Maare Marttila

ECOLOGICAL AND SOCIAL DIMENSIONS OF RESTORATION SUCCESS IN BOREAL RIVER SYSTEMS
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Academic dissertation to be presented with the assent of the Doctoral Training Committee of Technology and Natural Sciences of the University of Oulu for public defence in the Wetteri auditorium (IT115), Linnanmaa, on 8 December 2017, at 12 noon

UNIVERSITY OF OULU, OULU 2017
Marttila, Maare, Ecological and social dimensions of restoration success in boreal river systems.
University of Oulu Graduate School; University of Oulu, Faculty of Science; Natural Resources Institute Finland (Luke)
*Acta Univ. Oul. A 703, 2017*
University of Oulu, P.O. Box 8000, FI-90014 University of Oulu, Finland

**Abstract**

The degradation of rivers and streams has led to world-wide efforts to restore freshwater habitats. A good understanding of the social-ecological context is considered key to successful restoration. In this thesis, a multidisciplinary framework was applied to study ecological and social dimensions of restoration success. First, the long-term performance of in-stream restoration measures was examined by conducting repeated cross-sectional surveys in restored streams up to 20 years post-restoration. Next, nationwide electrofishing data were used to assess the density responses of juvenile salmonids to habitat restoration and factors influencing restoration success were examined. Finally, changes in the provision of ecosystem services were evaluated by comparing the perceptions of restoration outcomes between two user groups and three study rivers. The results indicated that the restoration-induced increase in habitat heterogeneity persisted over time, initiating an overall positive development also in biological metrics (i.e. juvenile salmonids and aquatic mosses). However, overall substrate variability in restored streams remained lower than in near-pristine streams, with a shortage of gravel beds. Fish responses varied strongly between rivers, which was explained mainly by watershed scale (e.g. river basin size, dominant geology) and local (potential interspecific competition) factors. Site-specific differences were also observed in the delivery of ecosystem services, mainly reflecting stakeholder perceptions of landscape value and fish provisioning. Overall, the results show that setting indicators and target levels for restoration success is grounded on perspective. Socially conscious ecological restoration that acknowledges local specialities and needs in priority setting, planning and implementation has the potential to provide multiple benefits for river ecosystems and society.

*Keywords:* ecosystem services, juvenile fish, physical habitat, river restoration, salmonids
Marttila, Maare, Virtavesikanostusten vaikutukset jokiluonnnon ja ekosysteemipalvelujen näkökulmasta.
Oulun yliopiston tutkimuskeskus; Oulun yliopisto, Luonnontieteellinen tiedekunta; Luonnonvarakeskus
Acta Univ. Oul. A 703, 2017
Oulun yliopisto, PL 8000, 90014 Oulun yliopisto

Tiivistelmä

Asiasanat: ekosysteemipalvelut, elinympäristö, kalanpoikaset, lohikalat, virtavesikanostus
Together
Acknowledgements

To me, multidisciplinary work is to a large extent an adventure with exciting and endless opportunities. It’s not only bridging between scientific disciplines, but also interaction with experts and stakeholders from various organizations. I feel privileged to have had the opportunity to work and come into contact with so many people during this journey.

Of all those people, first I would like to express my sincere gratitude to my supervisors Aki Mäki-Petäys, Timo Muotka and Timo P. Karjalainen. Aki, thank you for offering this opportunity in the first place and for your supportive guidance during all these years. Timo M., thank you for your endless patience and advice and for always taking time from your busy schedule to your students. Timo K., thank you for showing me that a research in a multidisciplinary context is not a mission impossible. Thank you also for genuine interest and commitment to your students. I would also like to thank all other members of my advisory group: Ari Huusko, Jaakko Erkinaro, Teppo Vehanen and Timo Yrjänä for your contribution and extremely valuable and delightful discussions. From the very beginning, you all trusted me to take responsibility for the paths of this journey, and still supported me whenever I needed. Ari is the person to thank for initially introducing me with the world of river research and migratory fish species. My sincere thanks go to Pauliina Louhi for your essential contribution in terms of data analyses and co-writing in two original papers. Thank you also for all your support as a friend and as a mentor. I highly appreciate the work of my two other co-authors, Kirsi Kyllönen and Jukka Syrjänen. Kirsi, you were the best possible master’s student and I enjoyed working with you.

Using extensive data sets in this thesis would not have been possible without the help of many collaborators. I thank field workers and assistants for your time and help. I’m truly grateful to Olli van der Meer for helping me in the field and for conducting the modelling for paper I. I will never forget those moments full of adrenaline in the middle of the river when the flow was so fast that the feet hardly stayed on the bottom and we were pretty much hanging there with the rope. To you, I’m also grateful for offering several work opportunities that have supported my career. Thanks boss!

I warmly thank all the respondents of the questionnaires for their participation. I’m also deeply grateful to all those helpful people who made reports and data accessible and provided information on restoration sites, including local fishery boards and experts at Luke, Metsähallitus, regional ELY
Centres, the University of Jyväskylä and fisheries/environmental consults. Your motivation and enthusiasm to improve the status of our streams and rivers and to gather high-quality monitoring data made this study possible. I wish we can continue this collaboration in the future.

I would like to thank Scott Hinch and Philip Roni for reviewing my thesis. I am also grateful to Tommi Linnansaari for agreeing to be my opponent and to my follow-up group for their time and guidance. My greatest appreciation and acknowledgements for the financial support of this thesis go to Luke, the University of Oulu, Academy of Finland, Maj and Tor Nessling Foundation, Olvi Foundation, Emil Aaltonen Foundation, Tauno Tönning Foundation, Natural History Society of Oulu, Maa- ja vesitekniikan tuki ry and VALUE doctoral programme.

Throughout this project, I have been fortunate to work in diverse research environments and working communities. My warmest thanks go to my past and present colleagues at Luke for all help, inspiring discussions, laughs during our coffee breaks and good atmosphere. Special thanks I owe to my dear roommate Riina for always being there for me both in the good and not so good days. I appreciate that we can talk about everything. Huge thanks go also to Henni, Mikko, Ville, Panu, Johanna, Atso, Teuvo, Alpo, Pekka, Ilpo, Tapio, Samuli, Antti, Sanna, Petri, Marianne, Anne, Jarno, Virpi, Salla, Jenni, Mari, Timo and many others in our extended Luke community. I have learned a lot from you of more or less scientifically relevant issues. I am extremely grateful to our stream ecology research group at the University of Oulu. Kaisa H., Kaisa M., Kaisa L., Mari, Mira, Heli, Jussi, Mikko, Jukka, Romain and everyone else: discussions with you over lunch, coffee or a pint have meant a lot to me. One of the most important things these years have given me is your friendship. For peer support and good company, I thank also Saija and Marleena, who perfectly understand all parts of this journey.

The most unforgettable period of this project took place in Christchurch, New Zealand. During the work days, I was intensively writing papers in the public library while the rest of the time was spent exploring the amazing country. All this would not have been possible without Julia helping to take care of our kids. Thank you for sharing all those precious moments with us! I would also like to thank M.S. and Bruce for their endless hospitality and for introducing us with the local research and everyday life.

All my dear friends who have supported me throughout these years, thank you! Ulla, Johanna, Sanna, Senni, Hanna-Leena, Hanna, Paula, Vilma, Heta, Tiina,
and Tuuli, I'm so grateful for having you in my life, some of you already more than 25 years. Your kind and encouraging words uplifted me in any occasion. I love that no matter how long it's been since we last talked that we can always pick up right where we left off. I thank all my friends in Koplaus for bringing great joy into my life during past three years. Thanks to you, Tuesday is absolutely the best day of the week giving me energy also for other work days. May there be many more polkas and train picnics yet to come! Of my relatives, I specially want to thank Jouko, Kristiina, Ella and Oula for being there for me from the day I moved to Oulu in 1999.

Mom and dad, there are no words enough to thank you for your love and support. You taught me to reach towards my dreams and never questioned my decisions. With your example, I understood the value of work, but also that it is the life outside the office that truly matters. My sister Saila and brother Sampo, with you I have learned to defend my thoughts and to stand for my closest ones. That’s what siblings are for, isn’t it? It was you Saila, who repeatedly encouraged me to start doctoral studies in the first place. I want to thank you also for commenting on this thesis and for helping us in many practical things. My warmest thanks go to Seija, Jussi, Heidi, Jussi, Teijo, Stina and the kids for supporting me and our busy life in so many ways and for taking my thoughts from work to the things and moments I cherish most.

And finally, I want to thank Hannu, Valtteri and Saana, my beloved family. Hannu, to you I owe my deepest gratitude for advising me in various scientific issues and for listening, encouraging and helping me to find solutions in confusing and disappointing moments. Thank you for also sharing the best parts of this life phase and for being my soulmate and companion in our life-time journey. Valtteri and Saana, in you, I see imagination and creativity that has no limits and endless motivation to explore life and make questions. I’m so proud of you. Each and every day, you teach me so much about life and also about myself. These years have been extremely busy. Too often, it was my loved ones who had to be flexible and understanding, while either me or my thoughts were absent. I cannot find words to describe how thankful I am to you for being always so patient. Your endless love and support have kept me going and mean a world to me. I love you all to the moon and back.

19.10.2017 Maare Marttila
List of original articles

This thesis is based on the following publications, which are referred throughout the text by their Roman numerals:


The author’s contribution to publications:

I: Designed the study with the co-authors, organised and conducted the most recent field work, participated in analysis and interpretation of the data and drafted the manuscript, which was then critically commented upon by the co-authors. The paper was finalised together with the co-authors.

II: Designed the study with the co-authors, collected the data, participated in analysis and interpretation of the data, drafted the manuscript and revised it according to critical comments from the co-authors.

III: Designed the study with the co-authors, contributed to data collection, participated in analysis and interpretation of the data and wrote the manuscript together with the co-authors. The paper was finalised together with the co-authors.
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Original articles
1 Introduction

Ecological restoration has become one of the most prominent approaches to environmental policy at local to global level (Wortley et al. 2013, Tolvanen & Aronson 2016). Annually, large amounts of financial resources are spent in rehabilitation efforts undertaken to re-establish biodiversity, ecosystem processes and services that were degraded or entirely lost through intensified anthropogenic use (Bernhardt et al. 2007, Wohl et al. 2015). Meeting the targets and obligations of restoration (Muhar et al. 2016, Tolvanen & Aronson 2016) is a great challenge for this century, particularly when the constantly changing conditions (e.g. climate change and population growth) impose an additional burden on ecosystems (Naiman 2013).

Ecological restoration of streams and rivers can be divided into three dominant approaches: i) restoration of channel morphology and flow, based on the assumption that ecological recovery will follow; ii) restoration of ecological functions, aiming to regain the biogeochemical, ecological and hydrogeomorphic processes that characterise a healthy river; and iii) restoration extending to the watershed area (Palmer et al. 2014). The larger the scope of restoration, the greater the number of disciplines required to advance understanding of the complex interactions (Palmer et al. 2014). All restoration actions include a human dimension and therefore a contribution from social sciences is essential (Gross 2014). A good understanding of the larger social-ecological context associated with degraded ecosystems is considered key to successful restoration (Naiman 2013). For example, knowledge is needed on how hydromorphological variability is related to biodiversity, ecosystem functioning and services (Schirmer et al. 2014).

The policy and practice of river restoration should be guided by the best available scientific information. To date, research has often addressed the efficacy of restoration measures (Roni et al. 2002, Louhi et al. 2016), the conceptual framework to guide restoration programmes (goal setting, monitoring and evaluation) (Kondolf & Micheli 1995, Palmer et al 2005, Gilvear et al. 2013), and indicators for judging restoration success (Woolsey et al. 2007, Pander & Geist 2013). Inconsistent ecological responses to restoration practices highlight the importance of further research (Alexander & Allan 2007, Whiteway et al. 2010, Nilsson et al. 2015), particularly on the factors that might enhance or constrain restoration success (Bond & Lake 2003, Naiman 2013, Nuruzzaman et al. 2017).
Restoration research to date has typically focused on natural and engineering sciences, while the delivery of multiple ecosystem services and social dimensions of restoration have gained far less attention (Acuña et al. 2013, Gilvear et al. 2013, Wortley et al. 2013). Today, it is widely recognised that scientific and technical knowledge alone does not yield effective restoration practices (Barthelemy & Armani 2015, Bennett et al. 2017) and improving knowledge on both the ecological and social dimensions of restoration success is important to support the use of restoration as a primary tool in environmental management (Schultz et al. 2012, Wortley et al. 2013).

This thesis addressed the question of restoration success from ecological and social perspectives. The aim is to contribute new insights to the discussion on ecological river restoration by providing a more complete understanding of the multiple benefits and social-ecological sustainability of restoration. In order to achieve this aim, a multidisciplinary framework was applied to study restoration-induced changes in habitat heterogeneity, juvenile salmonid density and stream ecosystem services, as well as the role of external factors (e.g. geology, fishing regulations, time, connectivity, water quality) in determining restoration success.
2 River ecosystems and human well-being

Rivers are closely related to the development and prosperity of human societies through the services they provide to people, communities and industries (Alahuhta et al. 2013, Parsons et al. 2016) (Figure 1). Riverine nature and culture have always been tightly interlinked and therefore should be viewed as social-ecological systems with complex interactions between humans and the natural world (Palmer 2009, Barthelemy & Armani 2015). Viewing rivers as a hybrid of nature and culture also has major implications for the science, practice and policies of river restoration (Wohl et al. 2015).

Fig. 1. During the course of history, rivers have delivered vital ecosystem services to humans, such as hydropower for mills and energy production, transportation of materials (e.g. timber) and humans, clean drinking water, recreational, aesthetic and educational values and fish stocks.

Ecosystem services (ES), i.e. benefits obtained from ecosystems to human society, are generally divided into provisioning, regulating, cultural and supporting services (MEA 2005). The ES concept is seen as particularly useful in
environmental management and conservation, as it provides a common ground for discussions and decisions regarding different actions and for identification of potential trade-offs required for their implementation (Terrado et al. 2016, Tolvanen & Aronson 2016). Attempts to turn the concept into a practical tool have become more frequent recently (Mononen et al. 2016). However, the gap between theory and practice hampers the implementation of ES, particularly at the regional and local levels. Currently, most ES studies focus on monetary valuation and expert opinions, while stakeholder perspectives gain less attention. Focusing more on stakeholder views in this context could enhance implementation of ES in management practices (Bock et al. 2015).

Streams and rivers have strong value for people, and even the invisible non-use services delivered by riverine ecosystems are often highly appreciated (Sarvilinna et al. 2017). Rivers provide ecosystem services in all four categories, such as fish stocks, clean water, hydropower and transportation (i.e. provisioning services, Fig. 1); flood control and regulation of water quality (regulating services); recreation, cultural heritage, inspirational, aesthetic and educational values (cultural services); and habitats, sedimentation, water and nutrient cycling (supporting services) (Alahuhta et al. 2013, Schirmer et al. 2014). Many fish species, such as salmonids, provide commercial harvest and food and also contribute to recreational opportunities, cultural heritage and identity (Kulmala et al. 2013).

The constant increase in human activities has exposed riverine ecosystems to degradation both directly in the channels and on floodplains, and also indirectly within their watersheds (Lake et al. 2007). This has disrupted the balance of natural ecosystems (Lamy et al. 2002), leading to the current rate of biodiversity loss (Lepori et al. 2005). Reduced biodiversity means that essential species are lost, which in turn may change the interactions between species, cause negative impacts on ecosystem functions and, eventually, threaten the services that rivers provide for human well-being (MEA 2005).
3 Stream restoration

3.1 Restoration objectives

Conceptually, ecological restoration is an effort to return an ecosystem to the state that preceded its degradation. However, the previous environmental context may no longer exist and it is not possible to recreate the past (Nilsson et al. 2005, Palmer 2009, Alexander et al. 2016). As the complete restoration of an ecosystem may not be achieved, it has been said that ‘rehabilitation’ would be a more appropriate term to describe these actions (e.g. Nuruzzaman et al. 2017). In this thesis, the term ‘restoration’ is used in a broader sense to describe the actions that seek to assist the recovery of an ecosystem that has been degraded, damaged or destroyed (SER 2004).

Ecological restoration has the potential to enhance the self-sustainability of an ecosystem and to re-establish the lost services (Rey Benayas et al. 2009, Aronson et al. 2010, Wohl et al. 2015). The ultimate goal is to re-establish “as much as possible of the historical structure, composition, and functioning of the ecosystem that existed prior to degradation” (Alexander et al. 2016). Importantly, some level of variability and unpredictability in the ecological outcomes should be accepted (Hughes et al. 2005). The rationale behind most restoration projects is the assumption that recreating habitat heterogeneity promotes recolonisation by species (Palmer et al. 1997, Lepori et al. 2005). This is based on the principle that heterogeneous landscapes increase niche diversity, allowing the survival and coexistence of a higher number of species (Peipoch et al. 2015).

In physically homogeneous streams, the availability of habitats for stream biota is reduced. Reconstruction of in-stream habitats is considered a key management option to improve the ecological status of modified streams (Miller et al. 2010). Restoration has traditionally been species-driven, recreating channel forms believed to be favoured by a particular species or species group (Clarke et al. 2003, Lake et al. 2007, Palmer et al. 2010). The desired outcome is often related to the enhancement of native fish populations, especially economically and culturally valuable salmonids (Stewart et al. 2009). The interest in restoring salmonid populations arises from their widespread decline (Bash & Ryan 2005, Erkinaro et al. 2011, Gibson et al. 2017). Large investments are made annually in, for example, North America and Europe to increase or restore salmonid populations that formerly sustained significant fisheries, but are now threatened
(Roni et al. 2008). Restoration of the longitudinal connectivity and in-stream habitat are considered particularly important for reversing salmonid population decline (Gibson et al. 2017).

Restoration schemes are now focusing more on the restoration of entire stream ecosystems, thereby potentially enhancing riverine species diversity (Lepori et al. 2005, Palmer et al. 2010, Nilsson et al. 2015). In the EU member states, this trend has been fostered by the European Water Framework Directive (WFD; 2000/60/EG) and related legal obligations. The ultimate goal of the directive is to maintain or re-establish good ecological status of all surface waters within the EU (Lorenz & Feld 2013, Muhar et al. 2016). Improvement of ecological status necessitates a measurable increase in the ecological quality derived from four biological quality elements: fish, benthic invertebrates, benthic algae and macrophytes (Lorenz & Feld 2013). In Finland, for example, approximately 15% of the total lake area, 35% of river length and 75% of coastal areas are currently designated as being in lower-than-good ecological status. In many cases, achieving good ecological status requires restoration of the stream habitat (SYKE 2013).

Ideally, river restoration meets both the ecological targets and public expectations related to, for example, landscape aesthetics, recreational value and attractiveness of the river (Junker & Buchecker 2008, Seidl & Stauffacher 2013, Åberg & Tapsell 2013). However, efforts to improve ecosystem state do not always result in improved human well-being (Terrado et al. 2016). There can sometimes be a significant gap between society’s expectations and the scientific understanding of a healthy and dynamic river (Wohl et al. 2015, Geist & Hawkins 2016). Different groups of stakeholders may also have conflicting expectations and reaching consensus on the desired restoration outcomes can be challenging. Identifying shared goals at an early stage of a restoration project may help to gain broader support for restoration actions (Gross 2014).

While setting goals for ecological restoration is essential, some level of unpredictability is always involved. For example, Gross (2014) states that “you can never know what to expect in ecological restoration practices”. Given the complex social-ecological linkages and a set timeframe for a restoration project, surprises in human-nature interactions are inherent to restoration (Gross 2014).
3.2 Restoration measures

River restoration is a wide term that refers to many different project types and management activities, including, for instance, riparian management, removal of dams, construction of fish passages, water quality management, in-stream habitat improvement and channel reconfiguration (Gillilan et al. 2005, Bernhardt et al. 2007). Restoration work is conducted on headwater streams, large lowland rivers and entire river networks and takes place both in urban and more rural environments with variable intensity of human activity (Wohl et al. 2015).

Finland has almost 40 years of experience in stream restoration and efforts have been undertaken to improve the hydromorphological and ecological state in a large proportion of Finnish rivers. The focus of restoration thus far has been on enhancing the physical heterogeneity of streams channelised for timber floating. The modifications introduced to enable timber floating took place in the 19th and 20th century and caused degradation of the stream habitat for fish and other riverine organisms (Lepori et al. 2005, Nilsson et al. 2005, Muotka & Syrjänen 2007). Eventually, the network of floatways covered almost all streams in Finland wide enough for timber floating (Muotka & Syrjänen 2007). Channelisation for timber floating took place also in many other boreal river systems around the northern hemisphere (Muotka & Syrjänen 2007, Nilsson et al. 2015). Although little historical data are available on the ecological effects of channelisation, it is considered one of the major causes of reduction, or even extinction, of fish populations in boreal streams and rivers (Muotka & Syrjänen 2007, Nilsson et al. 2015). For example, the habitat availability for different life stages of Atlantic salmon (Salmo salar) and brown trout (Salmo trutta) was reduced, which most likely affected their population viability (Palm et al. 2007).

Since the 1970s, timber floating in Fennoscandia was gradually replaced by road transportation (Muotka & Syrjänen 2007, Palm et al. 2007). Immediately thereafter, attempts to recreate habitat diversity were initiated with the primary aim of enhancing living conditions for salmonid populations (Muotka & Laasonen 2002, Luhta et al. 2012). In practice, different habitats (shelter, riffles, pools and spawning grounds) have been established by adding in-stream structures (e.g. current deflectors, boulder dams and gravel beds) and reopening side channels (Stewart et al. 2009, Luhta et al. 2012, Nilsson et al. 2015).
3.3 Evaluation of restoration success

Evaluation of restoration success is essential for providing information on project efficiency and for justifying and optimising future restoration efforts (Woolsey et al. 2007, Wortley et al. 2013). Although positive developments have been reported in the restoration evaluation literature in recent years (Wortley et al. 2013), disproportionately low resources are allocated to sound monitoring programmes (Schiff et al. 2011) (Figure 2). In particular, efforts to conduct standardised before-after sampling programmes remain limited (Jähnig et al. 2011). Furthermore, studies extending over 10 years and able to identify the long-term trajectory of stream restoration projects are rare, mainly because they tend to exceed the original project schedule and funding (Champoux et al. 2003, Schiff et al. 2011, Buchanan et al. 2014).

There is an ongoing debate on the features that characterise successful restoration and how best to measure it (Wortley et al. 2013). Ultimately, evaluation of restoration success means assessing whether the initial targets have been met. Indicators serve as tools to quantify the condition of a river in light of the restoration goals (Woolsey et al. 2007). Indicators should be easily measured, cost-effective, sensitive to responses, ecologically and socially relevant and reliable and, ideally, provide information on more than one project objectives (Palmer et al. 2005, Woolsey et al. 2007). Suitable indicators should be adopted primarily according to restoration objectives (Kondolf & Micheli 1995, Miller & Hobbs 2007, Woolsey et al. 2007).

To date, the debate on restoration success has relied primarily on objective and measurable biotic and abiotic indicators, while more subjective aspects, such as landscape aesthetics and recreational opportunities, have usually been ignored (Barthélym & Armani 2015) (Figure 2). However, socio-economic aspects play an important role in the perception and communication of restoration success (Jähnig et al. 2011). Evaluation of societal benefits and changes in the provision of ecosystem services would improve our understanding of restoration outcomes. In particular, more research is needed on the actual socio-economic outcomes of restoration. Thus far, socio-economic studies have focused mainly on issues related to resource input into projects, the extent of community involvement and implications for future restoration projects, while the actual socio-economic outcomes have gained little attention (Wortley et al. 2013: but see e.g. Vermaat et al. 2016).
It remains largely unknown how well the expectations of various stakeholders are met, the reasons for diverse local experiences and whether lost ecosystem services are truly recovered through ecological restoration (Schaich 2009, Barthélémy & Armani 2015). The ecosystem services approach applied in Paper III of this thesis provides an explicit framework to quantify and compare restoration benefits (Terrado et al. 2016, Vermaat et al. 2016, Sarvilinna et al. 2017). In addition, comparison of the perceptions among stakeholder groups and at different restoration sites may advance understanding of the reasons for social success or failure (Barthélémy & Armani 2015).

The main indicators measured in the context of in-stream restoration are often related to fish populations, channel morphology and stream flow (Schiff et al. 2011). Hydromorphological factors of a restored reach (Paper I) are ecologically essential, as they alter spatial and successional patterns of biological communities (Kondolf & Mitcheli 1995, Kemp et al. 2000). Interactions between stream channel, floodplain and stream flows provide the framework that supports aquatic and riparian structures and functions (Kondolf & Mitcheli 1995). While several studies have reported substantial improvement of the stream habitat soon after restoration (e.g. Muotka & Syrjänen 2007, Nilsson et al. 2015, Poppe et al. 2016), the long-term trajectory of stream habitats and the persistence of restoration measures have remained largely unexplored.

The recovery of salmonid populations is one of the most commonly used indicators of restoration success (Paper II), suggesting that this is also often considered to be primary objective of ecological restoration (Bash & Ryan 2005, Nilsson et al. 2005, Roni et al. 2008). Salmonid populations are also assessed because they are not only indicators of habitat suitability, but can also be a proxy for other restoration outcomes (Wortley et al. 2013). Unfortunately, the results of biotic responses from many local case studies remain unpublished. Yet, a lack of information on previous projects is considered one of the main impediments to the success of river restoration. A synthesis of the projects that have engaged adequate monitoring programmes would provide a valuable contribution to future restoration projects (Nuruzzaman et al. 2017).

Previous studies have shown variable biotic responses to river restoration (e.g. Stewart et al. 2009, Whiteway et al. 2010, Nilsson et al. 2015), resulting in a lively debate on the potential reasons for undesired outcomes. Reasons identified include, for instance, insufficient incorporation of socio-economic aspects (Hermoso et al. 2012), too short monitoring programmes (Nilsson et al. 2015) and poor long-term performance of restoration measures (Frissell & Nawa 1992).
In addition, some authors have suggested that inability to restore river function and ecological communities comparable to reference conditions stems from the scale of restoration, which is often inconsistent with the scale of human alteration (Schiff et al. 2011, Wohl et al. 2015). In many cases, the larger-scale variables that may affect ecosystem processes after restoration remain largely unidentified, despite the fact that they might explain why species either have not responded to restoration actions or have done so slowly (Nilsson et al. 2015).

Many of the research gaps mentioned above were addressed in this thesis, which placed particular emphasis on the use of long-term monitoring data and multidisciplinary response and explanatory variables (Figure 2).

![Fig. 2. Limitations of current restoration assessment and how these were addressed in this thesis (modified from Muhar et al. 2016).](image)
4 Aims of the thesis

The overall aim of this thesis was to explore ecological and social dimensions of restoration success and to contribute new insights to the current scientific debate on the sustainability and potential of ecological restoration. Each subproject (Paper I-III) was intended to shed light on different indicators of success (Figure 2), thus improving understanding of the extent to which restoration in boreal streams has achieved its goals. Commonalities and differences between different restoration projects were also assessed, to reveal potential factors influencing restoration outcomes. The results obtained can be applied in developing better predictive tools for restoration outcomes and to guide target setting, evaluation work and prioritisation of future restoration schemes.

The study reported in Paper I examined the long-term ($\geq 10$ years) persistence of habitat heterogeneity in restored stream sections, and in particular whether the initial positive effects of in-stream restoration on stream habitat structure have persisted over time. It also assessed whether the restored stream habitats resembled near-pristine reference conditions after a relatively long recovery period.

The study described in Paper II synthesised the density responses of juvenile salmonids to habitat restoration and assessed the factors that influenced restoration success. The focus was on young-of-the-year (YOY) Atlantic salmon and brown trout, as these are considered to indicate successful reproduction and fry survival.

In Paper III, the social success of restoration and changes in the provision of ecosystem services was evaluated by comparing the perceptions of restoration outcomes between two user groups and three study rivers.

The studies were conducted by using hydromorphological and ecological data collected from field investigations and data including subjective opinions and perceptions recorded via surveys. In the context of restoration success, the following ecological and social issues were specifically addressed:

1. Is the hydromorphological variability established by restoration persistent over time (Paper I)?
2. Does enhanced habitat heterogeneity translate into increased juvenile salmonid densities (Paper II)?
3. Does restoration change the provision of ecosystem services relevant for residents and fishermen (Paper III)?
5 Materials and methods

5.1 Study areas

The study sites represented second- to fourth-order boreal streams draining areas dominated by forests or peatlands. The streams are typically ice-covered from November-December to April-May, with snowmelt-induced flooding taking place thereafter. Historical hydromorphological degradation of the study sites (excluding near-pristine reference sites in Paper I) derived mainly from channelisation for timber floating. As a response to this degradation, in-stream habitat restoration took place between 1989 and 2013. Streams naturally contain alternating reaches of turbulent (run, riffle, step-pool or cascade bedforms) and tranquil (pools and lakes) channel sections (Nilsson et al. 2015) and the primary restoration measure aimed to recreate this variability.

Persistence of hydromorphological variability (Paper I) was studied in 10 restored rivers (27 study reaches) in northern and central Finland and their performance was compared with that of nine near-pristine reference streams (10 study reaches). Restoration effects on juvenile salmonid density (Paper II) were examined using data from 28 study rivers (88 study sites) covering most of Finland. The initial criterion for inclusion of a study site was that data on YOY salmonid density were available from at least two sampling years before and two years after restoration. Restoration-induced changes in ecosystem services (Paper III) were assessed in three recently restored rivers in Northern Finland: the Kiiminkijoki, Kostonjoki and Simojoki.

5.2 Hydromorphological surveys and modelling

In the mid-1990s, extensive hydromorphological measurements were carried out in 14 study reaches both before and shortly after restoration (the same or the next year) to quantify restoration-induced changes in habitat structure (Huusko & Yrjänä 1997, Korsu et al. 2010). Georeferenced measurements of water depth, mean flow velocity and dominant substrate size were conducted along cross-sectional transects (Korsu et al. 2010). In addition, cover of aquatic mosses was quantified in eight study reaches to study in-stream vegetation recovery after restoration. In 2010, the same cross-sectional transects were re-sampled 13–17 years post-restoration to detect changes, if any, over time. On that sampling
occasion, similar habitat surveys were also conducted in 10 near-pristine reference reaches. More detailed information on current substrate variability was also collected by recording relative proportions of substrate size classes in all these study reaches, and in 13 supplementary reaches restored 10–21 years ago.

A 1-D hydraulic model (EVHA 2.0; Ginot et al. 1998) was used to convert the georeferenced habitat data from the 1990s into comparable metrics with the data collected in 2010. This was ensured by modelling the habitat conditions before and shortly after restoration under the same discharges as recorded in 2010. The final analyses were conducted using mean and coefficient of variation (CV) for depth, flow velocity, dominant substratum size, moss cover and Froude number, as well as the maximum depth and proportion (%) of slow-flow microhabitats (0–10 cm s⁻¹) in each cross-sectional transect. Substratum data from the 2010 surveys were analysed using cumulative particle size distribution.

In 2010, the physical condition and functioning of restoration structures 10-21 years after their installation was also visually surveyed (16 reaches in six study streams). The current performance of boulder dams (13 study reaches), re-wetted side channels (15 reaches) and gravel beds (7 reaches) was compared with the original reach-specific designs and rated in one of three categories (success, impaired, failed) using a classification modified from Frissell and Nawa (1992, see also Buchanan et al. 2012).

### 5.3 Fish density data

Electrofishing data were collected by research partners between 1978 and 2014 (monitoring time ranging from 6 to 33 years), following the Finnish standard. Information on fish densities (individuals per 100 m²) obtained from the raw data or from reports was used. As the parameter of interest was density responses within a river, it was important to ensure that the density estimation method was consistent within a river, whereas differences in estimation methods between rivers were largely neglected (Thomas et al. 2015).

The focus was on young-of-the-year (YOY) Atlantic salmon and brown trout densities, as they were the target species of restoration in seven and 27 study rivers, respectively. Density data for other species were available for 21 rivers, and densities of northern pike (*Esox lucius*), European perch (*Perca fluviatile*), burbot (*Lotia lota*) and European bullhead (*Cottus gobio*) were included in the analyses of potential impacts of species interactions on restoration outcomes.
5.4 Environmental data

Environmental data were used to identify possible links between YOY salmonid responses to restoration and local and watershed-scale factors. Data on water quality (total phosphorus, pH, total suspended solids (SS), chemical oxygen demand (COD) and oxygen saturation), river basin size and dominant geology were compiled from the national database HERTTA managed by the Finnish Environment Institute. Water quality values were calculated as averages across the most recent 10 years. Geographical locations were recorded by latitude and ecoregion (hemiboreal, south-boreal, mid-boreal, north-boreal), the latter being based on vegetation zones. Additional information on migratory obstacles (downstream of a restored site), stocking of eggs and alevins/YOY, fishing pressure, recovery time and fish community was associated with the electrofishing data (for more details see Paper II).

5.5 Questionnaires

Two questionnaire surveys were conducted in this thesis. The first surveyed the expected level of improvement in YOY salmonid densities among Finnish stream restoration experts. An e-mail with a short survey was sent to 25 recipients, selected based on their experience in stream restoration and/or monitoring of fish densities across Finland. The recipients were asked to define the minimum improvement in YOY salmonid (salmon and/or trout) density needed to judge a restoration effort successful. Response rate to our survey was 68% (17 recipients). The two most frequently stated levels for success were derived from the survey data. One represented the minimum requirement for improvement (1.1 x pre-restoration density; ‘any increase in juvenile density indicates success’) and the other ‘distinct success’ (2 x pre-restoration density).

In the second questionnaire, user groups’ perceptions of restoration outcomes were investigated among residents and fishermen of three restored rivers. Both user groups were provided with the opportunity to answer the survey either on paper or via the Internet (Harava template, © Dimenteq Oy, https://www.eharava.fi/en/). The list of fishermen contacted (total 1462) consisted of all those who had bought a fishing licence in 2013 for one of the study rivers. The list of residents contacted (total 719) was compiled from household addresses in close proximity to the restored river sections. For fishermen the response rate was 26% (n = 380) and for residents 42% (n = 302). Respondents who were
aware of the restoration and had lived near or visited the river before restoration were treated as a subsample, as they were assumed to be able to compare the river conditions before and after restoration.

A combination of fixed-choice (questions and answer choice grids) and open questions that were partly group-specific and partly similar for both user groups were posed in the questionnaires. In data analyses, the focus was on the similarities and differences between user groups and study rivers. Interpretation of the quantitative data was supported by qualitative clustering of the open questions.

5.6 Statistical analysis

In Papers I and II, all statistical analyses were performed in R (R Core Team 2014). In Paper I, principal component analysis (PCA) was used to summarise visually how habitat characteristics (transect mean and CV for depth, flow velocity, dominant substrate size and moss cover) differed between the sampling conditions (near-pristine, before, shortly after or long after restoration). The differences between sampling conditions were also assessed for each habitat variable separately by fitting linear mixed models. The status of a sampling site was considered a fixed effect and rivers and sites nested within rivers as random effects. When comparisons of log-likelihoods of the preceding models and Akaike's Information Criterion (AIC) supported the removal of random variables (Zuur et al. 2009), a generalized least-square model with only fixed variables included was used (Pinheiro et al. 2011). In most cases, model goodness of fit was improved significantly by adding the varIdent variance function (Pinheiro et al. 2011) to the model, which allowed heterogeneity in variance among restoration status classes.

In Paper II, meta-analyses were conducted to synthesise the responses of YOY salmonids to multiple restoration projects. The grand mean effect size and its bootstrapped 95% confidence intervals were obtained separately for brown trout and salmon by fitting the random effects model with restricted maximum likelihood estimator (REML) for the amount of heterogeneity (Viechtbauer 2010). An unweighted approach for meta-analysis was employed to avoid overemphasising the studies with spuriously low variance resulting from very low salmonid numbers both before and after restoration (see Stewart 2010). Furthermore, trout responses in 13 projects were compared against the expected response rates (minimum level of improvement and distinct success) derived from
expert opinions. This analysis focused on projects with pre-restoration densities exceeding one individual per 100 m² to exclude sites where trout were only sporadically observed before restoration.

In Paper II, a generalized linear mixed model (GLMM) with a negative binomial distribution (Bates et al. 2014) was also used to explore YOY density response x explanatory variable interactions (i.e. latitude, ecoregion, river basin size, predominant geology, water quality, presence of migratory obstacles, stockings, fishing pressure and fish community; 27 rivers). Some of the interactions (ecoregion, migratory obstacles, stockings, fishing pressure and fish community structure) were assessed solely for trout because of the low number of salmon projects (n=7). In these models, treatment (before vs after restoration) was considered as a fixed factor, and sites nested within rivers and years as random effects. The model for recovery time included the four time phases (before restoration, short, medium and long term after restoration) as a fixed factor, and sites nested within rivers and calendar year of restoration action as random effects. For all models, random effects were found to improve the fit of the model (comparisons of log-likelihoods; Zuur et al. 2009). The differences in density responses between the ecoregions and time phases were analysed using each level of these factors as an intercept.

Questionnaire data in Paper III were analysed using factor analysis in SPSS version 21 (IBM, Armonk, New York, USA; principal axis factoring method using rotation with Varimax with Kaiser normalisation). The factors obtained were associated with an interpretable ecosystem service and a service category (MEA 2005) based on variables clearly loading onto them (>0.5 at the rotation factor; Table 2 in Paper III). Finally, mean factor scores were computed separately for each user group and study river to summarise how changes in given ecosystem services were perceived in these subgroups.
6 Results and discussion

6.1 Persistence of hydromorphological variability

The hydromorphological data obtained (Paper I) showed that restoration measures had beneficial long-term effects on riverine habitats and that the restored sites seemed to be on the desired trajectory to hydromorphological recovery. The PCA analyses revealed a clear shift in habitat structure immediately after restoration, although the recently restored reaches were still relatively similar to each other (Figure 1 in Paper I). In the long term, an increase in interreach variability was detected, with restored sites approaching the range of variation observed in near-pristine systems. Separate analysis of the changes in key habitat variables indicated a persistent increase also in within-reach heterogeneity. Restoration improved flow conditions by decreasing mean flow velocity and Froude number and increasing mean and maximum depth and the proportion of slow-flow patches, many of which were reinforced through time (Figure 2 in Paper I). Variation (CV) of Froude number became significantly higher compared with before restoration and similar to reference conditions only in the long-term, indicating that fluvial processes were diversifying flow patterns through time.

Aquatic mosses provide a valuable habitat for stream invertebrates and enhance organic matter retention, and are thus important for the ecological integrity of stream ecosystems (Muotka and Laasonen 2002, Lepori et al. 2005, Huttunen et al. 2017). In Paper I, moss cover initially declined due to disturbance from restoration, but within approximately 15 years full recovery of mosses had occurred, reaching the same level as in near-natural references (Figure 3 in Paper I). Previous studies have suggested that the re-colonisation by mosses after restoration may take years or even decades (Muotka & Laasonen 2002; Louhi et al. 2011).

Variation in dominant substrate size increased after restoration, being temporarily even higher than at the natural reference sites (Figures 2 and 4 in Paper I). However, overall substrate composition remained less variable among the restored than near-pristine sites, even up to 20 years after restoration (Figure 5 in Paper I). The restored sites showed a particular scarcity of bed material suitable for salmonid spawning. This result was supported by qualitative observations: the majority of the added gravel beds had deteriorated over time (Figure 6 in Paper I). Disappearance of added gravel beds was also observed by Louhi et al. (2016),
suggesting that this is a common phenomenon in restored Finnish streams. Therefore, in future restorations, more effective measures are needed to avoid failures in gravel placement (Barlaup et al. 2008). Availability of spawning grounds is of particular importance for the recovery of salmonid populations (Palm et al. 2007). Because of the low relief and low sediment yield in the Fennoscandian landscape, natural accumulation of fine sediments, such as gravel, could take centuries (Rosenfeld et al. 2011, Nilsson et al. 2015, Polvi et al. 2014).

Visual observations showed that, apart from the gravel beds, other restoration structures were functioning reasonably well (Figure 6 in Paper I). Similar results have been reported by White et al. (2011), who noted that in small, stable channels, added in-stream structures can function for more than two decades. In contrast, Louhi et al. (2016) noted that restoration structures and particularly boulder weirs had partly deteriorated over 13 years since restoration. Deterioration of restoration structures has also been noted in some other cases (Thompson 2002, Champoux et al. 2003, Schiff et al. 2011), resulting possibly from inadequate materials, structure placement, construction skills or maintenance (Champoux et al. 2003).

Although restoration projects frequently emphasise structural improvement of the stream channel (White 1996, Bernhardt & Palmer 2011), this does not automatically result in restoration of river processes. The restoration of natural geomorphic processes (e.g. organic matter and nutrient cycling, sediment transport, channel movement and river-floodplain exchanges; Champoux et al. 2003) is important to ensure that restoration structures function properly and are self-sustaining (Thompson 2002, Clarke et al. 2003). Instead of constructing fixed structures that resist channel evolution and delay the recovery of ecological integrity, it is more important to restore appropriate processes that create and maintain habitats for stream biota (Poff et al. 1997, Gillilan et al. 2005, Roni et al. 2008, Kristensen et al. 2013). The results from the study sites included in this subproject indicated that restoration had allowed natural fluvial processes to re-establish the physical habitat variability (Gillilan et al. 2005), although the restored sites were not fully comparable with natural streams even 20 years post-restoration. From the perspective of channel evolution, restoration was still fairly recent and it remains to be seen if the sites will continue on the trajectory of hydromorphological and ecological recovery.
6.2 Juvenile salmonid responses

The meta-analysis in Paper II demonstrated that habitat restoration had a variable, but on average positive, effect on YOY salmonid densities. Mean effect size was significantly positive for trout (4.32; 95% CI = 1.14 to 7.50, n = 30, P = 0.008; Figure 1 in Paper II), while for salmon the positive effect was not significant (5.06, 95% CI = −2.28 to 12.39, n = 7, P = 0.176). These findings support the claim that restoration has the potential to enhance the biological integrity of streams and the conservational status of salmonid populations. Similarly, Roni et al. (2008) and Whiteway et al. (2010) have also shown generally positive, but species-specific, responses of juvenile salmonids to restoration. The differences between the species may be related to how well restoration meets their habitat requirements in different life stages and seasons. For example, Koljonen et al. (2012) suggested that lack of suitable overwintering habitats may continue to restrict populations of Atlantic salmon. Due to their migratory life cycle, salmon populations are exposed to human impacts (e.g. loss of connectivity, fishing mortality) within an extensive migratory area, thus causing obstacles to their recovery. A substantial proportion of trout populations may remain as residents in their home river and, therefore, the pressures they are exposed to may be less extensive (Jonsson & Jonsson 2011).

Comparison of trout density responses against the target levels derived from the expert survey showed that restoration projects mainly reached the minimum expected success rate (1.1 x pre-restoration density), but remained short of distinct success (2 x pre-restoration density). The GLMM analysis showed that time since restoration did not influence YOY salmon responses, whereas for trout the densities were somewhat higher shortly after restoration (1–4 years) than in the two following phases (5–8 years and >8 years after restoration). The temporal dynamics of salmonid populations indicate a need for monitoring that spans a minimum of 10 years post-restoration (Kondolf & Micheli 1995, Roni et al. 2015).

According to the results in Paper II, opportunities for successful restoration are linked to watershed-scale context. The results on trout showed that restoration was more likely to be successful in mid-sized rivers than in large rivers, potentially indicating that larger rivers have greater problems (National Research Council 1992). Populations in rivers draining mineral soils showed more positive responses than those in peatland-dominated catchments, which may be related to the higher acidity caused by dissolved organic matter originating from peatlands.
Analysis of mean water quality values suggested, however, that water quality did not obscure the beneficial effects of in-stream restoration in the study rivers. Previous studies have suggested that physical habitat restoration may have beneficial effects only if water quality is improved (e.g. Haase et al. 2013, Mueller et al. 2014, Roni et al. 2015). However, such recommendations are based on knowledge from rivers that are much more nutrient enriched than rivers in Finland.

Other significant interactions with salmonid responses were related to geographical location, species interactions and stockings. The effect of latitude was significant only for salmon, with more positive responses detected in northern than in southern Finnish rivers. However, there were significant differences in trout responses between ecoregions, with the southernmost (hemiboreal and south-boreal) ecoregions showing more positive responses. Geographical patterns in restoration responses could be linked to, for example, potential differences in restoration procedures and the time needed for biotic recovery (related to, for example, generation length).

Contrary to our expectations, increased densities of potential predators (pike, burbot, perch) were not associated with reduced trout responses. Instead, European bullhead, which occupies partly similar resource niches to trout, limited trout response to restoration, potentially indicating asymmetric competition (Louhi et al. 2014, and references therein). Another important finding was that stockings of alevins/YOY were negatively related to restoration outcomes. Previous studies have also suggested that the benefits of current stockings are moderate at best (Luhta et al. 2012, Syrjänen et al. 2015). Therefore, it would be better to shift the focus of salmonid management from a strong reliance on stocking towards measures addressing factors that continue to limit natural recruitment and population establishment.

Finally, the data suggested that river-specific fishing regulations play a role in defining restoration outcomes. The outcomes for trout were more positive in the sites with fishing forbidden or only catch-and-release fishing allowed than in the sites with fishing allowed for the public on license (the result bordered at significance). It is likely that fishing regulations within the whole migratory area are essential to enhance the potential for salmonid recovery.
6.3 Changes in the provision of ecosystem services

The responses to the questionnaire in Paper III indicated that both user groups strongly supported restoration goals (76–91%, depending on the user group and goal in question), but they were not always satisfied with the restoration outcomes (Figure 1 in Paper III). Regarding the river Kostonjoki, the majority (72–76%) of both user groups were satisfied with the outcomes, whereas in the case of the river Simojoki less than half (39–46%) of river users were satisfied. Regarding the river Kiiminkijoki, a greater proportion of the residents (65%) than of the fishermen (51%) were satisfied. A recent study by Sarvilinna et al. (2017) also indicated strong public support for plans to improve nearby watercourses. In an earlier study, Connelly et al. (2002) observed that ecosystem restoration goals were more strongly approved than were the specific restoration actions.

Restoration-induced changes in ecosystem services showed clear variation between the study rivers, while the differences in the perceptions of the two user groups were less evident (Table 3 in Paper III). The results suggested that a cultural service related to landscape value and amenity (including e.g. aesthetic appearance, naturalness and suitability of the site for recreational purposes) was the public’s main criterion for judging restoration outcomes (Higgs 1997, Tunstall et al. 2000, Barthélémy & Armani 2015). This service explained the highest proportion of variation among the variables studied in Paper III (Table 2 in Paper III). It also showed the most profound and conflicting changes, with the strongest positive changes perceived for the river Kostonjoki and the strongest negative changes for the Simojoki, while opinions on the river Kiiminkijoki were on average neutral. Landscape and recreational values were also frequently mentioned in the answers to open questions, reflecting their importance to the public. Although the recreational opportunities were reported to have changed relatively little after restoration (Figure 2 in Paper III), many respondents, for example, near the river Kiiminkijoki, considered that the restored sites provided more enjoyment to the public.

In terms of perceived changes in habitat structural diversity, the data indicated that the river Kostonjoki was again most positive, whereas perceptions on other cultural services were more positive for the Simojoki (fisheries opportunities perceived by the fishermen) and Kiiminkijoki (travel on water perceived by the residents).

Perceived changes in fish provisioning were consistent with the pattern observed for general satisfaction (Simojoki < Kiiminkijoki < Kostonjoki; Table 3
The open questions supported the interpretation that this service had an important role in gaining approval for our study rivers (Acuña et al. 2013). In general, the majority of the fishermen reported either negative changes (28–37%; Table 4 in Paper III) or no change in the catch (32–33%) of the three most desired fish species. As an exception to this, relatively many of the fishermen at Kostonjoki reported that their catch, particularly that of grayling (*Thymallus thymallus*, 41% of the respondents), had increased. Many fishermen of the rivers Kiiminkijoki and Simojoki perceived that the restoration outcomes remained weak because of ineffective fishing regulations and inadequate water quality; they therefore called for larger-scale actions. On the other hand, many respondents showed confidence in more positive results in the future.

While the perceptions of the respondents cannot be used as a direct measure of fish abundances, our findings may partly reflect variability in ecological success in the study rivers. However, it is important to note that ecological improvements may be difficult for the public to perceive (Barthélemy & Armani 2015). Providing information on realistically achievable goals and ecosystem benefit trajectories over time could help to avoid disappointments (Tunstall et al. 2000, Åberg & Tapsell 2013).

One regulating service revealed in the analyses was related to the formation and fragmentation of river ice (river ice processes, Table 2 in Paper III). The residents living near the Kostonjoki and Simojoki rivers considered that restoration had not intensified the formation of frazil ice and ice jams during ice breakup. As regards the Kiiminkijoki, restoration effects on ice processes were perceived by neighbouring residents as slightly negative (Table 3 in Paper III).
7 Conclusions and implications for management

Despite extensive restoration activity, degradation of river ecosystems remains one of the main concerns in environmental management. This thesis contributes novel information to the current scientific debate on the potential to improve river conditions. The results showed that in-stream habitat restorations are in many cases a useful approach to improve the ecological status of streams and rivers. The restoration-induced increase in habitat heterogeneity appeared to be persistent over time, initiating an overall positive development also in biological metrics (e.g. juvenile salmonids and aquatic mosses). However, fish responses varied widely between rivers, with differences explained mainly by watershed-scale and local factors (e.g. river basin size, dominant geology and potential interspecific competition). Site-specific differences were also seen in the delivery of ecosystem services, reflecting stakeholder perceptions on ecological and recreational outcomes. In future studies, both ecological and social outcomes should be evaluated at the same study sites, to reveal the linkages between different dimensions of success (Barthelemy & Armani 2015, Parsons et al. 2016). Furthermore, drawing conclusions on the overall project success would require the use of all three aspects of sustainability; social, environmental and economic. In this thesis the emphasis was on environmental and social aspects of restoration, whereas the economic component was not addressed (Woolsey et al. 2007). This thesis also focused on ecosystem services relevant to two user groups, and did not attempt to quantify all services (Vermaat et al. 2016).

This thesis provides important insights for the debate on ecological resilience, the capacity of a system to recover from disturbance (Waldman et al. 2016). There was evidence that restoration initiates a shift towards naturalised river conditions. Such systems are likely to be more self-sustaining and provide resilience to, for example, climate change (Gilvear et al. 2013). On the other hand, it was found that spawning sites deteriorated over time, most likely affecting the overall sustainability of restorations. Although the results showed that restoration of natural processes allowed in-stream habitat to continue on the path of self-recovery, suitable spawning substrates are still unlikely to recover spontaneously in Fennoscandian lowland streams (Palm et al. 2007, Gilvear et al. 2013). Therefore, creating sustainable spawning substrates is one of the main challenges for future restoration efforts.
Another concern relates to external drivers that most likely influenced restoration benefits. For example, salmonid density responses to restoration were influenced in some degree by local fisheries management (fishing regulations and stockings). In future research, these factors need to be treated as an integral part of the system dynamics, not as problems external to ecosystem enhancement practices (Waldman et al. 2016). The first step to improving the outcome of restorations is to identify and understand the main constraints on their success (Naiman 2013, Nuruzzaman et al. 2017).

Some stakeholders that participated in our questionnaire suggested that in-stream habitat restoration did not improve river conditions for the target species because of inadequate water quality. Similar conclusions have also been made in several previous studies (e.g. Haase et al. 2013, Mueller et al. 2014, Roni et al. 2015). However, the fish metrics used in this thesis showed that water quality in the study rivers was sufficient to support salmonid populations. In the future, we will be facing new challenges. It has been predicted that with climate change, there will be changes in water quantity and quality (Arnell & Gosling 2013, de Wit et al. 2016). This, together with increasing temperatures, will place additional pressure on stream biota and should be acknowledged in management and restoration practices.

As this thesis demonstrated, in evaluations of restoration success perspective is highly important (Jähnig et al. 2011, Wohl et al. 2015). For example, the question of what success indicators should be considered is a matter of perspective. The results showed that for the public, success was mainly perceived through changes in landscape value and amenity and fish provisioning. The question of what is the expected level of improvement is also grounded on perspective. According to the results in this thesis, many experts believe that even a minor improvement in natural production of salmonids is sufficient to designate restoration efforts successful. Biological results suggested that this target was largely achieved in the study rivers. Furthermore, from the societal perspective, restoration might be justified even when it is unlikely to bring significant benefits for biodiversity (Lepori et al. 2005). This does not mean, however, that the projects that were primarily motivated by public needs and concerns could not also provide ecological benefits and vice versa (Gillilan et al. 2005). However, a shift towards more sustainable scheme that seeks to integrate both ecological and social perspectives would be desirable (Palmer et al. 2005).

While recent progress in the field of ecosystem restoration has been promising, great challenges remain. In the future, restoration schemes should be
operating more at the watershed scale, engaging stakeholders (Gilvear et al. 2013, Naiman 2013). Through doing so, restoration has potential to provide multiple benefits for ecosystems and the society. The inclusion of ecosystem services and different disciplines is important for gaining more sustainable and acceptable outcomes (Geist & Hawkins 2016). As Naiman (2013) states, “doing anything less means staying on the same river conservation and restoration trajectory; a trajectory that has a poor track record in terms of enduring success.” A failure to consider the stakeholder perspective may generate multiple economic, political and cultural obstacles (Barthélemy & Armani 2015). While a win-win situation is not always possible, addressing interdependencies between human well-being and ecosystem status can provide transparency and better predictive tools for decision-making (Terrado et al. 2016).

Based on the results in this thesis, I encourage future work in restoration science and practice focus on:

- defining clear objectives and setting priorities for restoration projects
- providing information on realistically achievable goals for all participants
- adopting a watershed-scale perspective that addresses multiple drivers of degradation, including water quality, morphology, fisheries regulations etc.
- harnessing natural recovery processes and, when possible, relying on them
- identifying key ecosystem services, such as landscape and recreational values, and fish provisioning
- engaging local communities and stakeholders in priority setting and restoration practices. This could be achieved using for example participatory methods in planning and voluntary work in the restoration actions
- learning from both positive and negative outcomes and implementing systematic reviews on the outcomes
- implementing a multidisciplinary, long-term monitoring programme for a good number of restoration projects
- sharing evaluation results with stakeholders and managers. The transfer of knowledge can be done efficiently using modern communication techniques.

Finally, the importance of rigorous evaluation programmes must be emphasised. Providing a scientific evidence base on multiple restoration benefits (i.e. material and immaterial benefits) can aid in gaining public acceptance. This in turn may improve public willingness to support and take part in restoration practices. Only through joint efforts and constant science-policy interactions can we find means to make restoration more effective and beneficial for ecosystems and for society.
References


SYKE (2013). The ecological status of Finland’s large lakes is good but the coastal waters are in a poor condition. Newsletter of the Finnish Environment Institute SYKE. Envelope 3/2013.


Original articles


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691. Hens, Hilde (2017) Population genetics and population ecology in management of endangered species


694. Schneider, Laura (2017) Mechanocatalytic pretreatment of lignocellulosic barley straw to reducing sugars


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698. Dong, Yue (2017) Bifunctionalised pretreatment of lignocellulosic biomass into reducing sugars : use of ionic liquids and acid-catalysed mechanical approach

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ECOLOGICAL AND SOCIAL DIMENSIONS OF RESTORATION SUCCESS IN BOREAL RIVER SYSTEMS