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Will the Oxygen-Phosphorus Paradigm Persist? – Expert Views of the Future of Management and Restoration of Eutrophic Lakes

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Abstract In the age of climate change, the demand and lack of pure water challenges many communities. Substantial amount of effort is put in every year to manage and restore degraded lakes while the long-term effects of those efforts are only poorly known or monitored. Oxygenation, or aeration, is used extensively for the restoration of eutrophic lakes, although many studies question whether this process improves the status of the lakes in the long-term. The desired effect of oxygenation is based on paradigmatic theories that, in the light of recent literature, might not be adequate when long-term improvements are sought. This article canvasses expert views on the feasibility of the 'oxygen–phosphorus paradigm' as well as the future of the management and restoration of eutrophic lakes, based on an international, two-rounded, expert panel survey (Delphi study), employing 200 freshwater experts from 33 nationalities, contacted at three conferences on the topic. The conclusion is that the oxygen-phosphorus paradigm seems to be rather persistent. The experts considered oxygenation to be a valid short-term lake restoration method, but not without harmful side-effects. In addition, experts' low level of trust in the adequacy of the scientific knowledge on the effects of restorations and in the use of the scientific knowledge as a basis of choice of restoration methods, could be signs of a paradigm shift towards an outlook emphasizing more effective catchment management over short-term restorations. The expert panel also anticipated that reducing external nutrient loads from both point and diffuse sources will succeed in the future.

Keywords Eutrophication · Lake restoration · Lake management · Oxygenation · Aeration · Delphi method

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Introduction

The 'Oxygen Paradigm' in Lake Restoration

In this age of climate change, the demand and lack of pure water challenges many communities (Postel 2000; Glenn and Florescu 2015). The lakes and freshwater reservoirs of the world are life-supporting global resources facing multiple demands and pressures. Freshwaters provide ecosystem services in the form of preserving habitats, various recreation possibilities, fishing opportunities, esthetic landscapes, and the provision of fresh water to human communities. The sustainability of these services is threatened by excess phosphorus (P) and nitrogen (N) flows, climate change, an increasing uptake of water in certain areas, chemical pollution, and a loss of biodiversity (Rockström et al. 2009). The excess P flows to freshwaters have resulted in eutrophication, which has been considered as the earth's most common and severe water quality problem (Cooke et al. 2005; Schindler 2012). Eutrophication has decreased the recreational value and usability of lakes, diminished the biodiversity, and changed the abundance of different fish species (Cooke et al. 2005; Smith and Schindler 2009).

In many lakes in the global north, the external nutrient flows have diminished due to improved wastewater treatment, but eutrophication problems continue, as a result of diffuse loading (run-off from, e.g., agriculture and forestry) and internal loading from the lake sediment (Cooke et al. 2005). Internal loading refers to a process in which nutrients already settled in the sediment are released back into the water body. When oxygen is present, it is usually the main electron acceptor in mineralization processes, but if oxygen is exhausted, alternative electron acceptors such as Mn^{2+}, NO_3^-, Fe^{3+}, and SO_4^{2-} are used with consequences for P and N cycling (Nielsen et al. 1990; Shaw et al. 1990; Cai and Sayles 1996). Over seven decades ago, Einsele (1936) and Mortimer (1941; 1942) showed that at low oxygen concentrations the ferric iron in the sediment (Fe^{3+}) is reduced to ferrous iron (Fe^{2+}), which results in the breakdown of Fe–P complexes and in the dissolution of the associated P. This mechanism has later been described by numerous studies (e.g., Boström et al. 1982; 1988; Petticrew and Arocena 2001; Søndergaard et al. 2003). As a result, high concentrations of soluble P are often found in the deeps of eutrophic lakes during periods of low oxygen concentrations. Therefore, the oxygen concentration of the hypolimnetic water (the water body near the bottom, below the thermocline) has been widely considered to be an important factor affecting the water quality and status of lakes (Hupfer and Lewandowski 2008).

To diminish this internal P loading, artificial oxygenation and aeration of the hypolimnetic water have been commonly used and recommended as a restoration tool of eutrophic lakes (Beutel and Horne 1999; Singleton and Little 2006). The effects of aeration and oxygenation are not restricted to P and Fe but they can also be used to diminish the release of ammonia and other reduced substances from anoxic sediments and to promote nitrification (Beutel and Horne 1999; Beutel et al. 2007; Holmroos et al. 2016), to increase the abundance and biodiversity of zoobenthos (Doke et al. 1995; Stigebrandt et al. 2015) and to reduce the rate of mercury methylation in the sediment (Regnell and Tunlid 1991). Moreover, oxygenation has been frequently used to prevent fish kills in eutrophic lakes (e.g., Müller and Stadelmann 2004).

The evidence on the long-term positive effects of oxygenation or aeration is however, sparse and the role of oxygen as a water quality regulator and the effectiveness of aeration as a restoration tool have been questioned. Numerous reasons for the minor effects of aeration have been presented. Gächter and Wehrli (1998) suggested that low concentrations of oxygen and high concentrations of dissolved P in lake deeps are not cause-effect related, but are parallel symptoms of eutrophication. Moosmann et al. (2006) have stated that P retention is regulated by the P concentration rather than by the oxygen concentration in the hypolimnion. Therefore, P release from the sediment cannot be effectively regulated through oxygen. Many studies have also reminded that aeration tends to increase the oxygen consumption in the water column through its effects on temperature and turbulence, which counteracts against the goals of aeration (Gantzer et al. 2009; Horppila et al. 2015; Niemistö et al. 2016). It has also been suggested that the area of anoxic deeps is often so small compared with shallow oxygen-rich areas that P released from the anoxic sediments does not generally affect the productivity of lakes (Tammeorg et al. 2017). Numerous mechanisms (diffusion, photosynthetically elevated pH, activities of the biota) promote the release of sediment P also from shallow oxic areas (e.g., Søndergaard et al. 2003; Holmroos et al. 2009). Accordingly, in numerous lakes aeration has increased the concentration of oxygen and decreased the concentrations of dissolved P in the deeps, but has had minor effects on the overall water quality (Liboriussen et al. 2009; Salmi 2015; Kuha et al. 2016; Horppila et al. 2017).

As a result, the long-lasting 'oxygen-phosphorus paradigm', emphasizing the effect of anoxic internal P loading to the lake water quality and recommending hypolimnetic oxygenation or aeration as a management tool of lakes, seems to be losing its scientific ground, and should be the object of closer examination. In the interdisciplinary research project AQUADIGM we studied the internal P loading in oxic and anoxic areas, effects of hypolimnetic aeration, and expert and stakeholder views on the future of the topic. We consider that if the aeration or oxygenation efforts are not reaching the desired results, there is a need to revise the lake restoration strategies of many countries that rely on aeration as a key restoration tool. To improve the quality of lakes in the long-term, diminishing of external, diffuse nutrient loading through effective catchment management is a prerequisite, but finding cost-efficient methods and policies to reach sufficient reductions in nutrient loading is challenging (Søndergaard et al. 2000; Schindler 2006). Often they are not easy to implement, as they contradict with other interests. This is one of the reasons why there has been a tendency to rely on relatively easy, and conflict-free short-term methods, such as oxygenation of a lake (Schönach et al. 2017).

The Possible Paradigm Shift

Grounding scientific knowledge on the ecological processes behind the degradation of freshwaters and the effects of management and restoration methods is essential, but not enough to solve the 'wicked problem' (Rittel and Webber 1973; Thornton et al. 2013). Socioeconomic forces must be also taken into account when planning ecosystem management and restoration (Mayer and Rietkerk 2004). As the oxygen-phosphorus paradigm comes under increasing scrutiny, it becomes necessary to evaluate what kind of futures are possible, probable, and preferable for reliable lake management and restoration (Masini 1993). Therefore, the objectives, paradigms, expectations, hopes and perceived threats shaping water management now and in the future should be explored.

Despite the challenges related to the principle of oxygen concentration regulating internal P loading and the controversial effects of oxygenation, it remains a common tool for management and restoration of eutrophic lakes. Change in lake management recommendations and practices would require a paradigm shift within the academic community. However, changes in the prevailing paradigms may not take place easily. Ecosystems that are being restored have been found to be resilient to further changes and, therefore, the success of the restoration efforts is often difficult to evaluate (Jeppesen et al. 1991; Carpenter and Cottingham 1997; Suding et al. 2004). In addition, it is often considered that a combination of different restoration measures is most effective (Sollie et al. 2008), but the outcomes of several simultaneously applied restoration procedures are difficult to discern (Søndergaard et al. 2007). Also, as lake ecosystems vary in their characteristics and evolve continuously due to natural processes and multiple human impacts, the reference baselines vary and shift, making target setting and forming of generally applicable management recommendations difficult (Bennion et al. 2011). Furthermore, changes in lake restoration *practices* may happen slowly even if there is clear evidence that the internal P loading is not regulated by the oxygen concentration. First, the scientific community may resist this new discovery and cause a delay in its publication and recognition (Barber 1961) and thereafter the stabilizing elements of the existing socio-technical system may prevent or decelerate changes in societal practices (Geels 2004).

According to Thomas Kuhn (1962), the introducer of the concept of *paradigm*, the adoption of a new paradigm requires new actors, usually young individuals, who question the prevailing paradigm. Eventually a new paradigm replaces the old one, as paradigmatic change will only happen through resistance and reconciliation inside the scientific community. Based on observations of previous scientific revolutions, Kuhn described a paradigm shift as a revolution of science that changes the central concepts, methods, and scopes of interest, and discards the old ones. Within biology and limnology, it has been stated that it is questionable whether there has ever been such a revolution after the introduction of Kuhn's theory (Wilkins 1996; Paine 2002; Walz and Adrian 2008). However, possible paradigm shifts are often discussed within disciplines and are usually understood in a less strict sense, referring to a major change in research agenda, concepts, or methods that replace the former conventions. Here, we use the term paradigm, but acknowledge that the oxygen-phosphorus paradigm may not be an overwhelming paradigm, in the strict Kuhnian sense.

After a paradigm shift within the scientific community, the next delay appears when introducing the new knowledge to stakeholders and other actors. New scientific knowledge and paradigmatic change will not necessarily change management practices easily, if the new knowledge contradicts the existing practices, interests, or other perspectives on the issue (Ludwig 2001). The efforts to manage a lake can be seen as a socio-technical system that involves actors (researchers, consulting agencies, other firms, environmental administration, politicians, funders, NGOs, local people, etc.), institutions (rules, norms, regulations, practices), and systems (resources, physical artefacts, knowledge) that are interrelated (Geels 2004). Interdependencies maintain the stability of the socio-technical system, and therefore a shift, i.e., a socio-technical transition, requires changes in several dimensions and takes time to unfold (Geels and Schot 2010). When a socio-technical transition is desired, transition management (TM) tools can accelerate the process. TM is a governance approach aiming at steering socio-technical transitions towards more sustainable practices through a participatory process of visioning, learning, and experimenting (Rotmans et al. 2001). The approach focuses on long-term thinking as a basis for short-term policy, considering several domains, actors and scales, learning, innovating, and keeping a large number of options (Loorbach 2010).

In this study, the purpose is to find out how strong the oxygen–phosphorus paradigm currently is within the scientific community of lake researchers, whether the paradigm may be changing, and how a possible paradigm shift might affect future lake restoration policies and practices. The aim is to reveal the views of international freshwater experts on the two dominant water management beliefs: 1) the role of oxygen concentration in the internal P loading process and 2) the effectiveness of oxygenation or aeration as a restoration method of eutrophic lakes. In addition, we explore the experts' insights on the future of alternative lake management and restoration strategies and tools up to the year 2030. The task is carried out by conducting an international Delphi study. Delphi is a multi-rounded survey method to utilize expert knowledge in creating future visions or forecasts (Linstone and Turoff 1975; Rowe and Wright 1999). We employ 200 freshwater experts in three conferences (Germany, Hungary and Finland) to evaluate objectives, statements and possible future changes regarding lake management and restoration. Our working hypothesis is that the trust in the major role of oxygen in internal phosphorus loading is still strong, but there may be signs of weakening of the paradigm. This could anticipate a shift towards the outlook suggesting that short-term

Table 1 Sampling of the expert panel

	LS, Finland	SEFS, Germany	SIL, Hungary	Total
Conference attendees total	81	488	487	1056
Sample size (approx. no of attendees in the session)	80	350 (approx.)	400 (approx.)	830
Taken questionnaires	81	189	298	568
Returned questionnaires, 1st round	**45**	**70**	**85**	**200**
Response percent (of taken questionnaires)	58%	37%	29%	35%
Response percent (of session attendees)	58%	20% (approx.)	21% (approx.)	24% (approx.)
Number of respondents enrolled in the 2nd Delphi round	43	48	55	146
Responses on the 2nd Delphi round	**19**	**20**	**19**	**58**
Response rate of the 2nd Delphi round (%)	44%	42%	35%	40%

Total number of responses in each round in bold

restoration methods, such as oxygenation, should be replaced, or at least effectively complemented, by methods that aim for long-term improvement in the quality of eutrophic lakes. These would probably emphasize diminishing external nutrient loading through effective catchment management.

Material and Methods

The Delphi study

Futures research provides an array of participatory methods suitable for anticipating the alternative futures of complex issues, by making the participants deliberate on the future of the topic (e.g., Bell 1997). The Delphi technique is a futures research method that employs expert knowledge in multiple rounds to synthesize the current knowledge and shed light on future pathways of a variety of issues (Linstone and Turoff 1975; Rowe and Wright 1999). The Delphi method is useful especially when dealing with issues that are expected to change in the future and where there are multiple options for future developments that depend on actor's decisions (Gordon 2012). Originally the Delphi method aimed at consensus forecast, but has evolved to multiple applications that usually aim at opening up the sphere of possible futures (Preble 1983; Tapio 2003; Steinert 2009; de Loë et al. 2016). The use of experts is based on the fact that experts have deep knowledge on the issue and insights as to what could shape the issue's future and thus, they are able to produce better argued and more rational future estimates than laypeople (Varho and Huutoniemi 2014). The Delphi process is anonymous in order to prevent disadvantageous group behavior, such as dominant characters suppressing the ideas of less dominant participants. The purpose is to create circumstances where mutual learning is possible through multiple rounds and a revision of opinions based on the given feedback (Van Dijk 1990). Usually Delphi studies employ an expert panel constituting of a few dozen experts (Gordon 2012; de Loë et al. 2016), but in this study, a larger panel employing several hundred experts was aspired in order to avoid a biased overview on the popularity of the oxygen-phosphorus paradigm. Therefore, the first Delphi round of this study was conducted at two international, large, scientific freshwater conferences gathering the top experts of the topic and a national, Finnish freshwater symposium, all arranged in close sequence at the time of the project.

Selection of the expert panel

Delphi studies do not usually aim for a statistically representative sample, but rather for a good coverage of views. As the panel in this study was constituted more randomly than the usual hand-picked expert panels, we will explain the statistical representativeness of the sample here. The population of the study included the attendees of each conference. However, the results may also more widely represent the views of freshwater researchers, as there are only limited number of researchers in the discipline and the chosen conferences are among the most visited and acknowledged in the field—SIL (International Society of Limnology) Congress globally, SEFS (Symposium for European Freshwater Sciences) in Europe, and the Limnology Symposium (LS) in the national Finnish context. The Finnish conference was added in the sample as the research project had a special interest in situation in Finland and it enabled comparison between the views of Finnish and international experts.

At the SEFS and SIL, cluster sampling was used, as a plenary session was chosen for recruiting the expert panel. All the attendees of the conferences had a chance to end up in the sample, although the topics of the plenary sessions may have affected the constitution of the sample. The Delphi study was presented orally at the end of the keynote lectures and the questionnaires were handed out to those present. The plenary sessions were chosen based on matching topics, early placement in conference schedule (larger audience) and preferences of the organizers of the conferences. At the LS, the sample of the study was the whole population, as all the conference guests were given the questionnaire at the reception. The study was presented orally also at LS after the plenary lecture. The numbers and percentages of the responses are presented in Table 1.

Many respondents spontaneously noted that despite the questionnaire being short, answering the questions required time and effort. This might have increased the loss percent since there was no specific time dedicated to filling in the questionnaire and the timetables of the conferences were rather tight. Some conference attendees also reported that they did not want to answer the questionnaire since they did not consider themselves as experts of lake restoration. Instead, their area of expertize was, for example, rivers. Also, it is probable that the conference attendees who considered the subject interesting were more likely to return the questionnaire. As a result, the expert panel is likely to include more lake restoration experts than the whole population and, subsequently, individuals more interested in the topic than the population on average. Following the principles of Delphi studies, this increases the usefulness of the responses, as they are based on more in-depth expert knowledge. It should be noted that the present study is not a standardized opinion survey, but a method to make experts ponder on the topic and learn from each other's answers.

The international conferences were the SEFS 8 2013 Symposium for European Freshwater Sciences on July 1–5, 2013 in Münster, Germany, organized by the European Federation for Freshwater Sciences, and the SIL XXXII Congress on August 4–9, 2013 in Budapest, Hungary, organized by the International Society of Limnology (SIL). A national, scientific freshwater conference, The Limnology Symposium on April 10–11, 2013 in Helsinki, Finland is organized by The Finnish Limnological Society (SLY). The LS is arranged every 3rd year and gathers together Finnish professional limnologists, working as researchers and in other lake related professions. The theme of the symposium was: "Are the lake research and management methods up to date?". The questionnaire at the LS was in Finnish, while at the other conferences, the language was English.

At SIL, the Delphi study was presented after the first plenary lecture after the opening ceremony, given by Robert J. Naiman and titled "Socio-ecological complexity and the restoration of river ecosystems". At SEFS, the study was presented on the 2nd day of the conference after two plenaries, "The LIFE programme: more than 20 years improving freshwater ecosystems" by Simona Bacchereti and Carlos de la Paz, and "From species level indication to functional group level" by Ellen van Donk.

Table 2 The characteristics of the respondents of the first round questionnaire: gender, education, age, and employer of the respondents in each conference

			LS	SEFS	SIL	Total
Gender	Male	Number	20	42	47	109
		Per cent	44%	61%	60%	57%
	Female	Number	25	25	29	79
		Per cent	56%	36%	37%	41%
	Prefer not to say	Number	0	2	3	5
		Per cent	0%	3%	4%	3%
Education	Undergraduate	Number	1	1	0	2
		Per cent	2%	1%	0%	1%
	Bachelor	Number	1	2	0	3
		Per cent	2%	3%	0%	2%
	M.Sc. or M.A.	Number	26	13	18	57
		Per cent	58%	19%	22%	29%
	Licentiate or Doctor	Number	17	53	63	133
		Per cent	38%	77%	78%	68%
Age	Under 30	Number	4	13	17	34
		Per cent	9%	19%	22%	18%
	30–39	Number	16	22	19	57
		Per cent	36%	32%	25%	30%
	40–49	Number	16	14	12	42
		Per cent	36%	21%	16%	22%
	50–59	Number	6	12	13	31
		Per cent	14%	18%	17%	17%
	60 and over	Number	2	7	15	24
		Per cent	5%	10%	20%	13%
Employer	University	Number	12	41	54	107
		Per cent	27%	60%	67%	55%
	State research institute or bureau	Number	16	21	19	56
		Per cent	36%	31%	24%	29%
	Private research institute	Number	2	3	4	9
		Per cent	4%	4%	5%	5%
	Municipality	Number	4	1	1	6
		Per cent	9%	2%	1%	3%
	Business	Number	6	0	1	7
		Per cent	13%	0%	1%	4%
	NGO	Number	4	1	0	5
		Per cent	9%	2%	0%	3%
	Not working	Number	1	1	2	4
		Per cent	2%	2%	3%	2%

The first and the second Delphi round and characteristics of the respondents

Based on the research objectives, the first-round questionnaire was co-designed by the interdisciplinary research team consisting of limnologists and futures researchers.. The questionnaire was designed as a single 2-sided A4-sheet with a concise introduction, five sets of questions and an inquiry for background and contact information. The background information is reported in Table 2. The respondents from different conferences differ from each other to some extent. In SEFS and SIL there was male predominance, as in LS it was vice versa. The education of the respondents was most often Licentiate or Doctor in SEFS and SIL, while in LS the Master's degree was the most common background degree. The respondents of SEFS and SIL were employed mostly in Universities, whereas in LS the respondents were employed mainly in other research institutes, and share of business, NGO and municipality employees was higher than in SEFS and SIL. These differences should be bore in mind when making comparisons between the conferences. The working countries of the respondents varied; the most common was Finland (55), as all of the respondents at the LS were working in Finland. Other common working countries were Germany (19 respondents), USA (9), Italy (8), UK (8), Spain (8), Austria (7), Brazil (7), Canada (6), the Czech Republic (6), Hungary (6), Poland (6), and Switzerland (6). Other countries varied and totaled less than five respondents each. Altogether, experts from 33 different nationalities responded.

The first round questionnaire enquired about the experts' views on a seven-point rating scale, seven-point Likert scale, and as open-ended questions (Table 3.) Likert scale is a symmetric rating scale commonly used in survey research to measure level of agreement (Likert 1932). When designed properly, it produces interval level data that can be analyzed and tested statistically in various ways and converted into sum variables.

The list of different lake management and restoration methods in question 3. (see Table 3), was based on the recommendations made by Finnish Environment Institute (Väisänen and Lakso 2005; Mattila 2005). Objectives for the management and restoration of eutrophic lakes in question 1. (see Table 3) was enquired to find out whether there are differences in the experienced importance of objectives between respondents from different conferences, as well as to see what objectives the respondents are aiming for while giving evaluations on the use of different management and restoration methods. The aim of the statements of question 2. (see Table 3.) was to find out how strongly the respondents believe in the major role of oxygen in the internal P loading process and whether they believe that oxygenation / aeration is a valid method to restore eutrophic lakes now and in the future. The aim of question 4. (see Table 3) was to pursue ideas on how to accelerate socio-technical transition as science evolves and new knowledge is obtained. That is, to recognize bottlenecks for knowledge diffusion and other obstacles preventing new scientific knowledge to be obtained.

In the first questionnaire round, 146 out of the 200 respondents submitted their email addresses for the execution of the second Delphi round. Approximately a year after the conferences, in the spring of 2014, the second Delphi round was conducted. The survey was sent by e-mail to those first-round respondents who had indicated their interest by submitting their e-mail addresses, and 58 responses (40%) were received. The summaries and conclusions of the answers from the first survey round were given next to the second-round questions, and the respondents were asked to re-evaluate and comment on their answers. The second-round respondents evaluated their professional experience within the field of freshwaters amounting to 20 years (Mean), and their level of expertize in lake management being 3.6 Mean (Mo and Md 4) on a five-point Likert scale (1 = No expertize, 3 = Moderate expertize, 5 = High expertize). Two respondents, who reported their level of expertize being 1 (No expertize) and had less than 2 years of professional experience in the field, were excluded from the analysis of the second Delphi round responses.

The analyses of the material

The numerical responses to the questions were processed using the SPSS 23 software and MS Excel. Emphasis was given to descriptive statistics, cross-tabulations, as well as Means, standard deviations, and Kruskal-Wallis tests (Kruskal and Wallis 1952). A non-parametric, independent-samples Kruskal–Wallis H test was applied in SPSS to search for statistically significant differences between the responses from the three conferences. The Kruskal–Wallis test was used, because the preconditions for the use of a one-way ANOVA were not met due to the heterogeneity of variances. The qualitative answers were analyzed using qualitative content analysis (Krippendorff 2004).

Results

Objectives for the Management of Eutrophic Lakes

According to the experts, *Biodiversity conservation* and *improving ecological status of a lake (according to EU Water Framework Directive)* were the most important objectives for the management and restoration of eutrophic

Table 3 Questions in the first Delphi round questionnaire

Question	Items to be evaluated	Scale
1. There are different objectives for management and restoration of eutrophicated lakes. How important are the different objectives in your personal opinion?	Biodiversity conservation; Improving recreational opportunities; Improving fishing opportunities; Landscape conservation; Improving residential environment; Improving the ecological status of a lake (according to EU Water Framework Directive); Other, what?	1–7 (1 = Not important at all… 7 = Very important
2. What is your opinion on the following statements regarding the eutrophicated lakes of the country you work in?	Oxygen concentration at the water-sediment interface regulates internal P loading; Oxygen concentration at the water-sediment interface is the primary regulator of internal P loading of a lake; In addition to oxygen depletion, also other factors induce internal P loading; Oxygenation/ aeration reduces internal P loading of a lake; Oxygenation/ aeration is an effective management method of eutrophicated lakes; Oxygenation/ aeration improves status of a lake in the long-term; Oxygenation/ aeration causes harmful side-effects to the lake ecosystem; Currently common view that oxygen concentration regulates internal P loading, will alter in the future; Currently common view that oxygenation/ aeration is an effective restoration method, will alter in the future; Overall, lake restoration efforts have improved the status of the lakes permanently; Lake restoration efforts generally reach the set targets; The choice of lake restoration methods is based on scientific knowledge on the effects of methods; Scientific knowledge on the effects of restoration methods is adequate; The status of lakes will be better in 2030 than today; Lakes are being restored more in 2030 than today	−3… + 3 (−3 = Completely disagree…0 = Neither disagree or agree… + 3 = Completely agree (Likert-scale)
3. Different lake management and restoration methods are listed below. Please evaluate probable and preferable change in each method's application volume by the year 2030 compared to present-day volumes. Consider the lakes of the country you work in.	Oxygenation/ aeration; Biomanipulation; Hypolimnetic water withdrawal; Raising and controlling the water level; Removal of macrophytes; Dredging; Chemical inactivation of phosphorus; Reducing external nutrient discharges from diffuse sources e.g., buffer zones; Reducing external nutrient load outside the discharge area e.g., sedimentation ponds; Reducing external nutrient discharges from point sources; Other method, what?	−3… + 3 (−3 = Strong decrease…0 = No change… + 3 = Strong increase
4. What would speed up or enhance new scientific knowledge to have an effect on water management practices?	Open-ended question	
5. Arguments supporting your answers above, e.g., ecological, societal or technological drivers of change:	Open-ended question referring to question 3.	

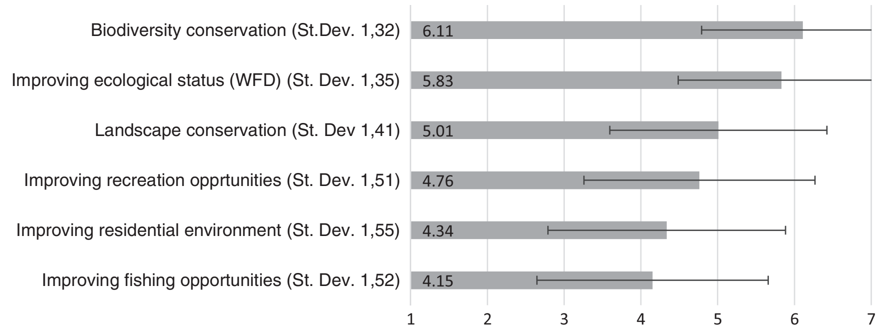

Fig. 1 Mean values and standard deviations for the question "There are different objectives for management and restoration of eutrophicated lakes. How important are the different objectives in your personal opinion? Please rate the importance on a scale 1–7 (1 = Not important at all; 7 = Very important)" ($N = 190$)

lakes (Fig. 1). *Improving fishing opportunities* and *residential environment* and other usefulness for humans were considered less important objectives. The open question for other objectives, not mentioned in the list, gained answers only from 12 % of the respondents, of which one third referred to drinking water and the others to a range of issues.

The responses from the different conferences seemed to be rather uniform, as most differences in responses were not found to be statistically significant. Interesting exceptions to this were the attitudes towards the objectives of *Improving recreational opportunities*, *Improving fishing opportunities* and *Improving residential environment* (Fig. 2). At the LS, these objectives were considered as more important compared to at SEFS and SIL, and the differences were found to be statistically significant ($p < 0.001$). In the case of the variable *Improving recreational opportunities*, the difference is also connected to the respondent's organizational background. When comparing the Means using the Independent-samples t-test, it was noted that the respondents employed in universities (Mean 4.43, St. Dev. 1.49) considered improving recreational opportunities as a less important objective for the management of lakes than the respondents employed in other organizations (Mean 5.15, St. Dev. 1.43). This difference was found to be statistically significant, as $t(188) = -3.358$, $p = 0.001$, 2-tailed. As for the other questions, there were no statistically significant differences found in relation to the respondent's employer. None of the variables showed statistically significant differences in relation to the level of education. A significant ($p < 0.03$) difference was found in the variable *Biodiversity conservation* between female (Mean 6.45) and male (Mean 5.93) respondents.

The Strength of the Oxygen-phosphorus Paradigm Now and in the Future

We measured the strength of the paradigm based on the responses of the first Delphi round. Several statements concerning the paradigm were computed to form two general sum variables: (1) Effectiveness of aeration, and (2) Role of oxygen. Cronbach's alpha was calculated to evaluate the reliability of the sum variables and, consequently, one variable was excluded from both of the sum variables in order to improve the Alpha. The resulting sum variable *Role of oxygen* constituted of three variables, with Cronbach's alpha 0.642 (considered acceptable). The *Effectiveness of aeration* constituted of five variables, with Cronbach's alpha 0.667 (considered acceptable). The sum variables are presented in Fig. 3.

The respondents seemed to trust that in general, oxygen has quite a remarkable role in regulating internal P loading and there were no significant differences between the responses from the different conferences. The effectiveness of oxygenation/ aeration as a restoration method of eutrophic lakes was considered mediocre, responses differing slightly between conferences. The difference between the responses from the LS and SEFS was statistically significant, as the respondents at SEFS trusted the effectiveness of aeration more (Adj. Sig 0.019).

The answers on the second Delphi round remained mostly parallel to the first round. The Means of the responses moved slightly further away from the middle (toward either disagree or agree), thus, being a little more extreme than on the first round. The Standard Deviations decreased in most questions, indicating increasing consensus, but in one fourth of the statements, Standard Deviation of answers increased. The relative distribution of responses to each statement (in question 2, Table 3) on the second round is presented in Fig. 4.

Figure 5 displays the probable and preferable future prospects up to 2030 of seven key restoration methods and three strategies to reduce external loading in the order of their desirability. The panel essentially agreed on the need to concentrate on decreasing external loading, and believed that it will become more common in the future. The least desirable methods, according to the panel, were dredging, the removal of macrophytes, and the chemical inactivation of phosphorus, although the use of all of these was considered to increase up to 2030. Biomanipulation was considered the most preferable in-lake restoration method. Aeration was anticipated to increase slightly, also in the preferred future. A closer look at the views on the probable

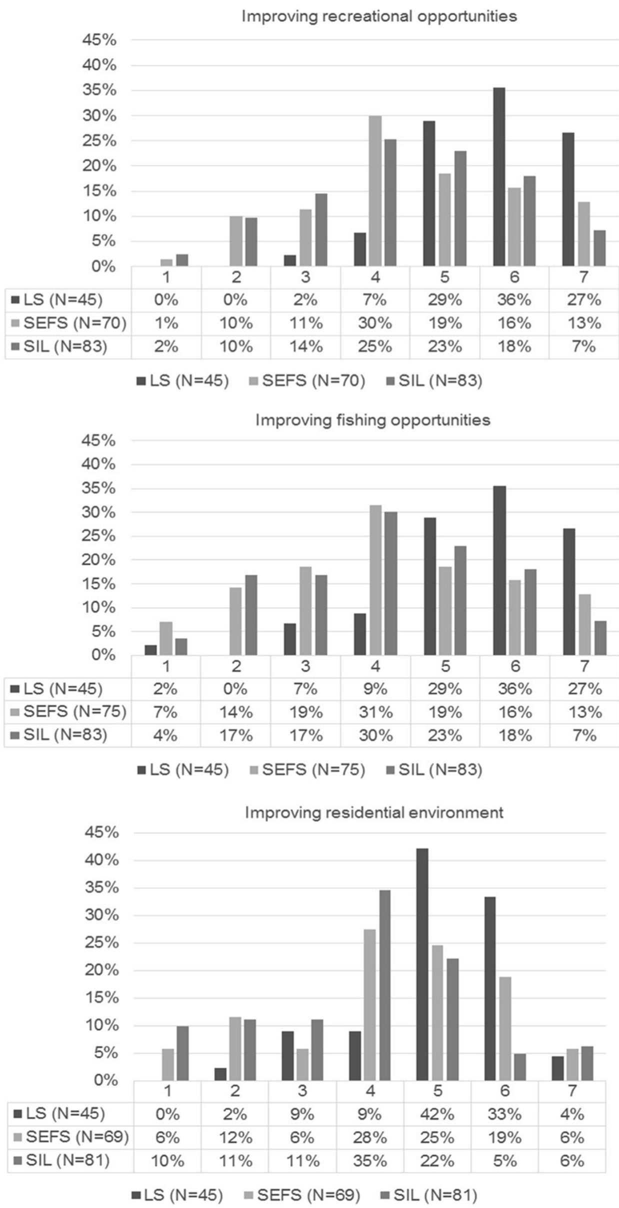

Fig. 2 Distribution of responses to the objectives *Improving recreational opportunities*, *Improving fishing opportunities*, and *Improving residential environment*, on a scale of 1–7 (1 = Not important; 7 = Very important). For these variables, the independent-samples Kruskal–Wallis test showed a statistically significant ($p < 0.001$) difference in distributions between the LS and the other two conferences

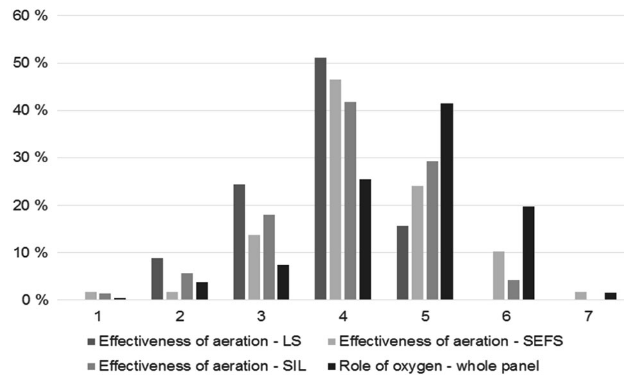

Fig. 3 The trust in the effectiveness of oxygenation / aeration as a management method of eutrophic lakes in different conferences (the sum variable of five variables, $N = 175$) and the trust in the role of oxygen concentration on the internal P loading (the sum variable of three variables, $N = 188$). Scale 1–7 (1 = small; 7 = great)

and the preferred future of aeration reveals that the experts seem to be pondering about the issue without a clear stance (Fig. 6). The respondents anticipated that the number of all lake restorations will increase by the year 2030 (Fig. 4). Efforts to reduce external loading is believed to increase considerably as well, but the quality of lakes is not believed to be better in 2030 than today, according to second round responses (Figs. 4 and 5).

Several second round comments on the questions pointed out that lakes are so different that the role of oxygen in lakes cannot be generalized. In some lakes oxygen is the primary regulator of P release from the sediment, but in other lakes for example fish or other factors are more significant, the respondents stated. It was also stated that oxygenation is suitable only in some occasions and in some lakes, while in others it may have harmful effects, e.g., warming of hypolimnion. The role of catchment and external loading was emphasized and some stated that without actions at the catchment area, the lake restoration efforts are often useless. It was believed that oxygenation or aeration is favored because something has to be done, but that the process acts as a first aid and will not affect the quality of water after it is stopped. According to some of the comments, the lake restoration projects are usually conducted without proper planning and knowledge and thus they fail to reach the targets.

To enhance new scientific knowledge to have an effect on water management practices (question 4, Table 3), a great majority of the responses stressed the importance of better interaction and communication between scientists and other stakeholders, including administrators, authorities, companies, citizens, and restoration managers. Use of media and producing articles for lay people in their own language was proposed, as well as seminars and other communication platforms. Also increasing research funding, having more long-term monitoring of freshwaters and the effects of restoration projects, doing more applied research and better planning of the restorations were often proposed. Also high quality education and political will were called for.

Discussion

Will the oxygen-phosphorus paradigm persist? Based on this research, the answer seems to be yes, at least in the

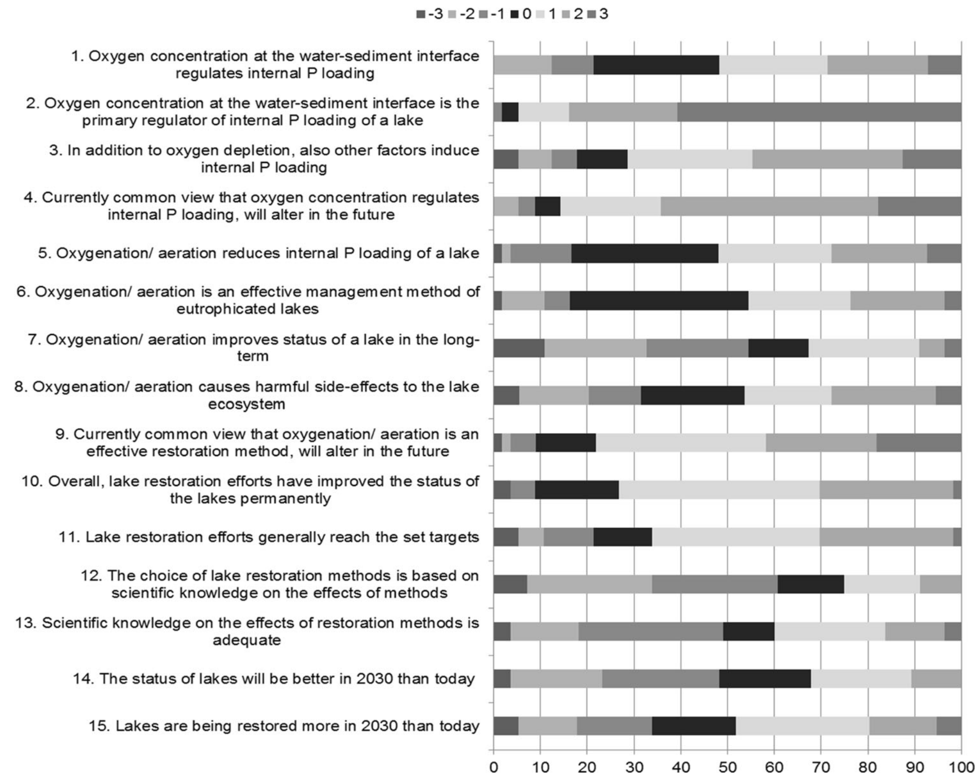

Fig. 4 Percent distribution of second round responses to statements concerning the role of oxygen in the lake ecosystems, oxygenation/ aeration as a restoration method and lake restorations in general on a scale $-3\ldots+3$ ($-3=$ completely disagree; $0=$ Neither disagree or agree; $+3=$ completely agree) $N=56$

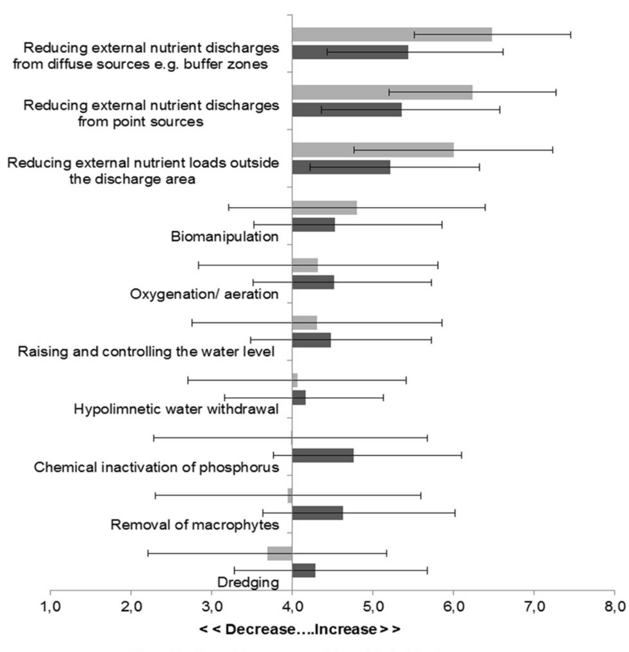

Fig. 5 Estimates of the probable and preferred futures of seven lake restoration methods and three strategies to reduce external loading – Mean values with standard deviation bars (Values above 4 indicate estimates of increase in the use of the method, values below 4 indicate a decrease. Maximum value 7, minimum value 1) $N=145$

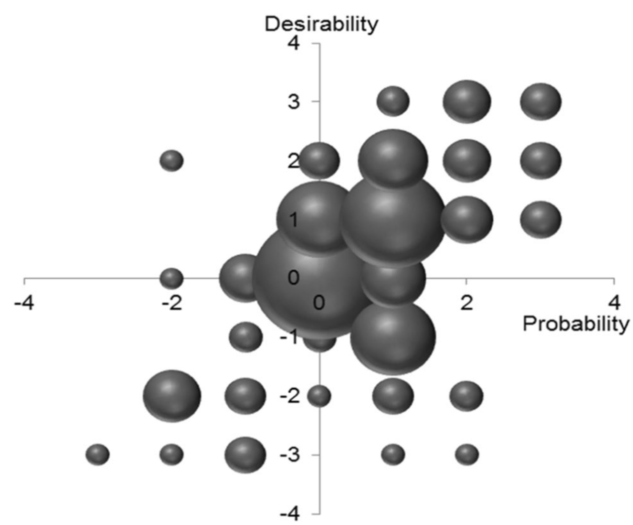

Fig. 6 Frequency of answers regarding the probable and the preferred future of oxygenation / aeration. ($-3=$ strong decrease in the use of the method, $0=$ No change, $+3=$ Strong increase in the use of the method)

near-term future. There are no strong signs of a paradigm shift and the expert panel's belief in the major role of oxygen concentration in regulating internal P loading of a lake seems to be rather uniform. On the contrary, it appears that the trust in oxygenation as a restoration method of eutrophic lakes is weakening, even though no decline in oxygenations was anticipated, instead, the use of oxygenation was believed to increase slightly. However, it seems that trust in the general applicability of oxygenation / aeration in lakes is not very strong. The panel found that it is not effective in the long-term, there are harmful side effects related (e.g. warming of the hypolimnion) and that it cannot be used as a routine practice for eutrophic lakes.

The panel stated that there are no general methods for lake restorations, but instead the methods and their application have to be evaluated case specifically. This presents a challenge to restoration projects, as the adequate knowledge and expertize to evaluate the precise conditions of the lake in question, and the ability to choose and apply the appropriate restoration and management methods is highlighted. The needed expertize or long-term follow-up information is not necessarily present in each restoration project, as the projects are often led by lay citizens or advisory groups with varying knowledge and interests. This brings about also advantages, as the local commitment and acceptability increases, but carries a risk of erroneous actions that might counteract the targets, if scientific knowledge on suitable restoration and management methods is not adequately heard.

The issue is further complicated taken into account that, according to the expert panel, the most important objective for restoration should be the conservation of biodiversity, while the lake users, managers, and funders are likely to have other objectives for restorations, for example recreational use, fishing opportunities, and landscape conservation. In this study, the respondents employed in universities considered recreational opportunities as a less important objective for restorations than the other respondents. A clear difference in objectives was also found between the respondents of the Finnish conference, and the other two conferences. The respondents of the Finnish conference valued recreation, fishing opportunities, and residential environments more than other respondents. In a country with approximately 188,000 lakes and a low population density, people, even experts, may have a more practical relationship with lakes. The Finnish respondents also trusted the efficacy of oxygenation less than the respondents from the European conference (SEFS), which might be related to the fact that in Finland, the lakes are relatively shallow.

Different targets will often require different methods and different kind of indicators for success. In addition, there are also other motives and restrictions involved in the restoration projects, including monetary resources, ownership of the water areas, and expected time frames for the outcomes of the restoration projects, which may override the experts' recommendations. Often, there is a need to reduce the external loading of nutrients in order to prevent further degrading of the water, but the stakeholders want visible results in the short-term, which leads to application of short-term measures that might even counteract the long-term improvements (Carpenter et al. 2001). It has been noted that conflicting targets in environmental management can result in a paralyzed situation, in which decisions on the needed actions will not be made, as the long- and short-term targets for management do not fit together (Hukkinen 1993).

These contradictions will probably become more common when more responsibility over water restoration is given to the citizens. The principle is presented in the EU Water Framework Directive (Directive 2000/60/EC) and in Finland's water policy as well. In Finland, the regional water resource management plans officially state that as state funding for water restorations will decrease, more effort will be expected from other actors (Valtioneuvoston et al. 2015). It will be challenging to reach a common understanding on what measures to take to meet the water quality targets, as a variety of different actors are involved and, simultaneously, very sophisticated expert knowledge is required. These challenges are related to many wicked problems of our time, and there are no easy solutions.

A dialog between stakeholders and scientists, as well as acknowledging the differing and conflicting values behind the different management strategies have been proposed in order to alleviate these problems (Ludwig 2001). Also in this study it was distinctively proposed that better interaction and communication between scientists and other stakeholders would help. Common forums, better communication between interest groups, popular articles, involving scientists in the restoration projects, presenting success stories, and increased collaboration were suggested for the promotion of the interaction and impact of scientific findings. This requires effort from scientists, but would probably be a good strategy for the future of lake management and other environmental management issues as well. The key question to be answered is then, how to persuade scientists to take part in the dialog, when it is not usually rewarded in the academia. Possibly, this could be changing in coming years, as the impact outside academia has become among the assessment criteria in some funding instruments.

As lakes are resilient and the effects of the restoration activities are somewhat unclear, there are no easy and effective means to alleviate eutrophication (Carpenter and Cottingham 1997; Søndergaard et al. 2007). Instead, often a combination of different management practices is considered the best strategy to improve water quality (e.g., Sollie et al. 2008; Papastergiadou et al. 2010). However, as concluded here, the oxygen is quite strongly believed to regulate the internal P loading of a lake and consequently attempts to affect oxygen concentration will probably persist until fundamentally different paradigm takes over. It could be 'sustainable restoration' entailing catchment care and ecosystem resilience instead of 'reactive management', as proposed by Carpenter and Cottingham (1997). It would emphasize long-term restoration with system drivers at the focus, which would mean an end to using solely short-term restoration methods that may delay reaching the long-term targets. This kind of thinking was also supported by the expert panel, as decreasing the external nutrient loading was highly favored over other restoration methods, both in the probable and the preferable futures. However, the mismatch of agricultural, forestry and land-use practices with catchment management prevents effective water management, and focuses the attention to less effective in-lake methods and local activities. Full employment of catchment management is dependent on national and international (e.g., EU) level agreements and policies, and therefore requires much more than co-operation between local actors and scientific community. To promote wider scale 'sustainable restoration', the scientific communication should be extended to cover national and international agricultural, forestry and land-use policies. Also, the ecosystem resilience should be considered as one of the specific objectives of the restoration projects, as then the potential shifts between alternative states and unintended side-effects would be better acknowledged (Brown and Williams 2015).

Even though the current oxygen-phosphorus paradigm seems persistent for now, there were some signs of perceived problems with it. The low levels of trust in the adequacy of the scientific knowledge on the effects of restoration methods and in the use of the scientific knowledge as a basis of choice of restoration methods could be signs of a forthcoming crisis that could shake the prevailing paradigm. The common view that the number of oxygenations will stay around current levels or increase only slightly, while the total number of restorations is anticipated to grow, also indicates that the role of oxygenation could be diminishing. To accelerate the transition towards an outlook that emphasizes catchment management at the expense of short-term reactive measures, such as oxygenation, activities of transition management could be utilized. This would comprehend long-term visioning as a basis for short-term actions and well-monitored small-scale experimenting and participatory activities as suggested by Loorbach (2010).

Despite of the difficulties in reaching the targets of the restorations, the expert panel anticipated the future of lake restorations to be quite good. According to the panel, the number of lake restorations will increase and external loading will be reduced by the year 2030. No fundamental changes or new groundbreaking methods are seen in the horizon nor did it seem any specific fears for the future emerge from the data. Taking into account the effects of climate change on waters and needed adaptation measures (Jeppesen et al. 2009; Whitehead et al. 2009), the panel seemed quite optimistic about the future. For this future to realize, it is essential to seriously invest in reductions of external loading by effective catchment management, supported by carefully selected in-lake restoration methods that promote the long-term nutrient reducing targets and resilience of the ecosystems.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no competing interests.

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