee implementation.

1. Introduction

Ecosystem services (ES) are defined as the contributions of ecosystems to human wellbeing (Costanza et al. 1997; MEA, 2005; TEEB, 2010). The concept of ES has drawn increasing attention amongst researchers due to its significance and relevance to practical management of diverse ecosystems (Müller and Burkhard, 2012; Salata et al., 2017). ES highlight the associated trade-offs between alternative management options (Goldstein et al., 2012). Research into ES has increased substantially in recent decades (Seppelt et al., 2011; Guerry et al., 2015; Costanza et al., 2017). However, studies still cannot meet the increasing demand by policy-decision makers for both data and robust evidence (Martinez-Harms et al., 2015; Förster et al., 2015), and the process of transforming research findings into actual management practice has been slow. Lake-wetland ecosystem is among the most important ecosystems on Earth, defined as the wetlands formed by the swamping process around the shores of lakes or shallow lakes, and include lakes in this study. The area of global wetlands is approximately 7–10 million km^2, accounting for 5–8% of the total land area (William and James, 2015). These systems provide humans with both intermediate ES and final ES, such as provisioning service (e.g., fresh water provision), regulating service (e.g., water purification, flood regulation, climatic regulation), supporting service (e.g., habitat for wildlife), and cultural service (e.g., recreation) (de Groot et al., 2012; MEA, 2005; William and James, 2015). Intermediate ecosystem services are attributes of ecosystems measured as processes and functions, which include supporting services and some regulating services in the MEA (2005). Final ecosystem services are the ultimate biophysical outcomes that are of obvious and clear relevance to human benefits, which include provisioning services, cultural service and some regulating services (Boyd and Banzhaf, 2007; Nahlik et al., 2012).

The value of ES provided by wetland ecosystems in the world was estimated by Costanza et al. (2014) to be 23.2% of the total global ES value of US$125 trillion/yr. Due to the important role of wetland

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ecosystems, a series of wetland conservation plans have been implemented, including Ramsar Convention (Ramsar Convention, 2008), the Wetlands Conservancy (http://wetlandsconservancy.org/about-us/), The Nature Conservancy (https://www.nature.org/), and China's National Wetland Conservation Program (NWCP) (Wang et al., 2012), etc. However, it is still in its early stage for policy-makers and practitioners to recognize ES as a potentially insightful approach to address wetland management challenges. In the past two decades, scientists have made important progress on lake-wetland ecosystem services (LWES) assessments. However, scant data has been a long-lasting issue. This has limited wetland management from achieving desirable outcomes.

This paper aims to increase our understanding about how ES are applied in environmental management to meet the demand for national and international wetland conservation and sustainability by supporting continuing human wellbeing. The paper is structured in three parts. First, we systematically review some key progress on ES research. Second, we outline the management needs for biophysical models and economic valuation methods to quantify trade-offs under alternative management scenarios, identifying three gaps hindering wetland management by comparing the management demands with current status of research in the field. Finally, we conclude lessons and a discussion about future research direction.

2. Methods

We conducted a systematic literature review comprising three steps. First, we used the ISI Web of Science (hereafter WoS) database to collect publications because it provides a practical way to identical studies on the research field. Searches in WoS using the keywords '*ecosystem service*∗' and '*lake*' or '*wetland*' by discipline and date (up to 21 June 2018) yielded 2114 matches. The WoS search introduces many irrelevant articles since this method includes the cited references of the searched articles. Second, from this set of publications, we then used EndNote to refine the articles by searching the same combined keywords in the "title" or "key words" domains, assuming that papers containing these terms in their titles or key words explicitly focus on LWES. The total number of publications was reduced to 1026 (Fig. 1). Many books, book chapters and reports were removed from the search and only 11 key references retained in this study, which may introduce some bias. Third, we imported the refined list of EndNote files into the WoS, and then researched and derived all information of these articles as the input of the CiteSpace software for literature analysis (Chen et al., 2010). We classified the literature into three categories: (1) LWES evaluation; (2) driving factors; and (3) ES trade-offs analysis. The authors were from 85 countries/regions, and the top 10 largest countries included the US, China, England, Australia, Canada, Netherlands, France, Spain, Germany, and Sweden, totaling up to 68.5% of the total number of articles used (Fig. 2).

3. Current status: gaps between progress and management

3.1. Current research progress

3.1.1. LWES evaluation

Evaluating LWES is an important part of global ES evaluation (Costanza et al. 1997, 2014; MEA, 2005; Notte et al., 2015; Angradi et al., 2016). In the past two decades, great progress has been made in this field, covering large and diversified lake-wetland areas (Schallenberg et al., 2013), different spatial scales (Bartsch et al., 2009), and various geographic locations (Reynaud and Lanzanova, 2017; Sun et al., 2017). Schallenberg et al. (2013) assessed the status and trends in 12 ES types across eight lakes with an area above 100 km^2 each in New Zealand, finding that the majority of 12 ES types exhibited degradation trends. Some perceived social priority ES of the Great Lakes of North America (e.g., water purification, water resource supply, biodiversity protection, and landscape aesthetics) were evaluated and showed an overall increase due to substantial land use and engineering initiatives (Lakes, 2016; Isely et al., 2018).

A more recent study by Steinman et al. (2017) further assessed the current state and future trend of ES change in the Great Lakes of North America. Sun et al. (2017) compared the differences in the ES provided by Lake Poyang wetland in China and the Tanguar Haor wetland in Bangladesh, indicating decreasing trends in food security and biodiversity services. Reynaud and Lanzanova (2017) used meta-analysis to estimate the average ES value provided by lakes from a worldwide data set of 699 observations drawn from 133 studies in the world, showing US$106-140 (in 2010 values) per respondent per year for non-hedonic price studies and US$169-403 (in 2010 values) per property per year for hedonic price studies. On a national scale, many countries, including Canada (Simon et al., 2016), China (Dearing et al., 2012; Li et al., 2014, 2015; Xu et al., 2017), Nepal (Bikash et al., 2015) and Ethiopia (Wondie, 2018), have estimated the value of LWES.

Sophisticated methods for quantifying and evaluating LWES found in the literature can be summarized as the following five categories (Fig. 3):

(1) benefit transfer to determine LWES by studying habitat types from the literature or a specific location and transferring functions and/or values via habitat type to new locations (deGroot et al. 2012. Li

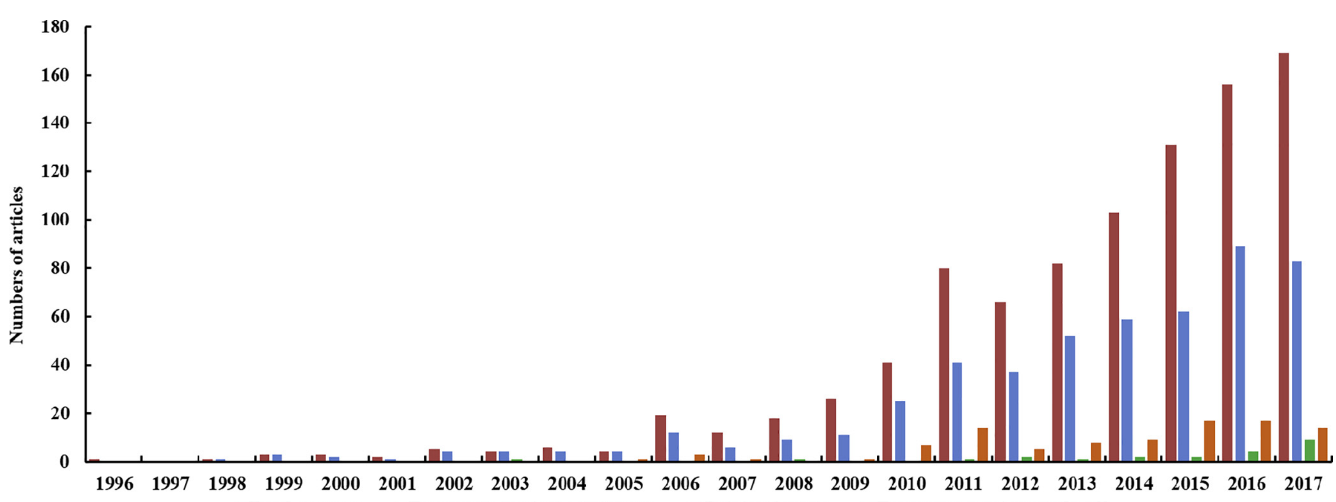

Fig. 1. Numbers of articles on LWES study published between 1996 and 2017.

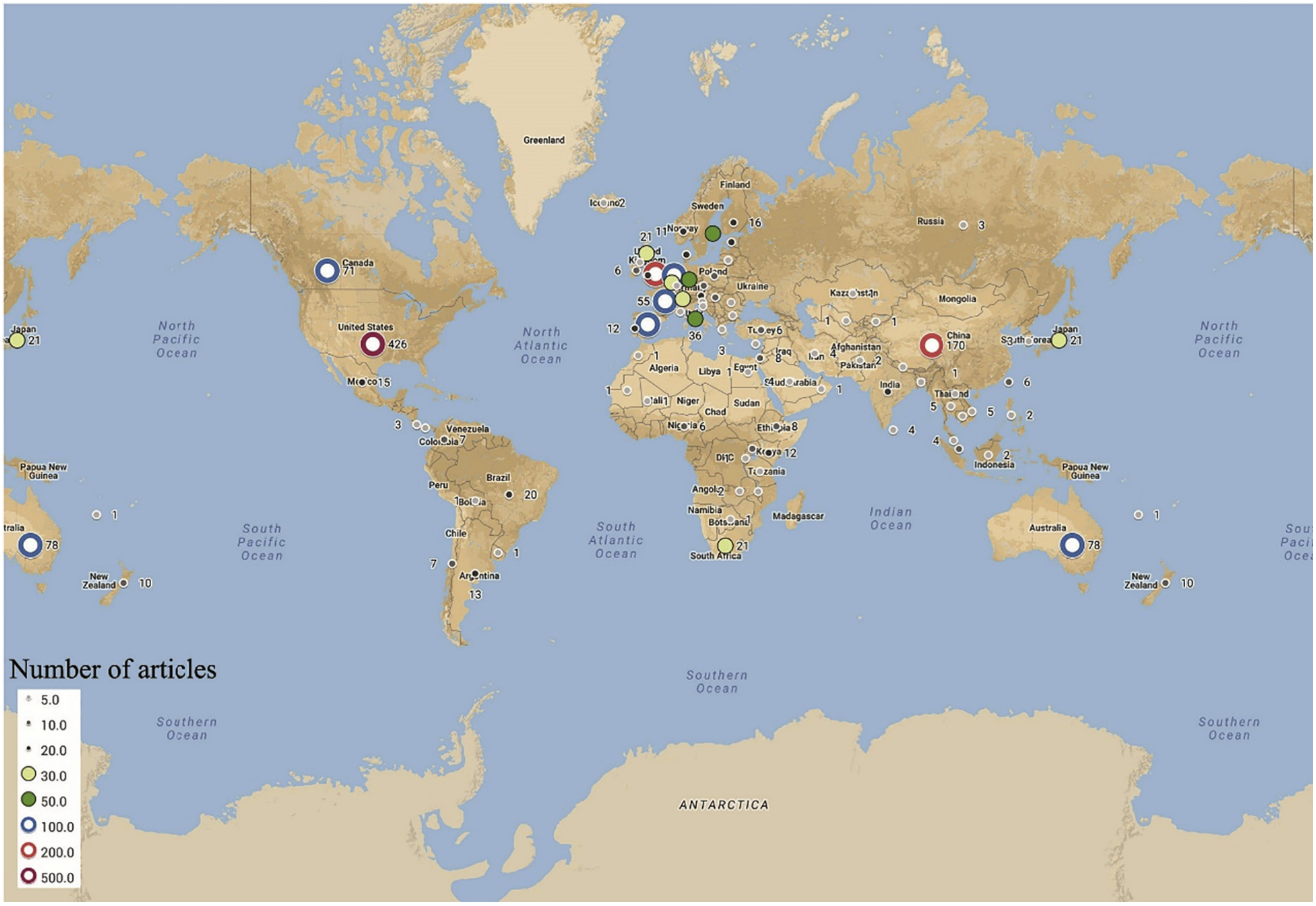

Fig. 2. Distribution of the authors from countries on LWES study.

et al., 2014; Allan et al., 2015);

(2) use of long-time series of palaeolimnological record data to estimate and address long-term dynamics of LWES (Dearing et al., 2012; Xu et al., 2017);

(3) contingent valuation and choice experiments methods (Bikash et al., 2015; Simon et al., 2016; Wondie, 2018);

(4) comprehensive analysis of LWES based on ES inventory (Schallenberg et al., 2013; Steinman et al., 2017); and

(5) integrated ES models to quantify and evaluate LWES (Boumans et al. 2002, Costanza et al. 2002, Goldstein et al., 2012; Li et al., 2015).

Advances in modelling have produced more than 20 ES evaluation models based on remote sensing and geographic information system (GIS), including InVEST, ARIES, SolVES, MIMES, EPM, InFOREST, Envision, EcoMetrix, and LUCI (Bagstad et al., 2011; Goldstein et al., 2012; Jackson et al., 2013). Due to the high complexity in linking lake-wetland structures, processes, functions to services and analyzing the interactions among multiple ecosystem services, the application of most existing models in evaluating LWES is in early development. For example, the InVEST model has been used to evaluate a limited subset of LWES, such as water supply, water purification and biodiversity conservation (Li et al., 2015; Yang et al., 2018). However, this application of InVEST cannot effectively simulate the high-frequency changes in water regime and the subsequent changes in LWES, due to its simplified hydrological module. The InVEST model also has considerable uncertainty in its simulations compared to the traditional hydrological and water quality models (Vigerstol and Aukema, 2011; Hallouin et al., 2018).

Despite great progress in LWES evaluation throughout the world, there is much still to be done. Five major limitations reflected in existing studies would have hindered the credibility of LWES outcomes. Firstly, terminology confusion on concepts lead to inconsistent and biased values of LWES (Boyd and Banzhaf, 2007; Fu et al., 2011). Secondly, inconsistent LWES indicators and evaluation methods would cause difficulties in comparing results across different case study areas (Bennett et al., 2015). Thirdly, there are many LWES integrated evaluation models and effective verification and regionalization of parameters across applications is difficult, leading to uncertainty and bias in model outcomes (Bagstad et al., 2013). Fourthly, non-systemic application of an inherently systemic model could result in the danger of merely using the 'new language' to describe a few services of interest sidelines' implications for other services and non-systemic management focused on pre-judged priorities whilst overlooking wider ramifications (Everard et al., 2014; Everard et al. (2017)). Most studies of LWES have a focus on provisioning and regulating ecosystem services, while research into supporting services and cultural services are less developed (Allan et al., 2015). Finally, the lack of focus on trade-offs would limit the incorporation of ecosystem services into policy making for optimal management practices, as depicted in Fig. 3.

3.1.2. Driving factors

Lake-wetlands are dynamic systems that are difficult to manage because they often respond to anthropogenic changes in a non-linear way, thereby demonstrating time lags to disturbances. Traditionally, lakes are managed for one or two ES in a manner that neglects the trade-offs and long-term consequences of choosing certain services over others. The main drivers regulating the structure and function of lake ecosystems can be grouped into five categories (Fig. 3): (1) change in hydrologic regime induced by river–lake interactions, dam construction

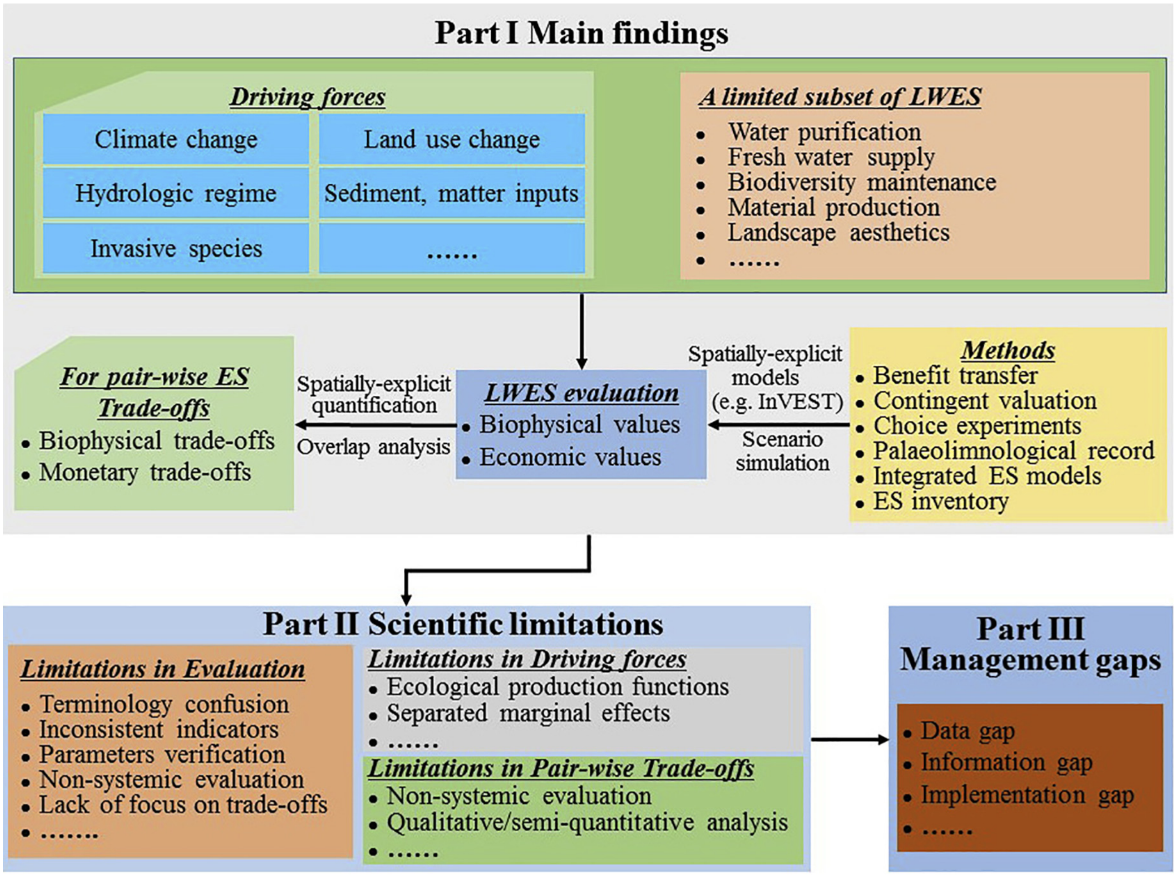

Fig. 3. Important findings of current LWES research, scientific limitations and gaps.

and unsustainable extraction (e.g., sand excavation) (Yang et al., 2016; Zhang et al., 2012); (2) land use change and tourism development (Schallenberg et al., 2013; Allan et al., 2015); (3) sediment, nutrient and organic matter inputs (Ricaurte et al., 2017; Meng et al., 2017); (4) climate change (Fossey and Rousseau, 2016; Withey and Kooten, 2011; Melly et al., 2017); and (5) biotic assemblage and invasive species (Baron et al. 2002; Schallenberg et al., 2013; Smith et al., 2015).

Smith et al. (2015) used expert-knowledge and questionnaire survey to analyze more than 50 stress factors on water supply, biodiversity protection, and landscape aesthetics services in the Great Lakes of North America. Their study indicated that individual stressors related to invasive and nuisance species and climate change had the greatest impacts on the selected subset of ES. Ricaurte et al. (2017) applied spatial indices derived from the matrix approach and participatory mapping (PGIS) to identify the important driving factors influencing future change of wetlands in Colombia. They noted that land use change, water resource demand and water pollution were the three most important factors. Water conservation projects are another important factor causing change in flow regime, and consequently influencing LWES. With an increasing frequency of climatic extremes in the context of climate change, dam and water conservation projects have exceptional effects on water-level fluctuation of the lake-wetland ecosystems (Yang et al., 2016). The long-term dynamic equilibrium between water-level fluctuation and hydrological demand of lake-wetlands might be broken, leading to a decrease in ES such as long-term water supply, water purification, and biodiversity maintenance service of lake-wetland ecosystems (Coops and Hosper, 2002; Riis and Hawes, 2002; Sophocleous, 2004; Fang et al., 2006; Graf, 2006; Zhang et al., 2012). Scientists have made great progress in identifying the main factors driving lake-wetland change. However, there is an enormous challenge in separating and quantifying specific effects of diverse factors on LWES, due to data unavailability and limited modelling capacity (Meng et al., 2017; Yang et al., 2016). Qualitative or semi-quantitative statistical analysis were often employed by researchers to analyze driving factors of ES, while model simulations were rarely used.

There are challenges in creating ecological production functions to identify the marginal influence of driving forces on LWES. In particular, it is difficult to quantitatively split the marginal effects of diverse factors (e.g., large-scale hydroelectric projects, climate change, and land use change) on LWES. Neglecting the spatial heterogeneity and spatial flow of LWES has hampered endeavors to identify the process and mechanism of driving forces on ES across various spatio-temporal scales.

3.1.3. LWES trade-off analysis

Lake-wetland management that attempts to maximize the production of one ES often results in substantial declines in the provision of other ES (Carpenter et al., 2009; Jopke et al., 2015). The general increase in provisioning services over the past century has been achieved at the expense of decreases in regulating and cultural services, and biodiversity (MEA, 2005; Carpenter et al., 2009; Yang et al., 2018). Effective lake-wetland management requires that ES be undertaken systemically with trade-off identified to assist managers in determining wise management options (Wong et al., 2015). Recent studies on LWES management have called for a need to quantify the relationships among multiple ES (Bennett et al., 2009; Bradford and D'Amato, 2012; Guerry et al., 2015), and identify the marginal changes of lake-wetland ecosystem characteristics on final ES to calculate potential trade-offs across ES and management options. The methods for ES trade-offs can be categorized into four major types: statistical analysis, spatial overlapping and analysis, scenario simulation, and ES flows analysis (Bagstad et al., 2013; Cord et al., 2017).

Research into trade-offs analysis of LWES is in its infancy. Most studies in this area have concentrated on qualitative analysis and semi-quantitative analysis using spatial mapping and geostatistical analysis (Jopke et al., 2015). There is a paucity of quantitative studies (Bradford and D'Amato, 2012; Cord et al., 2017). Employing field sampling and monitoring data, Jessop et al. (2015) used principal component analysis (PCA) and redundancy analysis (RA) to quantify the ES trade-offs for 30 restored wetlands within Illinois of the US, showing that there was a significant trade-off between biodiversity maintenance and nutrient cycling processes. This trade-off was characterized by the fact that soil organic matter, biomass, decomposition rates, and potential denitrification were greater at less biodiverse sites. Guida et al. (2016) applied a novel hydrodynamic, geospatial, economic, and habitat suitability framework to assess the tradeoffs of strategically reconnecting the Illinois River to its floodplain. They showed that the tradeoff of implementing lower-cost scenarios is that there is less flood-height reduction and less floodplain habitat available. Yang et al. (2018) used the InVEST model to evaluate how land reclamation influences wetland ES trade-offs in the Yellow River Delta of China, indicating that a trade-off existed between habitat quality and material production (grain, cotton, phragmites australis, aquaculture, salt, fruit) from 1989 to 2015, while the relationship between carbon storage and material production transformed from a synergy into a trade-off in 2008. Our reviewed studies mainly focused on diagnosis and spatial recognition of the trade-offs among multiple LWES using field sampling, geostatistical analysis, InVEST, and economic valuation. It is challenging to optimize any management action to meet the requirements for lake-wetland conservation between multiple stakeholders (Li et al., 2015).

Ecosystem service trade-offs might lead to conflicts between certain stakeholder groups, since they often result in changes in ecosystem service beneficiaries and targets (Bennett et al., 2015). Exploring tradeoffs among ecosystem services and linking them with stakeholders can help determine the potential losers and winners of wetland management (Guida et al., 2016). Managers need to manage ecosystem service trade-offs to either reduce their associated costs to society or enhance net human well-being (Kovács et al., 2015; Guida et al., 2016).

3.2. Management needs

Ecosystem-based management (EBM) has changed the traditional perspective on environmental management (Cheong, 2008), as EBM is aimed at maintaining ecosystems in healthy, productive and resilient conditions so that they can provide ES to meet the needs of people (Barbier et al., 2008). Yet the implementation of EBM cannot take place without addressing the complexity of ecosystems in ES assessment to credibly analyze trade-offs among multiple ES. Defining the linkage between drivers (e.g., lake-wetland exploitation, construction of dams and reservoirs, and joint operation of reservoirs), ecosystem characteristics, and production of final ES is critical for making ecosystem management decisions. Planners and practitioners need legitimate measurements to evaluate potential trade-offs among multiple ES across spatial–temporal scales to make wise decisions about how to manage ecosystems and mediate the drivers (White et al., 2012; Kovács et al., 2015; Li et al., 2015; Guida et al., 2016; Zhang et al., 2017a). ES values need to be presented as marginal changes to determine potential trade-offs among ES to select the best possible option for reducing ES shortfalls (Wong et al., 2015; Zheng et al., 2016). They also require approaching management actions as scientific choices to improve ES and avoid unwanted trade-offs. Ecological production functions address the management needs by calculating how marginal changes in ecosystem characteristics can lead to change in final services, which are useful to determine trade-offs among ES to select management actions (US NRC, 2005; Daily et al., 2009; Polasky and Segerson, 2009; US EPA, 2009; TEEB, 2010; Tallis and Polasky, 2009; Wong et al., 2015). The ecological production functions are used to predict final ES indicators under specific management scenarios to regulate ES trade-offs. Therefore, there are a range of requirements to turn the ES concept into practical management: ES monitoring programs to generate datasets around final ES indicators and ecosystem characteristic metrics, integrated model and ES risk assessment to evaluate wetland trade-offs and track ES trends, and financial incentives to compensate ES suppliers for conservation.

Stakeholder involvement can help ecologists derive final ES, and in turn they can translate stakeholder concerns and goals to measurable biophysical quantities (Ringold et al., 2013; Wong et al., 2015). Stakeholder involvement can clearly indicate who selected and benefited from the final ES and the spatial–temporal scale of the assessment (Wong et al., 2015), and increase the feasibility of changing management practices to reduce service shortfalls and trade-offs (Guida et al., 2016; Zheng et al., 2016). Finally, stakeholder involvement can help identify suppliers and beneficiaries of ES at various levels to adjust relative benefits and costs of environmental protection under alternative management options (White et al., 2012; Li et al., 2015).

3.3. Gaps between current progresses and management needs

The review identified three significant gaps hindering the application of wetland ES research to practical management (Fig. 4). The first gap is the lack of data on measuring the relationship between ecosystem characteristics and final ES. Current methods for measuring LWES focus on ecosystem functions (instead of final ES) and use data on land cover as a proxy, which neglects the underlying biophysical mechanisms and stakeholder concerns (Wong et al., 2015). For example, net primary production (NPP) is the ecosystem function of carbon sequestration or intermediate ES, while soil organic carbon (SOC) is the final ES. In particular, there is a lack of practical scientific datasets to connect functions to services. Furthermore, a lack of genuinely rapid assessment methods is another key factor leading to assessment gaps (McInnes and Everard, 2017). High time and cost data requirements limit the utility of many assessment methods, meaning that few studies are carried out in practice, and these generally tend to focus on a few selected ES (Bagstad et al., 2013; McInnes and Everard, 2017). The second gap is the lack of appropriate information that measures trade-offs to compare alternative management actions. Effective lake-wetland management requires that practitioners know the trade-offs among LWES to set effective management targets. However, there is a lack of dynamic and spatially explicit results to help managers identify trade-offs among ES across different spatial–temporal scales to adjust management actions. The third gap is the inadequate attention to incorporating information on trade-offs into wetland management. Stakeholders lack financial incentives to conserve lake-wetlands due to the challenge of determining the appropriate amount of compensation in economic or monetary terms. We need credible and legitimate ES values to determine proper financial compensation. How to fill these three gaps will be discussed in the section on future directions.

3.3.1. Data gap

There is a need to increase consistent understanding about ecosystem characteristic metrics, final ES indicators, and ecological production functions. This is a result of a data gap in biophysical measurements linking ecosystem characteristics to final ES (Wong et al., 2015). The data gap reduces the credibility of benefit transfer methods and limits the application of spatially explicit results (Wong et al., 2015), which in turn limits the ability of practitioners to set clear management goals on intersecting social and environmental problems (Reyers et al., 2013).

Globally, there are at least 155 lake-wetland ecosystem monitoring stations, mainly located in the US (50), China (41), Netherlands (11), Canada (7) and Finland (7) (Zhang et al., 2017b). However, there are few lake-wetland monitoring stations distributed in South America, Africa, Oceania and North Eurasia. Lack of field monitoring data on

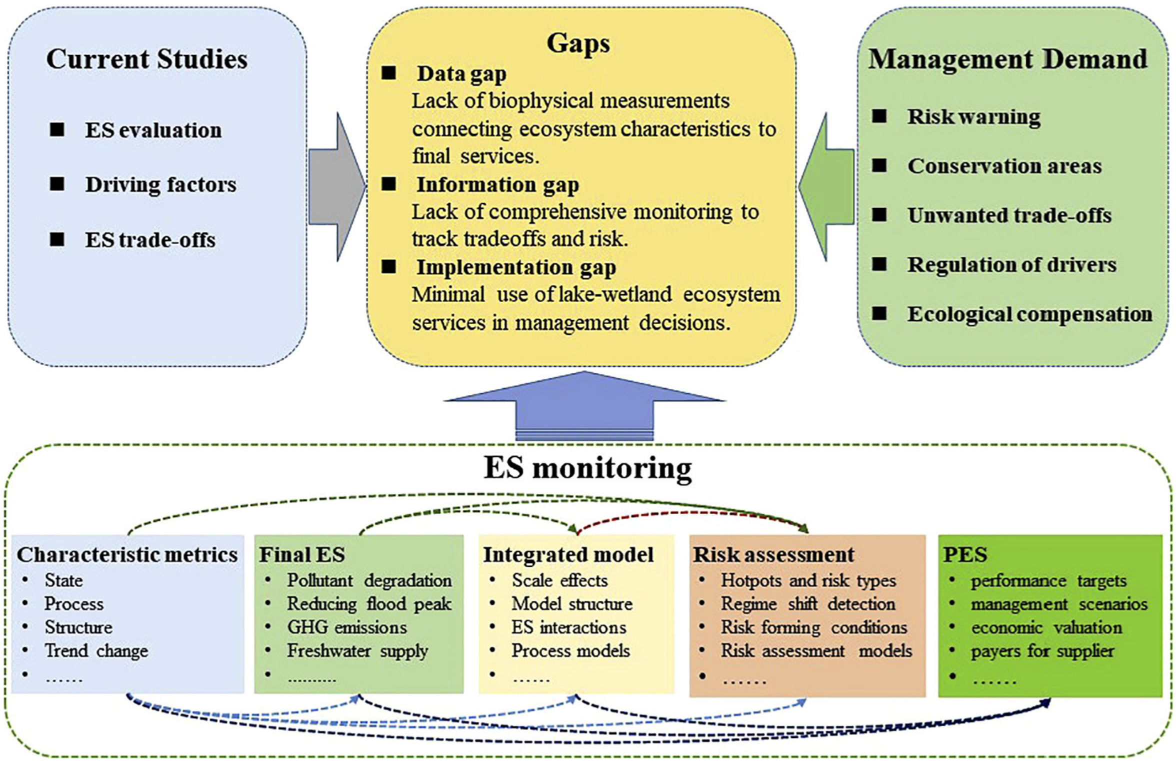

Fig. 4. Gaps and how to fill gaps in LWES management.

lake-wetland ecosystems across these regions leaves significant uncertainty and challenge for upscaling in model simulations. Furthermore, discrepancies between monitoring periods, monitoring stations, and indicators across lake-wetland ecosystems yield inconsistencies of data series and reduce the credibility of comparisons and benefit transfer. Existing lake-wetland ecosystem monitoring stations collect data on ecosystem characteristics, such as structure and composition (e.g., area, habitat type, water environment, and hydrological situation) (Bartsch et al., 2009; Ma et al., 2010; Niu et al., 2012), processes (primary productivity of phytoplankton) (Zhang et al., 2017b), and functions (bird diversity) (Wang et al., 2013). A lack of disciplinary frameworks separating ecology from economics and policy has resulted in slow progress on gathering data about ecosystem characteristics that also relate to final ES indicators.

3.3.2. Information gap

Information on a spectrum of tradeoff outcomes from alternative actions can help balance multiple needs. Therefore, ES outcomes need to be presented in a format for management representing legitimate interests and trade-offs so that decision-makers can easily compare options for their decision (Wong et al., 2015). To devise operational schemes, managers usually need information on trade-offs derived from process-based and/or agent-based models and ecological production functions. We need ecological production functions that link ecosystem characteristic metrics to final ES indicators for predicting how alternative actions might influence multiple ES trade-offs. Only a few studies have incorporated comprehensive, integrated ES models capable of assessing these trade-offs (i.e. Boumans et al., 2002; Costanza et al., 2002; Heckbert et al., 2014; Boumans et al., 2015).

Some studies have qualitatively or semi-quantitatively analyzed the trade-offs between LWES using statistical analysis and InVEST Models. Due to very limited data on measurements of multiple ES, the trade-off analysis involves limited ES types (e.g., water purification, material production, sediment retention, carbon sequestration, biodiversity maintenance) and at low-level scales (static evaluation and local scales) (Jessop et al., 2015; Li et al., 2015; Yang et al., 2018). Moreover, most studies assessed individual ecosystem services, and only in a few instances dealt with interactions between two or more services (MEA, 2005). When relationships between ES have been studied, researchers usually addressed only two ES at a time (Bennett et al., 2009). All these studies point to the lack of information on a spectrum of anticipated tradeoff outcomes from the inherently systemic framing of ES.

3.3.3. Implementation gap

Managers need to know how to manage and regulate lake-wetland ecosystems to improve ES, reduce shortfalls and avoid unwanted trade-offs. They need economic values of LWES to make ecological compensation to incentivize conservation where beneficiaries pay to suppliers to maintain ES flows (Jiang et al., 2015). There is a clear lack of concerted collaborations among different levels of the government, academics, industry, and the public. Ecological compensation programs attempt to reduce trade-offs by paying ES suppliers to make lake-wetland protection feasible (Jiang et al., 2015). But we are short of systematic and scientific process to accurately measure and evaluate the full spectrum of LWES to determine proper compensation levels and refine ecological compensation schemes (Jiang et al., 2015). Decision-makers and practitioners have made efforts to incorporate ES information into diverse management decisions. Some examples include the National Ecological Function Zones (NEFZ) and ecological red lines in China (NDRC, 2013; MEP, 2015), the payments for ecosystem services (PES) for reforestation in Costa Rica (Pagiola, 2008), water management in South Africa (Turpie et al., 2008), coastal management in Belize (Arkema et al., 2015), urban planning and green area management in Sweden (Growth and Planning, 2013), and assessment of natural resource damage in the US (National Research Council, 2013). However, incorporating ecosystem service information into diverse decision-making processes remains the exception, not the rule (Guerry et al., 2015). A practical challenge is how to incorporate ES synergies and trade-off information into wetland management and policy-making.

The implementation gap is also aggravated by significant data gaps, information gaps, and participation gap of stakeholders with interests in a diversity of ES outcomes. For example, the NEFZ and Natural Reserves (NR) in China were both delineated by the Chinese Ministry of Environmental Protection in a bottom-up approach. Due to remarkable inconsistencies among the conservation targets, scales and management, the lack of balance between conservation demand and conservation action, and no consideration of stakeholders with interests in various ES outcomes, there is a low level of spatial overlap between biodiversity targets and ecosystem services and between NR and NEFZ. The protected areas are not well defined to protect either biodiversity or key ecosystem services (Lü et al., 2017; Xu et al., 2017).

Due to limited knowledge, tools, and practices of ES, the concept of LWES has not yet been fully accepted by the administrative departments. This leads to unclear and unspecific management demands of ES. The LWES has not become an integral part of management and decision-making targets of administrative departments. This is a fundamental challenge in reforming policies and institutions by incorporating ES targets with the performance appraisal, to better align short-term milestones with long-term goals. Turning the conceptual framework of LWES into practice, especially for the management of the impact of water conservation projects and optimal operation of multi-reservoirs, should be one of core areas for future studies on LWES.

4. Future directions to assess LWES for management

4.1. Monitoring program on LWES

There are at least 155 monitoring stations on lake-wetland ecosystems in the world, with a focal interest in overseeing change in the structure, state, process and spatio-temporal change of the ecosystems. These monitoring systems collect fundamental data that can be used to reveal the process, mechanism and evaluation of the LWES (Layke, 2009; Lavorel et al., 2010; Zhang et al., 2017b). However, most indicators monitored pertain to the characteristic metrics of the lake-wetland ecosystems, not LWES. These indicators can neither effectively meet the demands of ES evaluation, trade-off analysis and management, nor satisfy the calibration and validation requirements for ES evaluation models. It is therefore important to form ES indicators and characteristic metrics of the lake-wetland ecosystem through identifying ES flow mechanisms and beneficiary concerns (Fig. 4). These key ES indicators are directly related to human activities and management measures, such as supply services (e.g., food, aquatic product, reed fiber, industrial freshwater consumption, sand provision), adjustment services (e.g., reduction of flood peak, greenhouse gas emissions, pollutant removal capability, removal of PM10, PM2.5 and dust), and cultural services (e.g., number of tourists, recreational trip length, primary recreation activity, frequency of visits, trip expenses). More monitoring stations for LWES need to be established to understand service indicators and characteristic metrics, and the linkage between these two. Monitoring programs on LWES not only help eliminate data gaps, but also provide key parameters for ES process models.

4.2. Integrated models on LWES

Establishing integrated ES assessment models to understand the dynamics of LWES and trade-offs is the key pathway towards filling information gaps. Most existing ES models were developed to address issues of interest to particular sectors (e.g., agriculture, marine fisheries, land use, water supply) or particular intersecting issues (e.g., biodiversity and land use change). Thus most existing models can simulate only one type or a few types of ES. There is a pressing need for building integrated ES assessment models to estimate and assess spatial and temporal changes of the LWES on a fully systemic basis under different management and regulation scenarios (e.g., lake governance, lake-control projects, climate change, and joint operation of reservoirs). Specific impacts of different management and regulation modes or scenarios need to be quantifiable, to reveal the dynamic trade-offs among multiple ES and the dynamic trade-offs between ES and economic development over time supporting informed and transparent management decisions. Doing this will provide sufficient information on ES trade-offs, thus filling in part the information gap in lake-wetland management (Fig. 4). Moreover, integrated ES assessment models should address the scales and drivers that are directly relevant to the question at hand (Carpenter et al., 2009). Meanwhile, the sensitivity and uncertainty of the integrated ES assessment models need to be assessed to enhance the capability, accuracy and reliability of comprehensive simulation.

Establishing risk assessment and warning models for LWES is another measure to address information gaps. Apart from the 'risk' concept and assessment methodology constructed by the US EPA (1998), theories and methodologies for detecting ecosystem regime shift (e.g., *T*-test, *F*-test, Mann–Kendall, Le Page) should be introduced to identify the high-risk types and critical points for sudden changes in the LWES, based on the long-term series of monitoring data or the estimated results by using integrated ES assessment models (Andersen et al., 2008; Munns et al., 2009; Xu et al., 2016). The threshold values for the ES indicators can be determined by frequency response analysis (e.g., Weibull, Wakeby, P-III) (Naghibi et al., 2018; Zhang et al., 2011). Then risk assessment models and warning platforms for LWES change need to be established by using ES monitoring, integrated ES assessment models and geographical information system (GIS), to monitoring real-time risks and to discern specific conditions for relevant risks (e.g., hydrology, lake restoration, land-use change, climate change, flood control projects of lakes, and joint operation of reservoirs).

4.3. Implementing ecological compensation programs

Ecological compensation for ES is an institutional arrangement that uses ES values to adjust relative benefits and costs of environmental protection among different stakeholders (CCICED, 2006). Successful ecological compensation programs must be grounded in science that clearly illustrates how lake-wetland management options influence the mismatch between supply of and demand for ES and trade-offs (Fig. 4). Firstly, it is necessary to consult with stakeholders at various levels to select final ES and related ecosystem characteristic metrics. Secondly, there is a need to build monitoring programs to obtain first-hand datasets on ecosystem characteristic metrics and final ES to create ecological production functions. Thirdly, it is important to set explicit performance targets and management scenarios and then construct integrated models to evaluate the optimal management options to reduce ES supply–demand shortfalls and multiple trade-offs across spatial–temporal scales. Lastly, expressing LWES in monetary units is needed to implement ecological compensation programs at various scales where beneficiaries pay suppliers to maintain ES and reduce trade-offs flows. Stakeholders (e.g., ES suppliers and beneficiaries) at all levels can seek collaborations between ecological compensation programs to eliminate contradictions between socio-economic development and management needs, and to make lake-wetland protection feasible through financial incentives.

5. Conclusion

This paper provides a systematic analysis of the way lake-wetland ecosystem services (LWES) has been modeled and evaluated, and in turn, how this has enhanced our understanding of the nexus between quantifiable trade-offs across different spatio-temporal scales and effective lake-wetland management. Effective lake-wetland management requires ecosystem services (ES) to be presented in terms of trade-offs to make suitable management options. Scientists have made important progress in LWES assessments, including LWES evaluation, driving factor analysis and trade-offs analysis. At the same time, we have pointed to some gaps and weaknesses in the existing literature—specifically that on data, information and implementation—and would encourage researchers to address these in future to further enhance our understanding of the relationship between LWES and lake-wetland management. Future research should focus on establishing monitoring programs on LWES to derive data that is crucial for connecting ES indicators with ecosystem characteristic metrics, integrating ES assessment models and ES risk assessment models to evaluate wetland trade-offs and track ES trends, and implementing ecological compensation programs at various scales where beneficiaries pay suppliers to maintain ES and reduce trade-off flows.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ecoser.2018.08.001.

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