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Commentary

Paradigm shifts required to promote ecosystem modeling for ecosystem-based fishery management for African inland lakes

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ABSTRACT

Ecosystem-based fishery management (EBFM) is the best option where other fishery management objectives have failed. This makes EBFM important for the African inland lakes and fisheries resources that are among the most threatened in the world despite existing management interventions. Ecosystem modeling provides information that guides EBFM, and, to promote EBFM for the African inland lakes and fisheries, we present strategies required to promote ecosystem modeling. The strategies are based on an examination, presented herein, of (i) publication trends in literature applying two leading aquatic ecosystem modeling platforms, Ecopath with Ecosim (EwE) and Atlantis, on the African Great Lakes as representatives of African inland lakes and (ii) deficiencies in data eminent in ecosystem models existing on these lakes. The examination indicated that ecosystem modeling is inactive on the African Great Lakes, and there is limited local and regional capacity for ecosystem modeling with existing models predominantly led by foreign researchers and marred by data deficiencies. The implications of these observations for ecosystem modeling and EBFM for the African Great Lakes are discussed. The strategies required to promote ecosystem modeling include supporting short-term training workshops to equip local scientists with basic skills for ecosystem modeling, mainstreaming ecosystem modeling in fisheries training curriculum of local universities, and conducting data collection surveys to fill data deficiencies. These are envisaged to increase capacity and activate ecosystem modeling, and consequently promote EBFM.

Introduction

Fish production from African inland fisheries is estimated at 2.7 million tonnes, a third of total fisheries production on the continent (FAO, 2014). The fisheries are important for food and income for riparian populations, national foreign exchange and revenue, employment for about 4,958, 000 people, 26.7% of them being women, and contributes 0.33% to GDP of African countries (De Graaf and Garibaldi, 2014). However, inland fisheries resources in Africa are the most threatened of anywhere in the world, apart from Asia (Welcomme et al., 2010), probably due to weaker fisheries governance and management institutions compared to developed countries (Sumaila et al., 2011). The fishery resources are faced with many socio-economic and environmental drivers, including overexploitation, eutrophication, pollution, habitat degradation, biodiversity loss, invasive species, water extraction and damming (Hecky et al., 2010), which modify aquatic ecosystem function and services. African fisheries are expected, also, to be hit the hardest by climate change, with associated challenges such as reductions in fish catch, which will intensify livelihood problems of millions of vulnerable people and lead to economic hardships and loss of development opportunities (Allison et al., 2009; Ogutu-Ohwayo et al., 2016).

Sustaining the benefits from fisheries resources, and particularly preventing or reversing the economic hardships and loss of development opportunities expected under the changing climate, requires interventions to increase production and promote sustainable exploitation. Indeed, there are management efforts in place in Africa to manage inland fisheries spearheaded by national and regional governments, and international development agencies, such as World Wildlife Fund (WWF) and The Nature Conservancy (TNC), that have made the management of some of the lakes that support fisheries and biodiversity a priority. A highlight of the fishery management approaches on the African inland lakes is co-management, where resource users such as fishers have a recognized role in management. Although this approach has been demonstrated to successfully solve problems in small scale fisheries (e.g. Castilla and Defeo, 2001), it has not been completely successful in Africa as lakes remain among the most overexploited in the world, and faced with multiple stressors (Njiru et al., 2007; Hecky et al., 2010; Welcomme et al., 2010). For sustainable

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development, business-as-usual is not an option, and, accordingly, immediate paradigm shifts to improve fishery management are required if the benefits and biodiversity supported by the lakes are to be sustained to contribute to sustenance of the African population projected to be over 2.4 billion by 2050 (United Nations, 2015).

The role of ecosystem-based fishery management (EBFM)

Ecosystem-based fishery management (EBFM) considers the ecosystem in totality in order to maintain its resilience rather than advancing single species-specific management measures (Pikitch et al., 2004). The approach facilitates tradeoffs between different fisheries and other aquatic resource stakeholders and their needs, improves access to information for management decisions, improves ability to predict management outcomes, and translates into better management plans. The approach, together with its sister approach in aquaculture, Ecosystem Approach to Aquaculture, (EAA), have been envisaged to facilitate the implementation of the FAO Code of Conduct for Responsible Fisheries, which was unanimously adopted by member states at the FAO Conference in October 1995 (FAO, 1995). Consequently, EBFM has been adopted by several developed countries, such as the United States of America (USA), where it currently underlies interventions for the National Oceanic and Atmospheric Administration (NOAA) Fisheries mission that is responsible for management of fisheries resources in the country (National Marine Fisheries Service, 1999). Countries that have complied with the FAO code of conduct, and therefore implementing EBFM (to some extent), such as USA, Norway, Canada, Australia, Iceland, Denmark, Ireland, Norway, United Kingdom, and Japan (Pitcher et al., 2008), have good scores for a health coupled human-ocean system based on diverse indicators (Halpern et al., 2012). Because these examples are not just anecdotes, EBFM can transform fisheries management to achieve fisheries management objectives where other approaches have failed. Thus, EBFM is most appropriate for inland water bodies in Africa, where, despite the existing management efforts, manageable challenges have persisted.

However, for EBFM to effectively counter threats of environmental change as it is designed to (Pauly et al., 1998; Worm et al., 2006), understanding and making predictions about the direction, magnitude, and consequences of the changes and designing the best mitigation options to counter their undesirable consequences have increasingly become very important given that threats are intensifying and becoming increasingly interconnected. These are best facilitated by ecosystem modeling (Canham et al., 2003; Evans, 2012), which makes it (ecosystem modeling) important for promoting EBFM (Christensen and Walters, 2005).

To recommend evidence-based strategies, to promote ecosystem modeling on the African inland lakes, and to ultimately promote implementation of EBFM, we examined the application of ecosystem modeling on African inland lakes by: (i) analyzing publishing trends of literature applying leading ecosystem modeling platforms on the lakes; and (ii) assessing data deficiencies on the lakes for ecosystem modeling. The results of the publishing trends and data assessment were used to identify implications for ecosystem models and modeling, fisheries research, and management and recommend the strategies required to promote application of ecosystem modeling.

Publication trends in literature applying leading aquatic ecosystem modeling platforms

To analyze publication trends in literature applying ecosystem models, we focused on African Great Lakes (AGL) in the AGL region as representative of other African inland lakes and two leading ecosystem modelling platforms, Ecopath with Ecosim (EwE) and Atlantis. The African Great Lakes (AGL) for the purposes of this paper are Lakes Victoria, Tanganyika, Malawi, Turkana, Albert, Kivu, and Edward. Consequently, the AGL Region includes any country that borders any of these lakes i.e. Democratic Republic of the Congo (DRC), Burundi, Rwanda, Uganda, Kenya, Tanzania, Zambia, Malawi, Mozambique, and Ethiopia (source: United States Department of State, Diplomacy in action. About the Great Lakes Region, http://www.state.gov/s/greatlakes_drc/191417.htm, accessed on 27April 2016). The AGL (Fig. 1) were considered for their exceptional attributes that make them outstanding, not only in AGL region or Africa but globally (Table 1).

EwE (Polovina, 1984; Christensen and Pauly, 1992; Pauly et al., 2000; Christensen et al., 2008), which has been described as one of the top ten breakthroughs of NOAA in 200 years (http://celebrating200years.noaa.gov/breakthroughs/ecopath/welcome.html), is a precursor of EBFM and the most widely used aquatic ecosystem modeling platform in the world (Christensen and Walters, 2005; Aydin et al., 2007; Heymans et al., 2014; Colléter et al., 2015). More recent and with only about a decade of application, Atlantis (http://atlantis.cmar.csiro.au/) is a platform designed to support EBFM through fostering the understanding of coupled social and natural dynamics of aquatic ecosystems to guide appropriate and model-tested management decisions (Fulton et al., 2011a).

Scientific publications applying EwE and Atlantis on the AGL were searched using relevant search terms, such as ecosystem modeling for Lake Victoria (or any other AGL), from web-based libraries such as Google Scholar, Online Access to Research in the Environment (http://www.fao.org/agora/en/; OARE) and Access to Global Online Research in Agriculture (http://www.fao.org/agora/en/; AGORA). EwE archives publications that have applied the platforms in a publicly available data base, EcoBase (http://sirs.agrocampus-ouest.fr/EcoBase/), which was also searched for prevalence of the scientific publications. The publication year, authorship, and affiliation were recorded for each selected publication. A closer look was undertaken on the published models to obtain information including their location (country), lake, model area, model period, and other features for the models. Basing on Christensen and Walters (2005), we present the trend in publications applying EwE on the AGL as indicators of how active ecosystem modeling is on the lakes.

As of August 2016, there was no single published Atlantis model on the AGL, with only one model indicated to be under development on Lake Victoria (http://atlantis.cmar.csiro.au/www/en/atlantis.html). The absence of publications applying Atlantis modeling framework on the lakes is surprising because, Atlantis has been in place for more than 10 years, which is a long time for a modelling framework with moderate data requirements to be adopted by fisheries scientists anywhere. Indeed, it has been applied in about 30 systems throughout the world (http://atlantis.cmar.csiro.au/www/en/atlantis.html), including the North American Great Lakes for management and for understanding invasive species, climate and acidification. Given that the AGL are among the most stressed inland lakes in the world (Welcomme et al., 2010), thus requiring EBFM supported by ecosystem modeling, absence of Atlantis model publications indicates inactive ecosystem modeling research activities in the region. This is a great concern because it demonstrates that fisheries management in the AGL region is predominantly limited to singles species management solutions, which have largely failed (Njiru et al., 2007).

The search for publications applying EwE on the AGL revealed 14 publications, including one thesis, published from 1988 to 2012, a period spanning 25 years (Table 2). This publication frequency over the period implies a publication rate of 0.6 papers per year, a dismal publication rate, and consequently limited application of EwE ecosystem modeling platform on the AGL in the last three decades, about the same period EwE has been used (Steenbeek et al., 2014). The rate further drops to 0.5 papers per year if the period is extended to cover up to 2015. Over the publication period (1988–2012), 16 of the years (64%) had no publications each; 6 years (24%) had one publication each, while 1993 had the highest number of publications, with four (Fig. 2). A closer look at the publications indicates that seven of the 14 publications (50%) were published within the first decade (1988–1997), since 1988, the year of publication for the first retrieved

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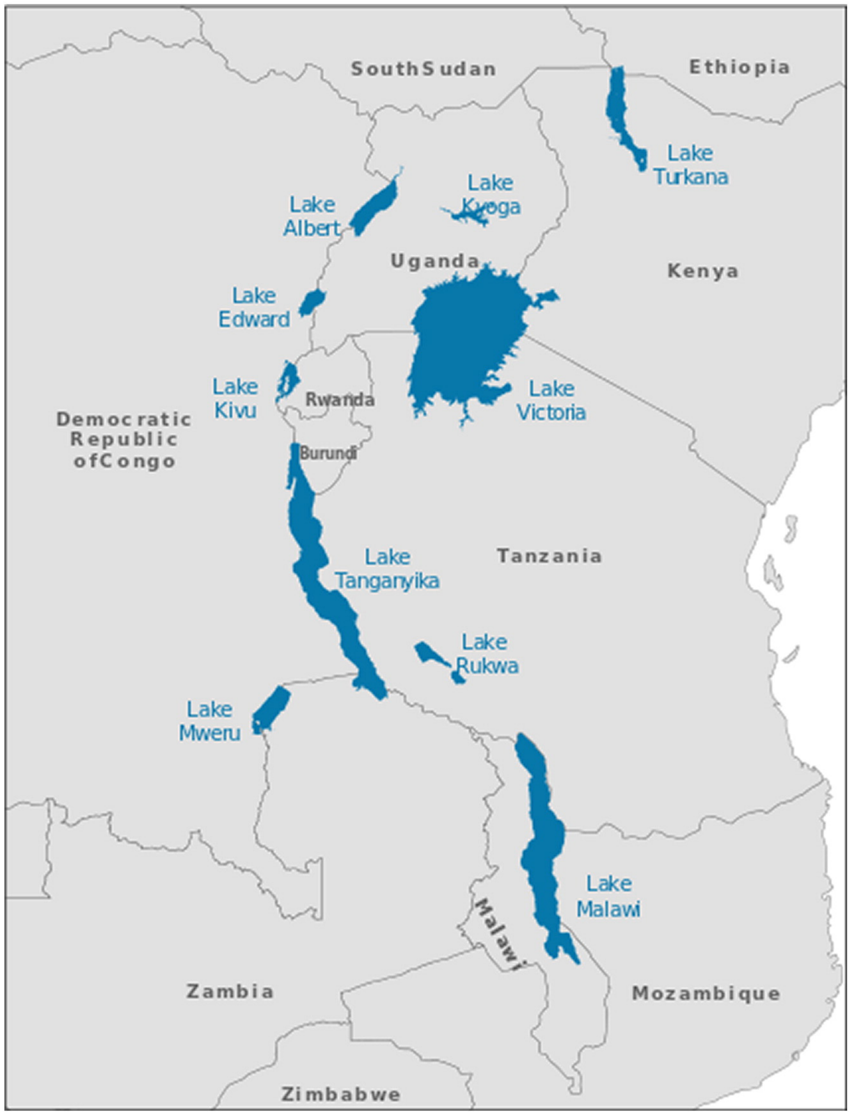

Fig. 1. The African Great Lakes system made up of Lakes Victoria, Tanganyika, Malawi, Turkana, Albert, Kivu and Edward (source: https://en.wikipedia.org/wiki/File:African_Great_Lakes.svg#filelinks; accessed 16th April 2016).

publication (Moreau and Nyakageni, 1988), which was four years after the first EwE model was published in the world (Polovina, 1984). The subsequent decade of 1998–2007 had 28.6% of the publications. Since 2008, only three publications (21.4%) were retrieved, with the most recent one (Downing et al., 2012) published in 2012. The number of publications applying EwE on the AGL were found to be decreasing over time, with almost every year of publication followed by decreased or no growth in number of publications in the following year (Fig. 2), indicating that ecosystem modeling is inactive on the lakes compared to global trends (Christensen and Walters, 2005; Colléter et al., 2015).

In comparison to the American Great Lakes, a search of publications applying EwE found 17 publications, published within 24 years since 1993 (Fig. 3). While the search probably underestimates the publications, it illustrated that the application of EwE is also underdeveloped on the American Great Lakes. However, unlike the AGL, 65% of the publications retrieved were for the most recent five years (212–2016), indicating that the application of EwE is increasing and ecosystem modelling is becoming more active on the American Great Lakes compared to the AGL, which have more challenges that have persisted despite their enormous economic importance to the AGL region.

The publications on the AGL showed that EwE has been applied only on Lakes Malawi, Kivu, Victoria, Tanganyika, and Turkana, with lakes Albert and Edward, located in both Uganda and DRC (Fig. 1), having never been considered. The most recent publications (in last recent decade-2007–2016) were only on two lakes, Victoria and Malawi, out of the seven AGL. All the publications retrieved presented steady state models, describing the trophic structure of the modeled areas and periods. Only four of the publications (Table 1), (Nsiku, 1999; Villanueva and Moreau, 2002; Matsuishi et al., 2006; Downing et al., 2012) extended the steady state models to explore different management options using the Ecosim component of EwE. No publication, so far, has utilized Ecospace and Ecotracer routines of the EwE modeling platform on the AGL, indicating that it has not been utilized to inform decisions on protected areas (one of the fisheries management tool promoted by EBFM) and predict movement and accumulation of contaminants and tracers. Only two were developed for a whole lake system, i.e. Nsiku (1999) for Lake Malawi and Matsuishi et al. (2006) for Victoria. The rest of the models were developed for localized parts within the water bodies considered.

Other interesting features of the publication trends were in authorship. With the exception of the thesis, the first authors of all the publications on AGL using EwE were nonnative, with their affiliations based at institutions out of the AGL region or Africa, but instead in foreign countries including United Kingdom, France, and Denmark (Table 3). Of the

Table 1
Selected key features of the African Great Lakes that make them unique not only in Africa but in the whole world. The features also justly why ecosystem-based fishery management (EBFM) is the best approach to achieve management objectives on the lakes.

Category	Key feature
Size matters	The African Great Lakes (AGL) cover a total surface of about 147,300 km^2 which is about 70% of surface area covered by inland lakes in Africa. Lake Victoria is the second largest fresh water lake in the world by surface area. Lake Tanganyika is the second largest fresh water lake by volume and depth in the world. Lakes Victoria Tanganyika, and Malawi hold a quarter of the planet's freshwater supply. The AGLs are the headwaters of the three longest rivers in Africa: the Nile, the Congo and the Zambezi.
Expanse of catchment areas	The lakes' catchments altogether cover about 683,553 km^2 and is shared by10 countries.
Gridlocks in exploitation and management	Each of the lakes is shared by at least two countries, with catchments of some of them like Lake Victoria spanning up to 5 countries. These make exploitation and management challenging
Fisheries	Support biggest fish supply from in inland water bodies in Africa. Lake Victoria alone supports the largest fresh water fishery in the world. Contribute to livelihoods of millions of people in the riparian countries Contribute to GDP (0.33%) obtained by African countries from inland fisheries
Biodiversity	10% of the world's fish species are found there. The AGL have very high biodiversity with at least ~2000 cichlid fish species most of them endemic, as well as other fish taxa, invertebrates and birds and mammals. The cichlids in the AGL have the greatest array of large, diverse fishes than anywhere in the world developed through adaptive radiation facilitated by phenotypic and molecular plasticity driven by ecological factors such as changes in habitats, population sizes, and hybridization (Meyer, 1990; Wagner et al., 2012; Brawand et al., 2014).

10 publications that had more than one author, only five had at least one native African as a coauthor or coauthors, affiliated to institutions within the AGL region where the lakes are located. Even where the native authors/coauthors were present, they were affiliated to only six institutions from only seven regional countries namely Kenya, Tanzania, Uganda, Burundi, Zambia and DRC (Table 3).

Deficiencies in data eminent in existing EwE models

Because no single publication was retrieved for Atlantis, the analyses on data deficiencies in existing models were based on EwE ecosystem modeling platform, for which publications were retrieved. Data gaps identified in the published models were consolidated, enabling the provision of information on data deficiencies on the AGL limiting ecosystem modeling. These were scrutinized in line with generic data required for the ecosystem modeling platform, obtained from a user guide for EwE (Christensen et al., 2008) as well as best practice for developing models using the platform.

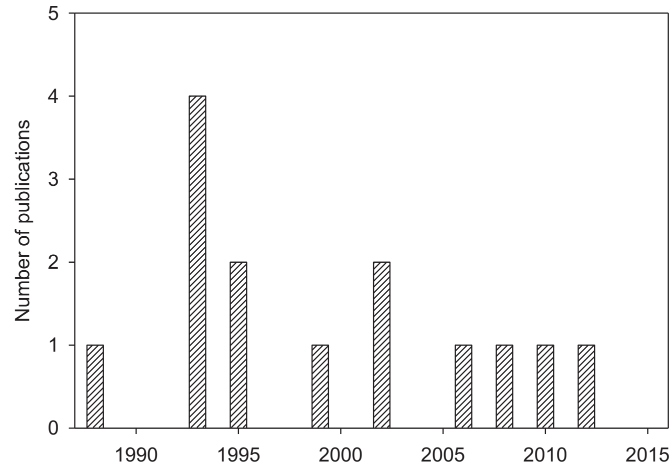

Fig. 2. Trend in number of publications available since 1988 in which the Ecopath with Ecosim (EwE) modeling approach was applied on the African Great Lakes (AGL).

Data for input parameters of EwE ecosystem models can be obtained from several sources, including field data collection surveys, published literature, where it occurs in sources including stock assessments and ecological studies for the systems being modeled or closely related systems (Christensen et al., 2008). The models existing on the AGL combined several data sources, and, because of data deficiencies, none of the models utilized data exclusively within the modeled area or period. Instead, where data were not collected or available in literature for the modeled areas or within the periods modeled, the modelers relied on data from outside the modeled areas or periods, obtained from literature, general knowledge and assumptions, and, in a very unusual modeling practice, left key input parameters, including biomass, to be estimated by the model.

The use of data from other systems and periods other than those modeled was a highly prevalent practice in most of the existing models on the AGL. Nsiku (1999) used input values for parameters including production to biomass ratio (P/B), consumption to biomass ratio (Q/B), and ecotrophic efficiency (EE) for some functional groups in the Lake Malawi model from other lakes including Lake Etang de Thau in

Table 2
A list of studies in literature in which Ecopath with Ecosim (EwE) modeling approach has been applied on the African Great Lakes.

Lake	Model area (country of location)	Modeled year/period	Main feature	Reference and year of publication
Malawi	Southern and western shelves (Malawi)	1998–1999	Steady state	Darwall et al. (2010)
Kivu	Southern part of Lake Kivu (DRC)	2002–2003	Steady state description	Villanueva et al. (2008)
Victoria	Kenya part of Lake Victoria	1971–1972 and 1985–1986	Steady state	Moreau et al. (1993a)
Malawi	Pelagic zone of central Lake Malawi	1979–1981	Steady state	Degnbol (1993)
Tanganyika	Pelagic zone (Burundi)	1974–1976 and 1980–1983	Steady state	Moreau et al. (1993b)
Tanganyika	Pelagic zone	1974–1975 and 1983–1984	Steady state	Moreau and Nyakageni (1988)
Turkana	Pelagic	1987 and 1973	Steady state	Kolding (1993)
Victoria	Kenyan sector of Lake Victoria	1985–86 to 1995–1996	Ecosim	Moreau and Villanueva (2002)
Victoria	Winam Gulf in the Kenyan sector of Lake Victoria	1985–1986 to 1995–996	Steady state and ecosim	Villanueva and Moreau (2002)
Victoria	Mwanza gulf in Tanzanian sector of Lake Victoria	1977, 1987, 2005	Steady state and ecosim	Downing et al. (2012)
Victoria	Parts of Lake Victoria (Kenya, Uganda, and Tanzania), and Lake Victoria	2000	Steady state and ecosim	Matsuishi et al. (2006)
Malawi	Lake Malawi	1976–1996	Steady state and ecosim	Nsiku (1999)
Malawi	Pelagic zone		Steady state	Allison et al. (1995)
Victoria	Kenya	1971–1972	Steady state	Moreau (1995)

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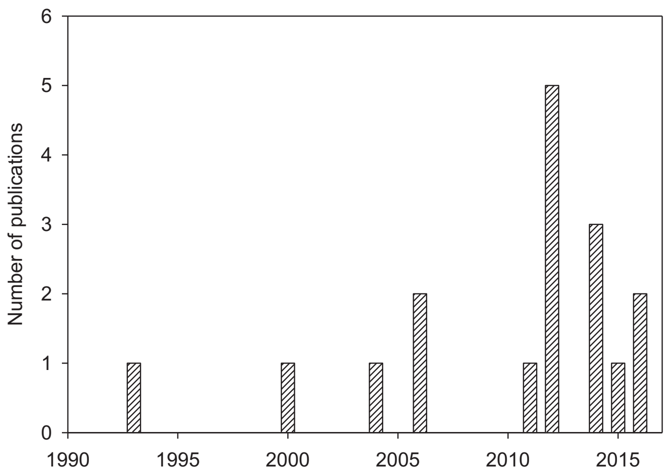

Fig. 3. Trend in number of retrieved publications in which the Ecopath with Ecosim (EwE) modeling approach has been applied on the American Great Lakes since 1993. Sources: Kitchell, J.F. et al., 2000. Ecosystems, 3: 545–560; Langseth, B.J. et al., 2012. Ecological Modelling, 247, 251–261; Stewart, T.J. and Sprules, W.G. 2011. Ecological Modelling, 222(3), 692–708; Cox, S·P and Kitchell, J.F. 2004. Bulletin of Marine Science, 74(3): 671–683; Hossain, M. et al., 2012. Journal of Great Lakes Research, 38(4), 628–642; Langseth, B.J. et al., 2014. Ecological Modelling, 273, 44–54; Yu-Chun, K. et al., 2014. Journal of Great Lakes Research, 40(1), 35–52; Zhang, H. et al., 2016. Transactions of the American Fisheries Society, 145,136–162; Rogers, M.W. et al., 2014. Can. J. Fish. Aquat. Sci., 71, 1072–1086; Koops, M.A. et al., 2006. Comparative modelling of the ecosystem impacts of exotic invertebrates and productivity changes on fisheries in the Bay of Quinte and Oneida Lake. In: Project Completion Report. Great Lakes Fishery Commission, Ann Arbor.; Langseth, B.J. 2012. An Assessment of Harvest Policies for a Multi-Species Fishery in Lake Huron Using a Food-Web Model. PhD Thesis, Michigan State University; Blukacz-Richards, E.A. and Koops, M.A. 2012. Aquatic Ecosystem Health & Management, 15(4):464–472; Yu-Chun, K. et al., 2016. Ecosystems, 19: 803–831; Yu-Chun, K. 2015. Modeling the Effects of Climate Change, Nutrients, and Invasive Species on Lake Huron Food Webs. PhD thesis, University of Michigan; Halfon E., and Schito N. (1993). Lake Ontario Food Web, an Energetic Mass Balance. pp. 29–39 In Christensen V., Pauly D., (eds). ICLARM Conf. Proc.; Jaeger, A.L. 2006. Invasive Species Impacts on Ecosystem Structure and Function. MSc. Thesis, Department of Fisheries and Wildlife, Michigan State University; Currie et al., 2012. Modelling Spread, Establishment and Impact of Bighead and Silver Carps in the Great Lakes. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/113. vi + 74 p.

France, Lake George in Uganda, and Lake Kinneret in Israel, all of which lie in different geographical areas and probably have different environmental conditions compared to Lake Malawi. Other models on the AGL that relied on data from other areas include the models of Lakes Turkana (Kolding, 1993), Malawi (Darwall et al., 2010), Victoria (Downing et al., 2012) and Kivu (Villanueva et al., 2008).

Assumptions that are perhaps unrealistic were also prevalent in the models. Nsiku (1999), while constructing an EwE model for Lake Malawi, assumed no significant difference in biomass of deep water catfishes in different regions of the lake in order to estimate their biomass for the whole lake and differentiate clariid catfishes into two groups based on the proportions of the catfishes in trawl catches from small areas in the lake. This is a problematic assumption because it has been known for a long time that Lake Malawi exhibits non-uniform distribution of fish species in its diverse habitats (Fryer, 1959; Lowe-McConnel, 1975). As a result, the biomass of the catfish fishes in the whole lake could have been poorly estimated in the model. Some existing models assumed no change in some input parameters such as biomass, diet composition, and P/B for functional groups between time periods due to unavailability of data, which could potentially underestimate or overestimate the parameter values. For instance, Kolding (1993) assumed no changes in diet composition of all fish groups in the model for Lake Turkana except one between 1973 and 1987, a period spanning about two decades. Matsuishi et al. (2006) assumed no changes in values for most of input parameters used in Moreau et al. (1993a) and Villanueva and Moreau (2002) and used them in their Lake Victoria models for 2000. Other practices prevalent in the models due to data deficiencies included assuming EE for functional groups whose P/B or biomass were unknown (e.g. Kolding, 1993), grouping together into one functional group, organisms that would otherwise be in different functional groups if data were available (e.g. Kolding, 1993; Nsiku, 1999), and excluding some organisms in functional groups (e.g. Nsiku, 1999).

Although reliance on data from other areas, models, and periods, other than the system being modeled, assumptions and general knowledge can be acceptable when necessary, it is an indicator of data deficiency that should be addressed because, for best practice in EwE, data for model parameterization should preferably come from an area or ecosystem of concern, and models should be based on average parameters for a given period being modeled (Heymans et al., 2016). In regard to this requirement, some level of best practice among the existing models for the AGL was observed in Degnbol (1993) and Allison et al. (1995), where most of the data was for the modeled area and within the model period, and estimates of biomass, production, and consumption for main functional groups in the model were annual averages for the modeled period.

Implications for ecosystem modeling

Although ecosystem models cannot exactly depict structures and dynamics in real ecosystems, models are built to ensure that they become the best possible representation of the basic features and

Table 3
Affiliation of first and coauthors, where applicable, of publications (excluding thesis) applying Ecopath with Ecosim (EwE) modeling approach on the African Great Lakes. The affiliation stated is that at the time of publication.

Reference	First author affiliation	Country of affiliation	Number of native coauthors	Number of native institution involved	Country (ies) of native institutions
Darwall et al. (2010)	Nonnative	United Kingdom	0	0	–
Villanueva et al. (2008)	Nonnative	France	2	1	Democratic Republic of Congo
Moreau et al. (1993a)	Nonnative	France	0	0	–
Degnbol (1993)	Nonnative	Denmark	N/A	N/A	
Moreau et al. (1993b)	Nonnative	France	2	2	Burundi & Zambia
Moreau and Nyakageni (1988)	Nonnative	France	1	1	Burundi
Kolding (1993)	Nonnative	Norway	N/A	N/A	
Moreau and Villanueva (2002)	Nonnative	France	0	0	–
Villanueva and Moreau (2002)	Nonnative	France	0	0	–
Downing et al. (2012)	Nonnative	Netherlands	0	0	–
Matsuishi et al. (2006)	Nonnative	Japan	6	3	Uganda, Tanzania & Kenya
Allison et al. (1995)	Nonnative		0	0	–
Moreau (1995)	Nonnative	France	N/A	N/A	–

dynamics of the ecosystems. The use of data from other sources, contrary to best practices, can lead to use of inappropriate data for input parameters leading to parametric errors in the models (Fulton et al., 2011b). Because several existing models for the AGL used such sources, their ability to provide the best picture of trophic interactions and ecosystem dynamics was degraded by errors due to use of inappropriate parameter values and assumptions (Fulton et al., 2011b). Indeed, Nsiku (1999) asserted that limited interpretations could be made from the model of Degnbol (1993) due to limitations and data gaps in zooplankton production dynamics, role of detritus and organic matter, and fish mortalities. Kolding (2013), also, argued that Downing et al. (2012) contributed little to defining drivers of ecosystem function and changes in Lake Victoria because outputs from their model presented conclusions that do not correspond with ecological reality, emanating from inappropriate parameter estimates. The reliability of other models is degraded by the pedigree index. For instance, Darwall et al. (2010) implemented a Pedigree Index routine in EwE to assess reliability of data obtained from other models and other systems, from which they obtained a Pedigree Index of 0.611. Although this is acceptable, the index indicated that their estimates obtained from other systems for Lake Malawi model were not the best for the model. In addition, due to data deficiencies, there are many known and unknown organisms, including fish species, which have not been included or misplaced in functional groups in the existing EwE models because they have either not been described in the lakes or are data deficient, further rendering the models weak.

Data deficiencies have also limited most ecosystem models to specific time periods and areas. For instance, Kolding (1993) and Nsiku (1999) could not build time series models for Lakes Turkana and Malawi, respectively, but limited their models to time periods where considerable data was available. Villanueva et al. (2008) considered the Bukavu basin of the Congolese sector of Lake Kivu for their model because it was better presented by data on biological communities and fisheries compared to the Rwandese part of the basin. Even the most recently built models were specifically for the time periods for which most data were available (Downing et al., 2012). As a result, time series models and models of some lakes or parts of lake ecosystems do not exist.

Implications for fishery management

Information from ecosystem models can be applied directly or indirectly to support decisions for fisheries management, and so it is particularly important to support the EBFM approach, which is intended to rebuild the fisheries resources from effects of multiple stressors including exploitation (Worm et al., 2009). From this analysis, it cannot be confirmed whether or not the information from the existing models was used to support decision making for fisheries management on the AGL. However, it is known that use of unrealistic models results into improper decisions because the parametric and structural model errors eminent in the models due to inaccurate parameter values and inappropriate assumptions inhibit proper decision making and fisheries management (Fulton et al., 2011b). Therefore, currently, there are no proper, and especially validated, models on which sound management decisions can be based, indicating that inactive ecosystem modeling could be limiting EBFM on the AGL compared to other global water bodies, where EBFM is only limited by disagreements between experts and conflicting country management priorities and guidelines (Essington and Punt, 2011).

Strategies to improve ecosystem modeling

Based on the observations presented here, needed strategies to improve ecosystem modeling on the AGL are: 1) increasing local and regional capacity for ecosystem modeling in order to accelerate ecosystem modeling research activities on the lakes; and 2) improving availability of data for ecosystem modeling which will require strengthening monitoring programs on the lakes.

Increasing local and regional capacity for ecosystem modeling and activating ecosystem modeling

The examination of publication trends indicated limited capacity for ecosystem modeling (Table 3), and that ecosystem modeling research is inactive on the AGL (Fig. 2). Strategies are required to increase the capacity, and consequently activate ecosystem modeling in the region. Christensen and Walters (2005) found that models applying EwE ecosystem modeling platform were increasing by 23% annually on a global scale due to training courses and workshops, among other factors, that have been conducted around the world involving about 600 scientists by 2005. This means that such training activities, which provide practical skills for ecosystem modeling platforms, are key to increase capacity and activate ecosystem modeling on the AGL. A course "Introduction to the Atlantis Ecosystem Model" has been developed to equip learners with basic skills for ecosystem modeling using Atlantis and knowledge of ecosystem modeling and Management Strategy Evaluation. Such courses also exist for EwE. Unfortunately, to the best of our knowledge, no such training workshop has ever been conducted in Africa. We appeal to the developers of these modelling platforms, conservation organizations, development agencies, and other stakeholders to consider trainings in underdeveloped parts of the world (including AGL region), and particularly among early career scientists as a pathway to develop capacity for ecosystem modeling and consequently promote EBFM. Increasing local capacity for ecosystem modeling may also require mainstreaming ecosystem modeling in training curricula for the tertiary institutions that conduct fisheries training, including local universities.

Improving data availability for ecosystem modeling

Although EBFM can commence with limited data, as on the AGL, it is important to implement appropriate strategies to improve availability of data on spatial and temporal scales. This will improve performance of models to provide knowledge of ecosystem status and interactions, promote EBFM and monitoring of its success (Pikitch et al., 2004). More data will also facilitate new ecosystem models, and refine and expand existing models to better depict real ecosystems and their physical, biotic and human interactions (Murawski, 2007). Targeted data collection surveys as well as strengthened monitoring should be conducted to fill data gaps in the existing models. Such data, important for both EwE and Atlantis include information on aquatic community composition, abundance per age class per year, growth rates of organisms, habitat preferences, migratory characteristics, biogenic habitats, diet of organisms and food chain interactions, and non-fish tertiary consumers such as birds and reptiles (e.g. crocodiles), import and export roles of other organisms, such as non-predatory birds and hippopotamus, which are frequent in freshwater aquatic systems, and describing unknown species of fish and invertebrates and their roles in the ecosystems. Indeed, some AGL such as Lake Albert (Fig. 1) have un-described fish groups which may not be put into appropriate functional groups if ecosystem models were to be built in the systems. Current data collection surveys should also be integrated with data collection on primary variables that can be used to estimate some input parameters for the ecosystem modeling platforms using empirical equations (Heymans et al., 2016). For fish, these parameters include catch, biomass, length, weight, height and the surface area of the caudal fin, which are important in estimating P/B and Q/B for EwE. Some of these parameters are not available for some fish species; and for others, they are not routinely collected. Other parameters such as height and surface area of the caudal fin are not highlighted in guidelines for collecting biological information on fishes on Lake Victoria (Lake Victoria Fisheries Organization, 2007) and have not been collected for many fish species for a long period of time. In addition, volumetric and gravimetric methods that provide the best ways to express diet composition (weight or volume) in EwE (Christensen et al., 2008) should be used in estimating diet composition of fish, replacing the most common methods in the region (points method and frequency of occurrence) that express diet composition as present occurrence and dominance which are of little use to quantify diets. Bycatch on the lakes is also increasingly becoming important and may need to be considered for proper estimates of parameters for some functional groups. For instance, on Lake Victoria, bycatch of fish-mainly haplochromines and juvenile Nile perch (*Lates niloticus*) and invertebrates.e.g.-fresh water shrimp (*Caridina nilotica*), and mollusks, is increasingly becoming important in the light fishery whose primary target is the silver cyprinid (*Rastrineobola argentea*).

Conclusion

Successful application of EBFM is essential for sustainable management and exploitation of the AGL. For EBFM to be effective, the regional capacity for ecosystem modeling in the AGL must be strengthened as well as monitoring and research programmes that provide the basic input and validation data for ecosystem models such as EwE and Atlantis. Because the AGL lakes, and especially their fisheries, are among the most important and stressed in the world, the need for regional and global action is urgent in order to protect the regions valuable fisheries as well as other ecosystem values provided by the lakes as well as safeguarding a substantial fraction of global freshwater biodiversity.

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