Chapter 7
Toward Sustainable Lake Ecosystem-Based Management: Lessons Learned from Interdisciplinary Research of Cage Aquaculture Management in Lake Maninjau

Ivana Yuniarti, Clare Barnes, Klaus Glenk, and Alistair McVittie

Abstract Understanding appropriate governance arrangements for managing cage aquaculture systems in tropical lakes is essential, yet it is still overlooked by current studies. Here we discuss the lessons obtained from our interdisciplinary research (environmental–social science, ecology, and ecological economics) evaluating cage aquaculture management scenarios with the aim of facilitating sustainable cage aquaculture management in Lake Maninjau, Indonesia. The lessons we present are based on our analysis of why current management fails to achieve its goals of reduced cage aquaculture and improved water quality in the lake, despite the presence of formal regulations for reaching these goals. The importance of understanding the social, ecological, and economic dimensions in designing management actions is highlighted. We discuss how our research framework embraces methodological and epistemological differences between natural and social scientists to improve research integration and how it supports an adaptive research approach to studying (interventions in) complex ecosystems. We compare the relative advantages of our framework with well-established interdisciplinary conceptual and

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research frameworks revealing that it fulfills pertinent knowledge gaps through detailing the process of discipline integration, embracing epistemological pluralism, and explicitly including the quantification of ecosystem-services trade-offs, uncertainties, and risks in the decision-making process. Finally, we use the lessons from applying our framework to propose a more integrated management action plan in the lake. We expect that the lessons in this research can be widely applied to other cage aquaculture management case studies and contribute to the development of inland water ecosystem management in Indonesia and other Global South Countries.

Keywords Ecosystem management · Interdisciplinary · Socio-ecological · lake · Governance · Aquaculture

7.1 Introduction

The roles of cage aquaculture in supporting livelihoods and alleviating poverty in rural areas are unarguably important (Njiru et al., 2019; Rajee & Mun, 2017; Shava & Gunhidzirai, 2017). They are one of the main reasons for cage aquaculture's massive expansion across lakes in the Global South. However, the operationalization of the cages causes externalities that are suffered by other water users, as the cages are private properties operated in common pool resources (CPR) such as lakes and reservoirs. The externalities (e.g., eutrophication) create conflicts between cage aquaculture and other water users. Entangled problems between cage aquaculture development and degradation of the water bodies are commonly referred to as "wicked problems"—problems that are nondichotomous, hard to define, nested, and complicated (Termeer et al., 2019). To help to solve these problems and to achieve sustainable management of cage aquaculture, research to support the development of suitable governance arrangements is particularly urgent (FAO Fisheries and Aquaculture Department, 2016). However, there are limitations to the current research we wish to address here. First, current literature on open aquaculture management rarely analyzes the institutional setting despite its recognized importance for how cage aquaculture is managed and the impacts it has on livelihoods and the environment (Nadarajah & Flaaten, 2017; Van-Houtte, 2001). Second, both research and management of cage aquaculture mostly follow sectoral lines: disciplines and the epistemological communities gathering around disciplines rarely intersect. This leads to research endorsing particular stakeholder perspectives above others. As will be discussed further below, this affects the **salience and legitimacy** of proposed management actions, ultimately increasing the chance of their failure when implemented at the local (operational) level.

We use the management of cage aquaculture in Lake Maninjau (Fig. 7.1) as our interdisciplinary case study. The management of the lake is representative of the management of many aquatic systems in Indonesia and in the tropical Global South, where sectoral management adopting a single epistemology (or limited epistemologies) is the norm. We use the framework of science–policy interfaces proposed by

Fig. 7.1 Cage aquaculture in Lake Maninjau. (Source: Authors' personal documentation, 2019)

Cash et al. (2003) to frame the presentation of our results. The authors argue that improving the salience, credibility, and legitimacy of research for envisaged stakeholders enhances its use in policy decision-making processes. Salience refers to how relevant the knowledge being produced is to policy stakeholders. Credibility means that the methodologies, evidence, and emerging recommendations are robust and accepted in the policymaking community. Research is legitimate when it has been produced in a manner that respects divergent views and beliefs and is seen as unbiased. Cash et al. (2003) argue that the fulfillment of these criteria helps to align the research with the stakeholders' needs and expectations, increasing the use of the research in the decision-making process. In this chapter, we extend this argument further to posit that these criteria are also relevant for understanding lake management decisions and the knowledges and assumptions such decisions are based upon. In this sense, the stakeholders of such management decisions include the lake users as their perceptions of the salience, credibility, and legitimacy of the management decisions arising from particular epistemologies are essential to their success.

Using these three criteria, we aim to analyze why Lake Maninjau's current management fails to achieve its goal and to provide recommendations and lessons learned for attaining more successful management actions. Furthermore, our central contribution to the academic literature on sustainable ecosystem-based management is a research framework that can be used to embrace the epistemological and methodological differences between (and within) natural and social scientists to better integrate knowledge on sustainable ecosystem-based management.

Cage aquaculture management in Lake Maninjau shows in detail how interweaving socioeconomic and ecological interests on the lake use create so-called wicked problems. The main problem in the lake has been ongoing water quality degradation resulting in mass fish kills and (potentially) declining tourist visits due to the proliferation of cage aquaculture. The cage aquaculture introduced in 1992 has helped to boost the local economy and has created employment opportunities for the locals (Asnil, 2012; Putri et al., 2020). However, due to its uncontrolled growth and unsustainable practices, it has caused severe water quality degradation. The lake also represents a case of sectoral management adopting a single epistemology approach (in this case, ecology), which has not solved the wicked problems at Lake Maninjau.

Ecologists started advocating for the reduction of cages in 2001, as they thought this would improve water quality (Hartoto & Ridwansyah, 2001). This insight was obtained by calculating the lake's carrying capacity and was formally supported by the issuance of Regency Regulation No. 3/2009 and 5/2014 (Aulia et al., 2019; Nanda et al., 2018). Yet, despite large efforts to reduce the number of cages, their number was still increasing in 2019 when we conducted our fieldwork.

There has been an effort to accommodate multisectoral targets, namely the Save Maninjau Program, which has been greatly promoted since 2017 (Presentation of the Head of Agam Regency, 2017). The program has two main goals (Ministry of Environment and Forestry, Government of Agam Regency, & Government of West Sumatra, 2018): (1) clean/ecologically functioning lake and (2) moving economic activities from being lake based to being land based to reduce cage aquaculture.

To achieve the goals, there are ten main targets of the program (ibid): (1) rehabilitating the catchment area; (2) regulating the hydropower's weir; (3) prohibiting new cages; (4) reducing cages; (5) cleaning surface water; (6) dredging or bioremediation; (7) saving endemic biotas; (8) economic transformation via alternative livelihood provisioning; (9) strengthening regulation; and (10) strengthening institutional support.

However, until recently, only targets 4 and 5 are strongly pursued, as evidenced by abundant reports on cage reduction efforts by local government staff (e.g., Metro Sumbar, 2019; Putra, 2020). Yet, indications of unsustainable management practice are still observed (e.g., exceeding the number of cages formally regulated, social conflicts, eutrophication, and mass fish killed (MFK)). MFK is still being frequently reported at the time of writing (April 2021) (Anwar, 2018; Endah & Nadjib, 2017; Kumparan, 2021). Moreover, alternative livelihood programs and cage reduction actions are not taken up by the cage farmers (Aulia et al., 2019). This impedes the achievement of management targets (ibid) and fuels farmers' resistance.

The failure to prevent MFK events led the Head of Agam Regency to issue a formal letter to ask for support from the Republic of Indonesia President on 6th April 2021 (The Head of Agam Regency, 2021), even though the lake had already been declared a National Priority Lake in 2015–2019 (Aulia et al., 2019), and was therefore already under the responsibility of central government. The letter received a reply from the Head of the Research Centre for Limnology, Indonesian Institute of Sciences, who enclosed a policy brief again endorsing cage reduction and other technical solutions such as creating artificial habitats for native fish (Director of RoL-IIOS, 2021; Pusat penelitian Limnologi LIPI, 2019). From this case, we realized that there had been a mismatch between the needs of local decision-makers and the technical solutions provided by the Research Centre for Limnology, Indonesian Institute of Sciences' reliance on a single epistemological approach, as also reflected by Nanda et al. (2018).

7.2 Methodological Approach

This research is informed stakeholder research informed by approaches in environmental–social science. This epistemology influences and is scrutinized by the other two epistemologies (ecology and ecological economics). The overall process is shown as the route from point A to D in the research framework (Fig. 7.2). The framework itself was generated at the end of our research and is drawn from our collective experiences of the research process, led by the first author.

First, we used the insights obtained from the stakeholders (cage farmers, fishers, hotel owners, regency, and national level government) to scope the analysis and to select suitable methodologies. We also considered data availability and quality in scoping the research. Second, stakeholder insights informed our understanding of the trade-offs between cage aquaculture and other ecosystem services. We use two ecological models (Maximum Entropy Model and Bayesian Belief Networks). This was used to undertake an economic appraisal of several management scenarios, which may help decision-makers to identify priorities for their management actions. We engaged Monte Carlo Simulation (MCS) to conceptualize and analyze the ecological economic data.

To acquire the data, fieldwork was conducted from January to April 2019, followed by the second field sampling in March 2020 to obtain independent data to validate the models used in the research. The fieldwork included interviews, species occurrence sampling, relative abundance of fish, and collection of secondary source data from several governmental institutions. We engaged qualitative research methodology in the environmental–social science section and quantitative research in the ecological and ecological economic modeling section. The qualitative data collection was undertaken through conducting semi-structured interviews and reviewing

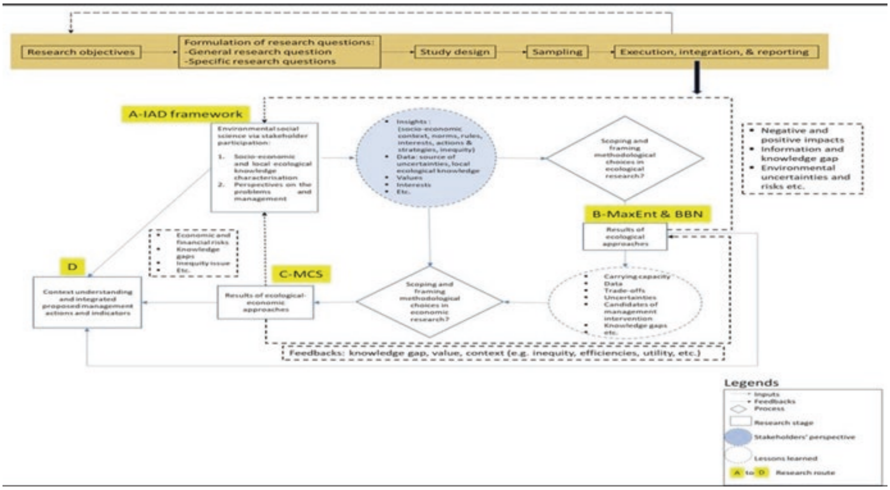

Fig. 7.2 The research framework

relevant policy documents, which generated data subsequently analyzed by employing the Institutional Analysis and Development (IAD) Framework. In the quantitative research sections, we performed the previously mentioned modeling techniques.

7.3 Results and Discussion

7.3.1 Why Does Current Management Fail to Achieve Its Goals?

To answer this question, we analyze the legitimacy and salience of the management actions based on the results obtained from the environmental–social science dimensions and from the ecological–economic dimensions.

7.3.2 The Legitimacy and Salience of Current Management Actions

The environmental–social science part elucidated in Yuniarti et al. (2021a) is summarized in Fig. 7.3. The application of the IAD framework is helpful for discussing targets 9 and 10 in the Save Maninjau targets listed above. Target number nine indicates that the lake managers aim to adopt a strong approach to force people to obey the regulations. The applicability of this approach has been questioned and shown as problematic in Yuniarti et al. (2021a). The application of the IAD framework revealed that a lack of monitoring resources inhibits the success of management actions.

Furthermore, we concluded that there are three main institutional challenges that have to be overcome in order for sustainable cage aquaculture governance to emerge in the study area. The first challenge is the contrasting property-rights definitions used by the people and the lake managers, which creates conditions whereby the common pool resources (CPRs) are managed as an open-access regime. The second obstacle is conflicting formal regulations and customary laws, leading local institutions to be undermined and restraining people from cooperatively supporting the cage reduction program. The third hurdle is inadequate communication and poor levels of trust between the people and the lake managers, which also inhibits cooperation across levels. Overall, these three challenges cause the reduction of the legitimacy of the lake managers and the current management plans at the operational level.

The contrasting definition of property rights has to be eloquently bridged. It can be done by endorsing the role of legitimate local institutions such as *Badan Musyawarah* (BAMUS), which aligns with Save Maninjau target number 10. Unfortunately, efforts to reach this target are still relatively inadequate, as proven by

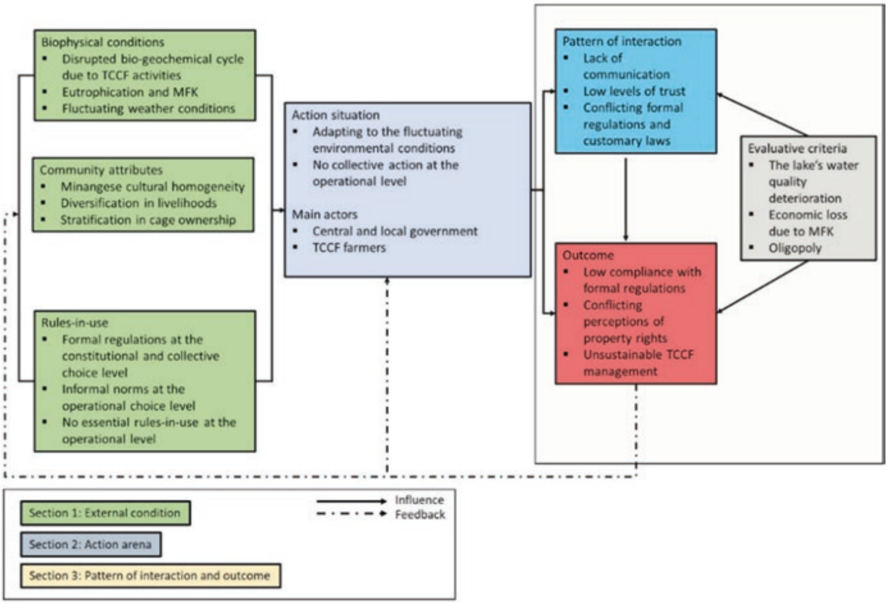

Fig. 7.3 The principal findings of governance of Lake Maninjau organized with the IAD framework. (Source: Yuniarti et al., 2021a)

the limited involvement of social scientists or local stakeholders in the Save Maninjau planning process.

Involving such social science experts is imperative, not merely as facilitators, but also as equal members in the whole management process. Thus, our research leads us to argue that selecting social scientists who have both commitment and capabilities in the managerial team is essential as the process of strengthening institutions requires a reflective approach and a strong understanding of local norms and cultures.

Moreover, substantial bureaucratic changes are required to align the formal regulations with customary laws in the study area, considering that strong religious and cultural norms guide local peoples' practices. Thus, soft approaches involving religious and customary leaders should be used to increase people's participation, rather than using hard law enforcement methods.

The economic dimension provides perspectives for the Save Maninjau program, especially applies to target numbers 3,4,8, 9, and 10. The detailed results of the economic analysis can be found in Yuniarti (2021). From the analysis, we infer that the efforts to reduce cage numbers and improve lake water quality are hampered by a lack of understanding of the economic context in the management planning and of people's economic motives, which influence their behavior. This results in the reduction of the salience of the current management actions proposed by the lake managers.

First, we show how ignoring information on local people's economic behavior from the management planning process (poor legitimacy) can hamper goal attainment by affecting the salience of the lake management approach for farmers. Farmers employ strategies to adapt to the uncertain bio-physical environment. One of the strategies mitigates severe loss in the rainy season when mass fish kills (MFKs) occur (evidenced by the sensitivity analysis, deterministic models, and Monte Carlo Simulation in Yuniarti, 2021). The strategy is observed to be beneficial to securing their livelihood. However, it becomes an impeding factor to governments' efforts to reduce the number of cages on the lake because it justifies that their farming is still profitable. This makes farmers unwilling to leave cage aquaculture, although they have sometimes experienced financial loss due to severe MFK (Fakhrudin et al., 2012; Hamdani et al., 2014; Henny, 2009; Henny & Nomosatryo, 2012, 2016; Henny et al., 2019). Therefore, cage aquaculture is still proliferating even though cage reduction policies have been introduced since 2014. Overall, our evidence reveals that farmers' behavior is (at least partially) driven by economic factors, which need to be considered for achieving the current management target. The significance of understanding local people's behavior and their economic motives to facilitate the success of ecosystem management has been a subject of much research (Black et al., 2013; Freya et al., 2010, 2014; Muhumuza & Balkwill, 2013).

Overall, the economy can be a determining factor for whether local people cooperate in ecosystem management. In the case study, we notice that Payment for Ecosystem Services (PES) may not be an appropriate economic incentive in Lake Maninjau because of the magnitude of private economic benefits from cage culture and concerns about clear attribution of property rights in the lake. Furthermore, as highlighted in Yuniarti et al. (2021a), payments may go to owners who may be city dwellers and thus bypass the local population. Nevertheless, it is clear that being indifferent to local peoples' economic behavior in designing a management plan backfires during its implementation.

Second, we observe from the economic analysis that the annual variable cost is considerably high, which has been a subject of concern for the farmers (see Yuniarti et al., 2021b). We also found that an oligopoly is present and established in the study area. Outsiders or a few wealthy locals fund most cages, and most locals are mere operators. This indicates that there is inequity in the cage aquaculture system. We are concerned that high variable costs, especially feed cost, which makes up more than 90% of the variable cost (Fig. 7.4), will further deepen the inequalities between the poor and the rich in cage funding and profit earning.

Because of the failure of the alternative livelihood project in the Save Maninjau program due to low levels of salience for the farmers, it is likely that the program does not significantly reduce cage aquaculture as intended. The alternative livelihood is mainly aimed at making local people stop practicing cage farming and, consequently, reducing the number of cages. However, most cages are funded by the wealthy and by outsiders. In the field setting, the nonwealthy locals can lease their cages while working as operators. They can also engage in alternative livelihoods.

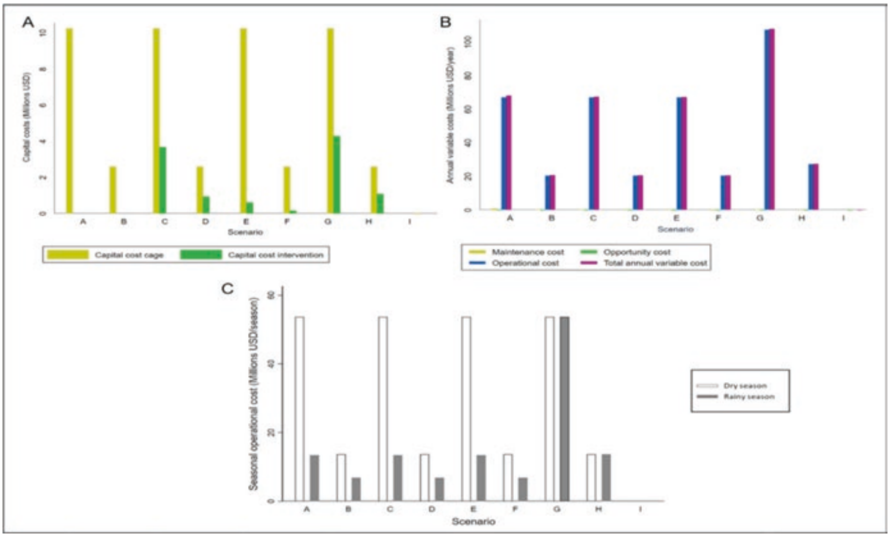

Fig. 7.4 (**a**) Capital costs of cage aquaculture and the proposed management interventions calculated from the deterministic models; (**b**) annual total variable costs (maintenance, operational, and opportunity costs) of cage aquaculture and the proposed management interventions; (**c**) annual operational costs of cage aquaculture. (Source: Yuniarti, 2021)

Thus, in the end, the number of active cages remains high. This circumstance shows that the economic incentive did not work as expected because its planning does not consider the underlying economic and social context.

The failure to design appropriate economic incentives to encourage pro-management behavior has also been well acknowledged by economic and conservation literature. Frey (2001), García-amado et al. (2013), Gneezy et al. (2011), and Rode et al. (2015) revealed that economic incentives could create crowding out effects—undermining intrinsic motives to engage in ecosystem management. However, some studies also recognized crowding in impacts—strengthening the intrinsic motives (Bowles et al., 2012; Janssen & Mendys-kamphorst, 2004; Rode et al., 2015). Learning from these studies, we again underline the pivotal role of understanding the socioeconomic context in designing appropriate management incentives (Frey, 2001; Vollan, 2008).

All in all, it is not enough to understand only the social dynamics or only the economic context. Both aspects are interwoven in people's lives. Therefore, analyses are needed to understand the ways these ***interweaving processes play out*** in a particular context such as the way customary law permitting for owning the area surrounding peoples' houses intertwines with people's motive to maximize profits, hampering their compliance with formal regulations.

7.3.3 The Credibility of Proposed Management Scenarios

In this section, we elaborate on the credibility of some proposed technical management scenarios (i.e., business as usual (Scenario A), cage reduction (Scenario B), cage eradication (Scenario I), and technological intervention via aeration and floating wetlands (Scenarios C to H)). We engaged two ecological modeling tools (MaxEnt and BBN) and an economic modeling tool (MCS). We analyzed both local ecological knowledge (LEK) and scientific ecological knowledge (SEK) to understand the externalities generated by the cage aquaculture and use them as valuable inputs in the constructed models (MaxEnt and BBN). Next, we apply MCS to calculate the economic efficiency of the proposed management scenarios. We conclude that using ecological modeling and economic modeling can assist in developing the credibility of the proposed management actions in the scientific communities' and the national and local decision-makers' perspectives.

In one of the ecological models, elucidated in Yuniarti et al. (2021b, in progress), we analyze a positive externality of the cage's operation. The analyzed externality is related to habitat services provisioning (food source and shelters) to a native fish species, *Gobiopterus* sp. This means that cage aquaculture in Lake Maninjau involves a trade-off, where its negative effect is represented by exacerbated up-welling that results in more frequent MFK and temporary forgone production of *Gobiopterus* sp. following the up-welling event (see Yuniarti et al., 2021c).

Using the results obtained from the BBNs (Fig. 7.5), we underline that controlling internal phosphorus (P) release is equally as important as reducing the external load. Therefore, we realized that the overarching management target should be a reduction of external and internal P load, not only cage reduction.

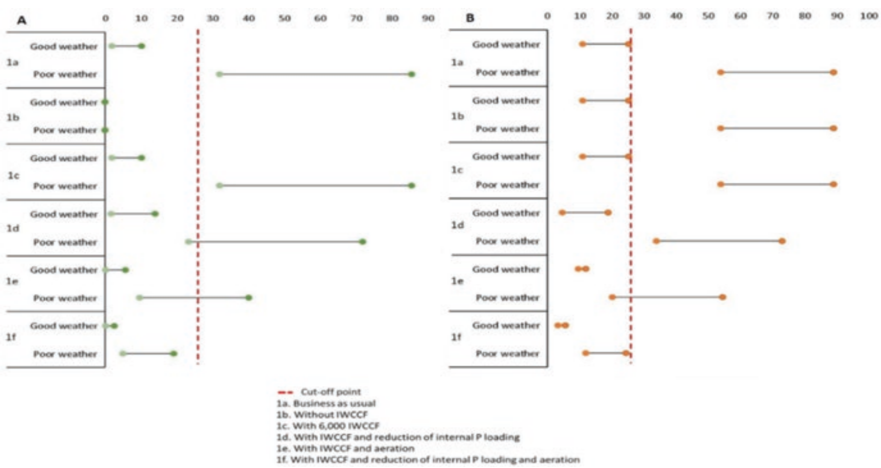

Fig. 7.5 Predicted probability of several short-term management scenarios representing current conditions. (**a**) MFK, (**b**) *Gobiopterus* disappearance. (Source: Yuniarti et al., 2021c)

We revealed that appropriate management in terms of a resource monitoring program is required to avoid ecological traps of habitat provision by the cages. An ecological trap describes a phenomenon when artificial habitat introduction leads to negative consequences for the fish such as overfishing in other regions (Nobile et al., 2018; Swearer et al., 2021). Furthermore, we emphasized the significance of understanding ecological carrying capacity to support cage aquaculture and how to increase this carrying capacity with several technological interventions.

Furthermore, other mitigating efforts such as aeration and floating wetlands can be seen as alternative actions (Fig. 7.6). We received criticism from our ecologist colleagues when we proposed the idea that these technologies can be short-term solutions, which indicates that cage reduction is still the main (or sole) target for most ecologists. This situation shows that professional norms and "normal" ways of doing things (i.e., informal institutions) are very important as practitioners and researchers are involved in making decisions about lake management, not only to understand the communities/research users (Giller et al., 2008; Mosse, 2014). Similar arguments are made by Fleischman et al. (2014) who analyzed how professional norms drive the continuation of specific management interventions (e.g., tree planting), which are widely adopted despite overwhelming evidence that they do not support the achievement of the project goals (e.g., reduced deforestation).

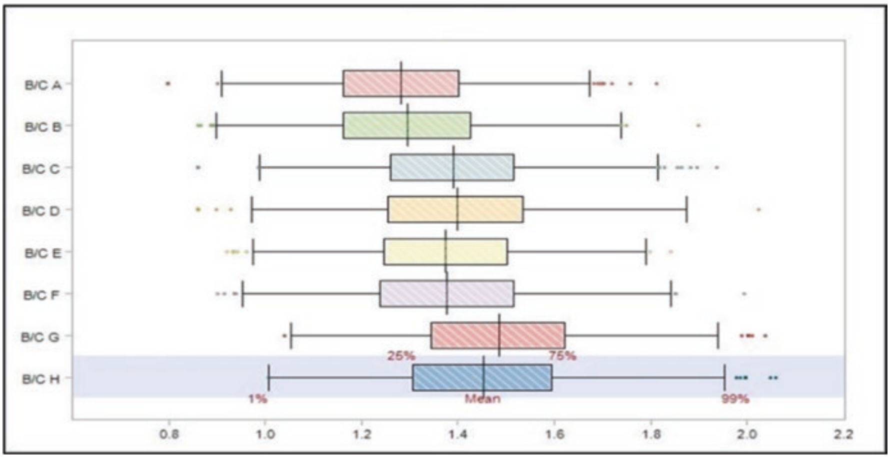

Fig. 7.6 Benefit–cost ratio (B/C) of the proposed management scenarios resulted from Monte Carlo simulation. (Source: Yuniarti, 2021)

7.3.4 Integrated Perspective of Socio–ecological–Economic Research and Proposed Recommendations to Improve Lake Maninjau Management

After reflecting on the importance of understanding the social and economic context of the case study for designing management plans, we question whether cage reduction is a feasible and effective management target. Although the limnologists have emphasized that it will be the main target, we would rather suggest that cage reduction should be considered as one of the various alternative management actions. The economic analysis shows that cage reduction alone will significantly diminish the lake's economic value (see Yuniarti, 2021). More importantly, enforcing cage reduction alone or cage eradication without addressing the inequality and other socioeconomic issues will trigger adverse social impacts such as deepened social conflicts due to the marginalization of local people from the resources, as shown by many fortress-conservation practices (Baynham-herd et al., 2018; Büscher, 2016; Czech, 2008; Vedeld et al., 2012). Fortress conservation is a conservation practice that creates an isolated protected area by excluding people from the natural resources (Doolittle, 2007).

More importantly, we underline the significance of shifting the management goal from a clean, ecologically functioning lake to a sustainable lake. This broad management goal will give an umbrella to a wider perspective as sustainability can be defined from environmental, economic, and social perspectives (Degnbol et al., 2006).

As a consequence, new success indicators must be agreed upon among different scientists and stakeholders because sustainability can be perceived differently from social, environmental, and economic perspectives or even within each of these perspectives. Therefore, we suggest the formation of a management board comprised of social–ecological–economic scientists, decision-makers, and other involved stakeholders to discuss potential indicators. Furthermore, we advise that the board discussion should be facilitated by experienced facilitators to avoid epistemological sovereignty: domination of one epistemic while reducing others to mere support roles (Miller et al., 2008; Robinson et al., 2019). This would further increase the salience and legitimacy of the management plans.

Changing indicators would point to a need for new management action plans. For example, agreeing on maximizing the economic value of water quality improvement includes both economic and ecological aspects. It creates new insights for the action plans such as reduction of P loading by endorsing the application of integrated multitrophic aquaculture (IMTA). This technology is proven to not only reduce P loading but also increase economic benefits (Chopin et al., 2004; Hishamunda et al., 2014; Mungkung et al., 2013; Said et al., 2020). Other alternative actions to control P loading such as internal P-control (i.e., sediment capping) are also endorsed. Furthermore, if the agreed indicators are reduced P loading and maintaining the current level of local peoples' well-being, cage reduction will be only one of the various alternative actions. Consequently, if it is a chosen action, then it should be accompanied by actions to address the inequity and poverty issues.

Next, imposing cage reduction by enforcing formal policy failed as a viable strategy. The new paradigm of management planning should shift to improving peoples' cooperation rather than emphasizing peoples' compliance with formal management regulations. To achieve this cooperation, we have suggested that economic incentives can help with generating a positive attitude toward management to a certain extent, although there is evidence that economic incentives can also have opposite effects. In this case, combining economic incentives with strengthening social norms and moral obligations can provide a solution, as suggested by Berkes et al. (2000) and Ostrom et al. (1994).

Moreover, we suggest channeling the planned management incentives through a trustworthy authority to improve people's cooperation. One option could be the Fisheries Agency mediated by local leaders that our research reveals are trusted by the locals (Yuniarti et al., 2021a). Another option is forming an independent lake management commission such as exhibited in The Great Lakes, USA, and Lake Biwa, Japan (Gaden et al., 2021; Nakatsuka et al., 2020).

Learning from ecological and ecological economics research, we suggest that future management of Lake Maninjau should incorporate uncertainties (data, human, environmental) and ecosystem capacity in the management planning and implementation. This can be done by employing modeling tools, which can help design user-friendly and credible decision-support systems (DSS). Tools that can overcome an old and common problem, data limitation, and can facilitate participatory decision-making, such as BBN, are particularly endorsed. Tools that can take into account local people's perspectives to form recommendations can increase trust, salience, and legitimacy of the results (Ruckelshaus et al., 2015; van Voorn et al., 2016).

As a consequence, researchers whose work relates to Lake Maninjau management should transform their research paradigm from business-as-usual project-oriented research to supporting the development of flexible, inclusive, and adaptive DSS by incorporating various disciplinary perspectives (salience) as reflected by Jacobson et al. (2009). Related to this, future research in the study area is advised to focus on the application of technological interventions related to lake restoration and its impacts.

Overall, we conclude that to embrace the diverse perspectives for improving management of Lake Maninjau, significant work on managerial and research levels is required. This includes shifting management goals, agreeing on integrated management action plans (increasing salience and legitimacy), conceptualizing integrated success indicators (increasing legitimacy), and possibly forming a special commission (increasing credibility, salience, and legitimacy). Similar suggestions arise from reflections on long-term interdisciplinary research in fisheries management by Degnbol et al. (2006). They found that improvement of the management can only be achieved by accepting and responding to the complexity of the management problem rather than the promotion of technical fixes. In other words, the management needs to be more adaptive and acknowledge system uncertainties and complexities. In short, we adopt the popular jargon that "complex problems require complex solutions and explanations" (Lara, 2015, p. 573).

7.3.5 *The Role of the Research Framework in Conducting an Interdisciplinary Study*

In this section, we discuss how the research framework helps embrace methodological and knowledge discrepancies between natural and social scientists. In this study, we use the research framework (Fig. 7.2) by adopting one epistemology (environmental–social science epistemology by employing stakeholder-informed research), which then is influenced (supported and criticized) by other epistemologies (ecology and ecological economics). We used the framework by following the route from point A to D and focused the discussion of the framework on how stakeholders' insights obtained through environmental–social science research influence and are scrutinized by the other two disciplines. However, it would be possible to follow the framework using a different path (e.g., starting from ecology). This flexibility makes its application consistent with Ostrom's suggestion to not excessively use a single theory of a discipline to understand and solve complex social problems (Lara 2015). In other words, the framework is mainly aimed at avoiding epistemological sovereignty—other disciplines are merely acting as support for one discipline—or epistemological silos—preserving an individual's epistemology, while finding validation from other disciplines (Healy, 2003; Miller et al., 2008).

The research framework encompasses interdisciplinary research principles, which may bridge methodological and knowledge differences between ecologists and social scientists by providing room for an iterative approach (Fig. 7.2). First, it uses stakeholders' perspectives to shape methodological choices. The stakeholders involved in this research were cage farmers, fishers, hotel owners, and sub-regency, regency, and central government. Second, it gives room for feedback from one discipline to another and back to stakeholders representing an iterative approach of learning. Iterative methods, an important aspect in conducting interdisciplinary research (Steffen, 2009), can be used to evaluate gaps that need to be jointly addressed.

Figure 7.2 illustrates how incorporating environmental-science research is useful to shape the choices of methodologies. It is revealed in the figure that it contributes by giving inputs (stakeholders' insights, data, values, interests, etc.), which are useful in various ways to scope and frame methodological choices to incorporate the obtained inputs. First, the research produces stakeholders' insights including on their economic behaviors, working rules that shape their behaviors, and wider socioeconomic context such as inequality. These insights provide context as to what they value, their actions, and their interests, which further enhances the understanding of the system context among the researchers. The understanding of context is useful for us, the researchers, to frame the research methodology by providing scope and focus for the study. Furthermore, it directs us to choose appropriate methodologies.

As an example, the choice to use MaxEnt and BBN is fostered by the aim to accommodate fishers' insightful knowledge that cage aquaculture provides a habitat and causes temporary forgone production for the native fish. We believe that without their insights, we would have proceeded in a different direction such as cage aquaculture disrupting fish native habitat as hinted at by many scholars (Alcanices et al., 2001; Zhou et al., 2011). Furthermore, we use the context of the two fish species (*Gobiopterus* sp. and *Rasbora maninjau*) to give an insight that aquaculture can provide not only negative but also positive impacts on native fish. We would not have reached this conclusion without obtaining stakeholders' insights through environmental–social science methods and employing an inductive approach using the context provided by the stakeholders, validated by the ecological model. This inductive method is contrasted with most hypothetical-deductive approaches arguing that the impact of fish introduction via aquaculture is merely negative and depends on the ecology of the introduced species. Overall, it shows that embracing another epistemology can influence the conventional methodological approach in one already established discipline.

Another example is related to the information from the hotel owners about the negative impact of new tourism spots on the number of tourist visits to the lake. Without having this discussion with them, we would have assumed that the decline was merely caused by water quality deterioration. Then, we might have ended up engaging simple linear regression to calculate the economic value of trade-offs of water quality and tourism as undertaken by a previous study in the study area (see Everina et al., 2017). By obtaining this information, the relevance of an alternative methodology can be seen, such as mixed-effects models or other models if quality data can be obtained in the future. This insight supports calls for working with local ecological knowledge (LEK) to shape methodological choices. LEK is defined as knowledge related to ecological interaction obtained from local people's experience while interacting with the environment (Joa et al., 2018). This lesson aligns with the finding of the research conducted by Berkström et al. (2019), Cebrián-Piqueras et al. (2020), and Ruddle and Davis (2013), who found that LEK is frequently coherent and complementary to scientific ecological knowledge, further justifying the usefulness of LEK to inform decision-making processes.

Furthermore, stakeholders' perspectives also provide data and information for this research, for example, by providing information on sources of uncertainties. It is important to address the uncertainties, as mentioned in the previous chapters. Knowledge on the occurrence of uncertainties affects the methodological choices in sequential ecological and economic research (cf. Refsgaard et al., 2007), who concluded that suitable approaches are needed to address data and human uncertainties. In this research, we chose to use BBN and MCS due to their ability to include uncertainty.

Apart from providing room for the stakeholders' perspective to give input, the research framework also gives space for iterative learning by incorporating feedback from each step to inform other preceding stages. The accommodation of iterative processes in the research ultimately assists in adopting epistemological and methodological differences between natural and social scientists. One example taken from this case study is how input from social environmental science and feedback from ecological economic science helps ecological research become more relevant to human systems. Furthermore, iterative processes aid in building more adaptive research in the uncertain lake ecosystem to generate more comprehensive management recommendations.

The iterative process consists of two parts: framing and reframing processes (Oughton & Bracken, 2009). In this case study, one example of a framing process is shown by the role of stakeholders' inputs in scoping and driving the methodological choices of the economics research. Meanwhile, an example of a reframing process is taking the feedback from studying the economic context (efficiency, equity, etc.) to evaluate the feasibility of recommendations from ecological research.

This reframing process may trigger an initiative for the ecologists to re-evaluate and reconsider other alternative scenarios (referred to as a **knock-on effect**). An example of this is shifting our perspective from cage reduction as a main management target to one of the alternative actions (e.g., sediment capping and IMTA).

By allowing framing and reframing processes to happen, ecological research is directed to align better with human systems (as expected by Dietze et al., 2018; Endter-Wada et al., 1998). Thus, in this case, ecology has shifted from a discipline merely used to understand natural systems and how humans influence them, as previously observed by Bastow et al. (2000) and Lowe et al. (2009). It gives ecology a new direction as a science to depict human influence on systems to support sustainable decision-making (Williams & Hooten, 2016).

Another example of an iterative process is provided by the feedback from economists and ecologists to environmental social scientists about the presence of knowledge gaps such as how the selected management scenario may affect residents' livelihoods and their well-being. This feedback can be used by the environmental social scientists to analyze why certain scenarios are adapted more (or in a different way) than others. Therefore, it can provide a new research question for the team to address in the future.

In short, from the examples, we conclude that iterative approaches facilitated by the framework can break disciplinary isolation and help bridge epistemological and methodological differences between natural and social scientists. More importantly, the framework adopts flexibility, learning, and integrated problem-solving principles, providing a more explicit connection of the research to the decision-making support system (DSS) and adaptive management, as argued by Arnold et al. (2017).

7.3.6 The Connection Between the Framework and Previously Developed Interdisciplinary Frameworks

Our framework shares commonalities with existing interdisciplinary frameworks, but it is also distinctly different in certain aspects. The connection between our framework and the well-known drivers–pressures–states–impacts–responses (DPSIR) framework is observed because our research framework in Fig. 7.2 describes the operational methodology to quantify risks and uncertainties of human activities on the natural system and vice versa. DPSIR is a conceptual framework describing the connections between human and natural systems (Baldwin et al., 2016; Kristensen, 2004; Lewison et al., 2016). Although DPSIR has been widely used to generate conceptual models, its application lacks quantification of the reciprocal relationships between human and natural systems (trade-offs) (Patrício et al., 2016). In this case, our research framework extends the application of DPSIR by endorsing the quantification of trade-offs, uncertainties, and risks shown in our case study, as reflected by Patrício et al. (2016) and Smith et al. (2016) and by relating the DPSIR application to DSS as proposed by Dolbeth et al. (2016).

Likewise, the framework connects to the epistemological pluralism framework proposed by Miller et al. (2008). Our research framework is an actual example of their framework's third stage (co-production of research framework). Specifically, our research framework aligns with the epistemological pluralism concept in their framework. One main similarity between our research framework and theirs is that both embrace different epistemologies among the researchers to produce an iterative learning process. Furthermore, both frameworks acknowledge negotiating knowledge and values between researchers (i.e., the knock-on effect in this case study).

In relation to previously proposed interdisciplinary research frameworks, we associate this framework with the MIR (Methodology in Interdisciplinary Research) framework proposed by Tobi & Kampen (2018). The MIR framework was selected because it started with a solid foundation of conducting good research design, and it was formulated in an educational environment where the students as the respondents of the frameworks were firstly reluctant and had prejudice to other disciplines. This condition is similar to the research condition in the study area. Moreover, the MIR framework is increasingly used in teaching multidisciplinary and interdisciplinary students (Tobi & Kampen, 2018; Vuye et al., 2016).

The brown part of our framework (Fig. 7.2) is a general approach used by MIR framework. Our research framework describes details and focuses on the execution and integration part of the MIR framework. The MIR framework itself did not provide details on how the integration should be conducted, for example, what information should be taken from each discipline (Tobi & Kampen 2018). Therefore, this framework acts as an extension of the MIR framework in terms of details on the integration process.

Furthermore, we highlight that the framework aligns with the iterative research framework proposed by Grace et al. (2021), which underlines that methods should evolve during the research process and not be determined at the beginning of the study. Both frameworks also emphasize the development of adaptive research by generating an iterative process. Again, our research framework delivers details on how the iteration is done, which was not elucidated by the iterative frameworks. Moreover, it elaborates on what aspects should be focused on in each learning step to overcoming differences between the disciplines being compared.

In sum, our framework complements previous interdisciplinary research frameworks by providing details on operational aspects of the integration and iterative part of the research. More importantly, it also explicitly describes the inclusion of uncertainties and risks and how all these aspects are connected to the DSS.

Overall, most interdisciplinary frameworks describe the connection of the components of the systems, but seldom do they elucidate how to operationalize research to overcome the challenges of integration (Brandt et al., 2013; MacLeod, 2018). Our research framework fills this gap by elaborating the details on how to bridge methodological and epistemological differences between natural and social scientists. Furthermore, it also acts as an operational guideline to operationalize several interdisciplinary conceptual frameworks.

7.4 Conclusion

Our interdisciplinary approach enables an analysis of the causes of low salience and legitimacy of current management actions, which lead to failure in the implementation of the plans at the operational level. The approach is also useful for demonstrating the credibility of several proposed management scenarios. We suggest that the lake managers in the area should consider facilitating the formation of a locally legitimate agency as a channel to accommodate various perspectives and to increase the likelihood that the management plans are salient and legitimate.

Furthermore, our research framework helps operationalize previously developed conceptual frameworks for interdisciplinary research and encourages researchers and resource managers to embrace epistemological and methodological differences between natural and social sciences. We expect that this research can be a solid and useful foundation to develop a more integrated ecosystem management in the study area and for other lakes in Indonesia.

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