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The past, present, and future of a lake: Interdisciplinary analysis of long-term lake restoration

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ABSTRACT

The history and future of the restoration efforts at the hypereutrophic southern Finnish lake, Tuusulanjärvi, are investigated. The interdisciplinary study is conducted within a modified DPSIR- framework, which allows us to both trace back and envision the future of the dynamics of the complex socio-ecological processes involved in restoration. The study covers the time period from the early 1970s up to 2030. The longitudinal study integrates environmental historical, limnological, and futures studies. The analyses reveal the multiple time scales of social and ecological processes present in long term restoration, the changing perceptions of and emphasis on restoration goals and outcomes over time, and the challenges that incidental and uncertain parameters, such as weather conditions, pose to sustainable and efficient restoration endeavors.

1. Introduction

Despite the great advances that have been made in fresh water protection, such as qualitative and quantitative improvements in waste water treatment, the anthropogenic eutrophication of lakes remains one of the most obvious and prevalent water quality problems (e.g. Schindler, 2012). Phosphorus (P) is usually the limiting nutrient for productivity in lakes, and is thus of key importance in the process of eutrophication (Schindler, 1978; Keeneleyside et al., 2012). The total phosphorus (TP) concentration in lake water is a function of the externally delivered P, lake hydraulic residence time, and the tendency of P to settle from the water column (Brett and Benjamin, 2008). Under certain conditions, settled P can be released back into the water column, providing an important internal source of P for algae (Marsden, 1989). Internal P release has been related to anoxic conditions in hypolimnetic water (Hupfer and Lewandowski, 2008), and can be induced by diffusion, bioturbation by dense fish stocks, or photosynthetically elevated water pH (e.g., Søndergaard et al., 2003; Holmroos et al., 2009).

Efforts to remedy or reverse the human-induced environmental damages of the past, known collectively as ‘ecological restoration’, have grown over recent decades into an acknowledged field of research, and are being put into practice on a broad scale. Restoration aims to improve the environmental quality of degraded lakes through the “re-establishment of important missing altered processes, habitats, concentrations and species [.] to attainable approximation of pre-disturbance conditions” (Cooke et al., 2005, 14). In practice, this may sometimes involve more limited goals, such as reducing systemic pressures and enabling natural recovery, but may also involve significant interventions (Keeneleyside et al., 2012). The restoration of eutrophicated lakes is usually realized via the reduction of external (i.e. originating from the lake catchment) and internal phosphorus (P) loads, aiming at reducing algal biomass (e.g., Spears et al., 2013). In the limnological approach, the relationship between chlorophyll *a* (Chl *a*), a surrogate for algal biomass, and total phosphorus (TP) has served as a framework for predicting the bio-chemical outcome of nutrient controls (Stow and Cha, 2013; Filstrup et al., 2014; Jones and Brett, 2014). As for the anthropogenic perspective on lake restoration, the roles of the culturally determined values and societally preferred functions attached to the respective lake are highlighted.

Lake restoration can be understood both as a process of transition and as a product, i.e. an outcome of these transitions (Higgs, 2003, 110–112). While the goal of the *recovery* of a disturbed ecosystem suggests the workings of autonomous natural processes, the notion of restoration as the *assisted recovery* of a lake includes both intentional human action and ecological processes which are steered or accelerated through human interventions. Human restorative actions are intentionally directed towards specific ends, including a diverse set of anticipated, observed, and interpreted outcomes of restoration activities (cf. Higgs, 2003, 110–112). Determining restoration goals, and the

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best practices to achieve these goals, are necessarily value-laden activities, as they involve human perceptions, beliefs, and emotions. They are influenced by preferences, possibilities, and knowledges that are context-dependent variables that shift over time.

While hydro-ecological literature has identified several factors contributing and confounding to the desired outcomes of aquatic restoration endeavors (Verdonschot et al., 2013), the literature is scarce on empirical cases that take into consideration both ecological and societal processes, and additionally capture the changes over time in the dynamics of these processes. We propose that by utilizing a long time span perspective we can increase our understanding of the complex and intertwined nature of the societal and ecological processes active in lake restoration, and of how these contribute to the anticipated and realized outcomes of restoration. Through the study of six decades of restoration at the hypereutrophic Lake Tuusulanjärvi, located in southern Finland – and also how the results of these efforts were perceived – we aim to answer the following research questions:

- What kind of interventions have taken place at the lake in the past, and are anticipated to take place in the future?
- What were, and will presumably be, the respective goals for restoration?
- What temporal dimensions are related to the social and ecological processes of restoration, and how did they affect both the restoration endeavors and the perceived and anticipated outcomes of that restoration?

In order to pursue these goals, we propose an interdisciplinary case study approach that benefits from multiple sets of source material, which are introduced in Section 2.2 (and in more detail in the Supplementary material appendix), together with the Drivers-Pressures-State-Impact-Responses (DPSIR)-framework, which we apply to our analysis. The results of the study are chronologically organized according to the identified key phases and significant ruptures during the six decades of restoration efforts. The changes in the relationship between Chl *a* and TP throughout these phases are analyzed. The article concludes by highlighting the multiple time scales of social and ecological processes that are inherent to long-term restoration projects, the changing perceptions of and emphasis on various restoration goals and outcomes over time, and the challenges that incidental and uncertain parameters – such as weather and climate conditions – pose to sustainable and efficient restoration endeavors.

2. Materials and methods

2.1. Case study approach

Our research design includes a longitudinal case study covering six decades (1970–2030), and an interdisciplinary approach including contributions from environmental history, limnology, and futures studies. The study was performed in the context of a southern Finnish lake with an extensive restoration history, Lake Tuusulanjärvi. It is located approximately 40 km north of the capital, Helsinki, and belongs to the catchment area of the River Vantaa, through the Tuusula River. The lake surface area comprises 6 km^2, and its mean depth is 3.2 m, with one main basin reaching 10 m depth. It has a fairly narrow (max 2 km) and extended (7–8 km long) form, with municipal centers (Järvenpää and Hyrylä) at both ends (see Fig. 1). The catchment of the lake (92 km^2) belongs to the jurisdiction of two municipalities. The populations of both Järvenpää and Hyrylä have grown continuously since the 1950s, with present totals of 41.000 and roughly 20.000 people, respectively.

Tuusulanjärvi is the largest lake in the country's most densely populated Uusimaa province and thus has considerable recreational significance. Popular uses of the lake include summer and winter swimming, fishing, boating, and ice skating; the lake is also surrounded by a scenic bike route. The lake and its shores are home to great biodiversity, and it has been included in both the National Waterfowl Habitat Protection Programme and the EU-wide Nature 2000-network, as part of the EU Habitat Directive. The aesthetic value of the lake scenery is highly prized by the growing local population.

Tuusulanjärvi is naturally eutrophic, and with the predominant clay soils in the catchment the water is greyish-brown in color. Early signs of anthropogenically inflicted eutrophication have been observed since the 1920s, becoming more pronounced between the 1930s and 1950s, and rapidly advancing in the post-WWII decades (Tolonen et al., 1990). The hypereutrophic lake has been subject to various interventionist restorative activities for more than four decades, and the current restoration efforts are expected to continue into the future, which makes Tuusulanjärvi a fruitful case to explore the socio-ecological dynamics of lake restoration over time.

2.2. Materials, methods and integrated analysis

The analysis of Tuusulanjärvi's restoration history and future prospects was performed using the systemic DPSIR framework (Fig. 2), which is a tool aiming to integrate the natural scientific and social aspects of environmental problems in order to comprehensively understand and analyze environmental change. It has been widely used since 1995, e.g. in the environmental indicator reporting of the European Environment Agency (EEA, 1995), and has thus become broadly known and applied in the European context. The model presents a causal chain of *driving forces* (D) which are linked to the underlying needs of individuals, societies, industries and the like, followed by the *pressures* (P) (e.g. emissions) that stem from fulfilling these needs. Pressures affect the physical, chemical, and/or biological *states* (S) of the environment, which in turn have *impacts* (I) on ecosystems, human health, and other functions. The *responses* (R) denote the societal actions that derive from unwanted impacts, and can be targeted at any stage of the model (Smeets and Weterings, 1999). Despite some critique directed at the framework, most importantly addressing the simplified, linear causal chains that obscure the complexity of real socio-ecological dynamics and the conceptual ambiguity of the nodal points (e.g. Lundberg, 2005; Maxim et al., 2009), in our case the value of the framework lies in its utility for providing structure to the integration of interdisciplinary analysis. Restoration is characterized through concepts present in the DPSIR-framework, such as pressures and states, making it conceptually apt to the discussion of restoration problematics (see e.g. Keeneleyside et al., 2012). Moreover, the simple structure of the framework directs the focus of analysis towards the key social and ecological factors that have formed and influenced restorative actions in the past and will also affect future actions. Since active restorative interventions are always targeted at some defined goals, which might be attached to any of the stages of the model, we included a study of these restoration goals in the overall analysis (see Tapio and Willamo, 2008).

The study is based on the individual and integrated analysis of several types of materials. The historical analysis is based on documentary material, most importantly from the local Tuusulanjärvi Water Protection Association (TWPA, *Tuusulanjärven vesiensuojeluyhdistys*), as well as from newspaper articles (for more details see the Supplement). The historical data pertaining to the Tuusulanjärvi restoration process was gathered in a heuristic process typical for environmental historical research (Winiwarter and Knoll, 2007). The various interventionist responses to the eutrophication of the lake since 1970 were first identified, after which the content of the historical documents was analyzed against the different stages included in the analytical DPSIR framework. The limnological data included records of concentrations of TP and Chl *a* for different time periods. The sources of the limnological data and applied tests are presented in Table 1, and in more detail in the Supplement.

The future prospects for Tuusulanjärvi were gathered by applying the scenario approach (e.g. Bishop et al., 2007) and the futures