Impacts of SCUBA Divers in the Silfra Groundwater Fissure: Ecological Disturbance and Management

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90 ECTS thesis submitted in partial fulfillment
of a Magister Scientarium degree in Aquatic Biology

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Abstract

As is common with increasing tourism the world over, the rapid growth of the Icelandic tourism industry may negatively impact ecosystems in areas that tourists visit. The Silfra groundwater fissure in the Thingvellir National Park has seen a rapid increase in the number of entrees, receiving just below 20.000 divers and snorkelers in 2014. This interdisciplinary thesis explored the relationship between the growing number of dive tourists and potential environmental impacts by: 1) comparing algal biomass and zoobenthic diversity of Silfra to Flosagjá, a fissure where diving is prohibited, 2) comparing algal biomass and zoobenthic diversity between areas of different dive-usage within Silfra, 3) recording diver underwater behavior to assess the mechanisms and ecological consequences behind diver-related ecological disturbances and 4) analyzing perceptions and experiences of dive company operators, dive-guides, dive-tour customers and the Thingvellir National Park officials surrounding the use of Silfra as a dive-site. Results indicated the presence of ecological disturbance in Silfra, especially through algal detachment as algal biomass was less in Silfra than Flosagjá and exhibited a negative correlation with dive-use in Silfra. Zoobenthic diversity appeared mostly unaffected, except for species PEI, which decreased with dive-use, providing evidence for the dominance of disturbance-tolerant species in sites with heavy dive-use within Silfra. By assessing diver underwater behavior it was estimated that each diver entering Silfra caused an average of 81 disturbance events, resulting in the removal of algae and the raising of sediment. These consequences mostly occurred as a result of diver fin-generated currents, but contacts by divers were also frequent. Ecological disturbance is likely to escalate with increasing numbers of divers. Analysis of stakeholder perceptions indicated that a further increase in Silfra visitor numbers may damage the tourism experience. This thesis recommends improved management in the currently open fissures for diving in Thingvellir National Park, in addition to a limitation on the number of visitors allowed into Silfra on an annual basis. These management protocols would simultaneously reduce future ecological disturbance and enhance the quality of the tourism experience. For this to be fully achieved, future research need to focus on the establishment of ecological, social and economic carrying capacities for fissure diving and snorkeling in Thingvellir National Park.

Útdráttur

Líkt og oft vill fylgja vaxandi ferðamennsku í heiminum getur stækkun ferðamannaiðnaðarins á Íslandi ollið raski á vistkerfum. Í ferskvatnsgjánni Silfru, í Þingvallaþjóðgarði, hefur aukning ferðamanna verið ör og á síðastliðnu ári (2014) heimsóttu rétt um 20.000 kafarar og yfirborðskafarar gjána. Í þessari þverfaglegu ritgerð er fjallað um hugsanleg umhverfisleg áhrif kafara á vistkerfi Silfru með því að: 1) bera saman fjölbreytileika ferskvatnshryggleysingja og lífmassa þörunga milli Silfru og gjár þar sem köfun er ekki leyfð, í þessu tilviki Flosagjá, 2) bera saman fjölbreytileika ferskvatnshryggleysingja og lífmassa þörunga milli svæða í Silfru þar sem mismikil köfun á sér stað 3) nota myndbandsupptöku á hegðun kafara neðanvatns til þess að meta tildrög bak vistfræðilegs rasks af þeirra völdum í Silfru og 4) greina upplifanir og sjónarmið eigenda köfunarfyrirtækja, leiðsögumanna, viðskiptavina í köfunarferðum og starfsmanna Þingvallarþjóðgarðs varðandi rekstur köfunarþjónustu í Silfru. Niðurstöður bentu til þess að vistfræðilegt rask eigi sér stað í Silfru. Þetta orsakaðist helst vegna losunar þörungagróðurs, en lífmassi þörungagróðurs var marktækt minni í Silfru en Flosagjá og sýndi einnig neikvætt samband með aukinni köfun innan Silfru. Köfun virtist ekki hafa viðamikil áhrif á fjölbreytileika ferskvatnshryggleysingja, nema á jafndreifingu hópa sem minnkaði með auknu köfunarálagi og gaf vísbendingar um að þar sem mikið köfunarálag er til staðar eru ríkjandi tegundir sem þola rask betur en aðrar. Mat á hegðun kafara neðanvatns sýndi að hver kafari olli að meðaltali 81 tilviki rasks í hverri köfun í Silfru. Þetta stuðlaði að losun þörungagróðurs og raski á setbotni. Straummyndun vegna hreyfinga sundfita var helsta orsök vistfræðilegs rasks en snerting kafara á þörungagróðri var einnig tíður raskvaldur. Vistfræðilegt rask köfunar í Silfru mun líklega aukast með auknum fjölda kafara. Greining á sjónarmiði hagsmunaaðila gaf til kynna að aukning í fjölda kafara og yfirborðskafara í Silfru geti skaðað upplifun þeirra ferðamanna sem sækja gjána heim. Mælt er með bættri stýringu á gjám innan Þingvallaþjóðgarðs sem opnar eru fyrir köfun og yfirborðsköfun. Auk þess er mælt með því að fjöldi kafara og yfirborðskafara sé takmarkaður á ársgrundvelli. Þessar aðferðir til stjórnunar gætu minnkað vistfræðilegt rask og aukið gæði köfunarferðaþjónustu í Silfru. Mikilvægt er að framtíðarrannsóknir beinist að vistfræðilegum, félagslegum og efnahagslegum þolmörkum köfunar í ferskvatnsgjám Þingvallaþjóðgarðs.

To my mother, Hildur Karen, who has deeply inspired me with her instinct-based nature-wisdom.

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Abbreviations and explanations

1. Concepts

Concept	Abbreviation
Chlorophyll a	Chl*a*
Dive-use index	DUI
Dry algal biomass	DAB
Dynamic Equilibrium Model	DEM
Intermediate Disturbance Hypothesis	IDH
Minimal algal disturbance	A1
Minimal sediment disturbance	S1
Pielou´s evenness index	PEI
Redundancy Analysis	RDA
Self Contained Underwater Breathing Apparatus	SCUBA
Severe algal disturbance	A2
Severe sediment disturbance	S2
Shannon diversity index	SDI
Suspended organic matter	SOM
Thingvellir National Park	TNP

2. Sampling sites in Silfra

Abbreviation	Sampling site	
	Transect	**Depth (m)**
1-1m	1	1
1-4m	1	4
2-1m	2	1
2-10m	2	10
3-1m	3	1
3-9m	3	9
4-1m	4	1
4-9m	4	9
5-1m	5	1
5-10m	5	10

3. Sampling sites in Flosagjá

Abbreviation	Sampling site	
	Transect	**Depth (m)**
1-1m	1	1
1-4m	1	4
2-1m	2	1
2-5m	2	5
3-1m	3	1
3-5m	3	5
4-1m	4	1
4-10m	4	10
5-1m	5	1
5-5m	5	5

4. Taxa list

Abbreviation	Taxa name
Acarina	Acarina
A.harp	*Acroperus harpae*
A.affin	*Alona affinis*
A.quadr	*Alona quadrangularis*
A.werest	*Alona werestschagini*
Chaetocld	*Chaetocladius vitellinus* group
Chydor	*Chydorus cf. sphaericus*
Copep	Copepoda
Cyprid	*Cypridoidea* sp.
D. ber	*Diamesa bertrami*
Dia.zer	*Diamesa zernyi* group
E.minor	*Eukiefferiella minor*
Fabaef	*Fabaeformiscandona* sp.
Microp	*Micropsectra* sp.
O.frig	*Orthocladius frigidus*
O.obli	*Orthocladius oblidens*
Plecopt	Plecoptera
Rheocr	*Rheocricotopus cf. effusus*
Thienem	*Thienemaniella* sp.
Trichopt	Trichoptera

5. Factors that may affect diver disturbance

Abbreviation	Explanation
Cert. 1	Basic dive certification
Cert. 2	Advanced dive certification
Cert. DS+	Dry-suit certified
Cert.DS-	Not dry-suit certified
>100 dives	More than 100 dives logged
<100 dives	Less than 100 dives logged
DS logged+	Dru-suit dives logged
DS logged-	No dry suit dives logged
Damage+	Diving damage on freshwater ecosystems perceived
Damage-	Diving damage on freshwater ecosystems not perceived
Briefing+	Briefing on the environmental impacts of diving received
Briefing -	Briefing on the environmental impacts of diving not received
Difficulty	The perceived difficulty of the dive in Silfra
Loc. 1-2	Observation locations 1-2 in Silfra
Loc.2-3	Observation locations 2-3 in Silfra

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1. General introduction

Anthropogenic disturbance in natural environments has caused the degradation of ecosystems (Vitousek *et al.* 1997; Barnosky *et al.* 2012). Although anthropogenic disturbance can occur by numerous means, the rapid increase in world tourism, validates a need to investigate tourist-based ecological disturbances, especially in natural tourist areas (Wong 2004). This chapter will provide an overview of key human interactions with the environment and discuss and define ecological disturbance before introducing the current status of tourism in the modern world. As the focus of the thesis is dive tourism in a national park, these topics will be briefly discussed before the objectives and related research questions of the thesis are introduced.

1.1. Humans and the environment

Humans (*Homo sapiens*) have long impacted the environments they inhabit. The ability to modify natural landscapes to our own benefit has made humans greatly successful but also threatens the planets biosphere through mechanisms attributed to population growth. These include the consumption of resources, fragmentation and transformation of habitats and energy production (Barnosky *et al*. 2012).

Homo sapiens became geomorphic agents 400.000 years ago when our prehistoric ancestors started utilizing rocks for shelter and making tools for hunting (Hooke 2000). This allowed us to readily acquire high quality foods (Kaplan *et al.* 2000) and in the late Pleistocene human hunting is thought to have at least partially caused the extinction of around half of the large terrestrial mammals present at the time, known as the Pleistocene extinctions (Martin 1984; Alroy 2001; Barnosky *et al.* 2004; Barnosky *et al.* 2012; Sandom *et al.* 2014). The subsequent agricultural revolution commenced 10.000 years ago in the Fertile Crescent (Lev-Yadun *et al*. 2008) with the domestication of animals, some of which were invasive to numerous endemic species (Zeder 2008). Agriculture then allowed humans to form settlements (Sjoberg 1965). The invention of the wheel greatly expanded our ability to modify landscapes on a grander scale, as machines and tools grew in size and capacity (Hooke 2000). Since the start of the modern colonial era humans have eroded global island environments (Mairs 2007), and caused depletion of native habitats (Lewis and Berry 1988; Murrin 1997). In addition, technological advancements commenced by the industrial revolution in 1780 (Deane 1965; Crutzen 2006) expanded our environmental impacts with improved production, farming and transportation methods still present in the modern world (Berry 1990; McDowell *et al.* 1990).

The biodiversity loss in the last few centuries has greatly exceeded natural patterns (Sarukhán *et al.* 2005; Ceballos *et al.* 2015). Some scholars suggest that the planet´s sixth mass extinction is underway, for the first time in world history as a consequence of the interaction of one species with their environment (Barnosky *et al.* 2011; Dirzo 2014). Currently, all the world´s ecosystems are disturbed by anthropogenic forces to at least some extent (Walker and Willig 1999), leading some to suggest that the current geological epoch be named after our species, the Anthropocene (Crutzen 2006; Monasterasky 2015).

1.2. Disturbance

Human-induced environmental impacts from the late Pleistocene to modern times can be classified as ecological disturbances on natural environments. However, as few ecosystems remain in equilibrium, and damaging forces can affect everything from single individuals to entire populations (Sousa 1984) defining the concept of ecological disturbance can be difficult. Nevertheless, numerous attempts have been made to present a working definition that reaches a general consensus among ecologists. White and Jentsch (2001) presented a classification with "relative" and "absolute" definitions of disturbance. Relative definitions seek to classify any event outside the normal dynamics of an ecosystem as disturbance while absolute definitions are "based on physical and measureable changes in variables or in the disposal of resources whether or not these changes are recurrent, expected or normal" (White and Jentsch 2001, p. 405). Consequently, absolute definitions are more concise and applicable to the various conditions present in ecosystems. Following are some of the most common definitions in disturbance literature that can be classified as absolute. Grime (1977, 2001) described disturbance as a process associated with a partial or total destruction of biomass within a plant ecosystem. Rykiel (1985, p. 365) defined disturbance as "A cause; a physical force, agent, or process, either abiotic or biotic, causing a perturbation (which includes stress) in an ecological component or system; relative to a specified reference state and system; defined by specific characteristics." Furthermore, he subcategorized disturbance into four distinct processes: 1) destruction, where "existing biomass is reduced in quantity", 2) discomposition, causing "particular populations to be selectively eliminated, reduced, added or expanded", 3) interference, where "matter/energy, information exchange processes are inhibited" and 4) suppression, where natural disturbances are prevented. Sousa (1984, p. 356) stated that "a disturbance is a discrete, punctuated killing, displacement, or damaging of one or more individuals (or colonies) that directly or indirectly creates an opportunity for new individuals (or colonies) to become established". Finally, Pickett and White (1985, p. 7) described disturbance as "any relatively discrete event in time that disrupts the ecosystem, community, or population structure, and changes resources, substrate availability, or the physical environment." Since this includes any event that may disturb an ecosystem and its composition, it is perhaps the broadest existing definition of disturbance.

Biotic and abiotic disturbances play an important role in the evolution of ecosystems (White and Jentsch 2001). Impacts from biological entities such as invasive species, herbivores, disease and other animal activities (Dayton 1971; White 1979) including the effects of humans (Walker and Willig 1999) cause biotic disturbances. Abiotic disturbances emerge from the damage caused by natural phenomena, such as fire, weather, avalanches and landslides (White 1979; Gadgil and Bain 1999). Both negative and beneficial consequences can arise from these disturbing impacts on an ecosystem (Walker 2012). In many cases, biodiversity can decrease, such as in rainforest ecosystems, when large forested areas are replaced by grasslands as a result of forest fire disturbance (Cochrane 2003). Conversely disturbance can be beneficial, such as when forest fires help to maintain ecosystem health (Bowman and Murphy 2010) and when natural disturbances in coral reefs benefit coral reef interactions, species diversity and evolution (Richmond 1993).

Two hypotheses can help explain the occurrence of beneficial disturbance: the intermediate disturbance hypothesis (IDH) and the dynamic equilibrium model (DEM). The IDH suggests that disturbance at intermediate magnitudes and/or frequencies maximizes diversity, while minimal or severe disturbance has the opposite effect, minimizing the biodiversity of an ecological community (Figure 1.2. A). According to the IDH, competitive exclusion occurs at low levels of disturbance, where superior species eliminate the inferior. At high levels of disturbance the recruitment of new species to the system does not balance the high mortality rates, allowing for the dominance of only a few species. However, at intermediate disturbance mortality is moderately increased resulting in the opening of space for new individuals to inhabit, resulting in maximized biological diversity within the system (Connell 1978). The other hypothesis the DEM, is based on the same mechanisms as the IDH. However, it suggests that diversity is influenced by the interaction of ecosystem production, competition and disturbance. In that manner, diversity will peak depending on the rate of population growth and competitive displacement. When rates of growth and competitive displacement are low, maximum diversity occurs at minimal disturbance. When at intermediate rates, diversity will be highest at intermediate disturbance, and when growth and competitive displacement rates are high, diversity will peak at high disturbance (Huston 1979) (Figure 1.2. B).

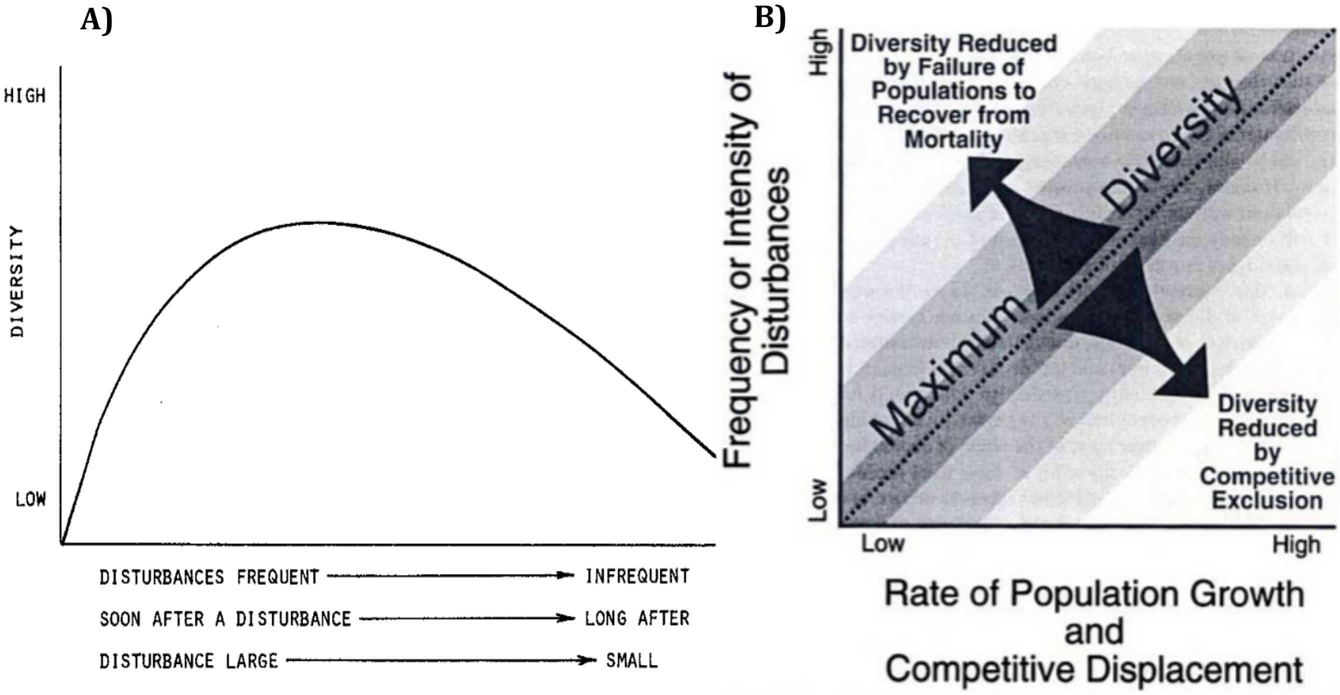

Figure 1.2. *A schematic figure explaining the A) intermediate disturbance hypothesis, which states that diversity is highest at intermediate disturbance (Connell 1978) and B) the dynamic equilibrium model, which suggests that diversity peaks depending on rates of growth and competitive displacement (Huston 1994).*

Even in the absence of disturbance most ecological systems do not remain in equilibrium, but are dynamic and fluctuate around a mean condition over time (Hobbs and Harris 2002; Barnosky *et al.* 2012). Hence, changes in structure can be expected naturally even if the ecosystem is left undisturbed (*see* Einarsson *et al.* 2004). However, when under disturbance, changes may become more dramatic, potentially resulting in ecosystems shifting from their mean conditions to alternative stable states (Holling 1973; May 1977; Hastings 2013) where they can remain unless restored back to the original condition or further disturbed (Hobbs and Norton 1996). When disturbances are of high magnitude and/or frequency the resulting ecosystem decline can reach thresholds controlled by biotic interactions and abiotic limitations (Whisenant 1999). Ecosystems have natural self-repair mechanisms, but disturbance-induced damages may be too great to naturally restore the ecosystem without the aid of intervention (Whisenant 1999). When a biotic threshold is reached, manipulation of biotic interactions may be needed in order to restore the ecosystem. This can be achieved, for example, by the input of key species or the removal of invasive species (Hobbs 2002). When an ecosystem reaches an abiotic threshold however, alterations of physical variables are needed before the manipulation of biotic interactions can commence. In order to restore ecosystems by these means, an extensive knowledge of the disturbance factor is needed (Hobbs 2002).

Human population growth and consumption rate in the modern world are the current sources of the greatest disturbances in the biosphere (Walker and Willig 1999; Barnosky *et al.* 2012), which in many cases exceeds optimal disturbance levels and the ability for ecosystems to naturally self-repair (Whisenant 1999). In terrestrial systems, humans have fragmented habitats by the means of direct disturbances through agriculture, mining and transportation but also indirectly such as through the introduction of alien species (Walker 2012). In addition, no marine ecosystems are absent of anthropogenic influence (Halpern *et al.* 2008) and freshwater ecosystems have been extensively impacted by humans (Dudgeon *et al.* 2005). Predictions indicate that as long as the human population continues to increase, so too will habitat fragmentation, possibly leading to a future state shift in the earth´s biosphere (Barnosky *et al.* 2012).

1.3. Modern world tourism and Iceland

Since the start of the mid-20th century world tourism has greatly expanded as a result of population growth and technological advancements that have allowed travel to become easier (Towner 1995; Buckley 2012). The number of international travelers has grown to such an extent that tourism is currently one of the world´s largest and fastest growing industries (UNWTO 2015). Services associated with the industry have provided significant income with the creation of jobs that have helped economies in many countries (WTTC 2014).

Alongside the increase in tourism, environmental impacts of tourist activities have expanded (Sunlu 2003). Major concerns are associated with long-distance travel resulting in increased carbon emissions (Gössling 2000). Tourism can also impact local ecosystems in various ways (Wong 2004), such as through the placement of transport infrastructure in habitats, the trampling of vegetation (Newsome *et al.* 2012), disturbance of wildlife (Burns *et al.* 2011) and the trampling of corals in marine ecosystems (Hawkings and Roberts 1992a; Tratalos and Austin 2001; Milazzo *et al.* 2002; Hasler and Ott 2008). Visitation to natural environments is an increasingly important aspect of the modern tourism industry (Balmford *et al.* 2009). Degradation by tourism in natural environments can inhibit the long-term profit for local people as well as irreversibly impact local ecosystems. If local residents, politicians, and tourism operators seek to attract tourists to natural environments it is in their best interest to protect the environment (Wood 2002). The emergence of the fields of ecotourism and sustainable tourism have considered the issues of both the global and local environmental impacts of tourism and attempted to develop strategies to minimize negative impacts (Kiper 2013).

Ceballos-Lascuráin (1993, p.4) defined ecotourism for the IUCN as: "Environmentally responsible travel and visitation to relatively undisturbed natural areas, in order to enjoy and appreciate nature (and any accompanying cultural features — both past and present) that promotes conservation, has low visitor impact, and provides for beneficially active socio-economic involvement of local populations". Sustainable tourism has been defined with reference to sustainable development, as: “Tourism that takes full account of its current and future economic, social and environmental impacts, addressing the needs of visitors, the industry, the environment, and host communities.” (UNWTO 2005, p.12). Although ambiguous, the above concepts are important guidelines for authorities, mangers, operators and tourists. Sustainable tourism guidelines have been proposed by the IUCN (Eagles et al. 2002) and the World Tourism Organization (UNWTO 2005), and in countries like Costa Rica and Sweden, certifications have been administered to service-providers complying with domestic ecotourism schemes (Sander 2010).

In Iceland, the tourism industry has expanded greatly since the start of the millennia, with the number of international arrivals rapidly increasing (Figure 1.3). As Icelandic nature is the most important factor influencing travelers decisions to visit the island (Íslandsstofa 2013a), marketing schemes have focused on advertising Iceland as destination with vast and unspoiled nature (Íslandsstofa 2013a) and as a sustainable tourist destination (Íslandsstofa 2013b). The vision for future years according to Promote Iceland (a public-private partnership for the economic growth through export from Iceland) is to make Iceland a world leading sustainable tourism destination (Íslandsstofa 2013b). However, with the number of visitors on the rise, detailed plans on how to manage specific destinations are needed, in addition to ecotourism and sustainable tourism certifications and training for service providers. Because environmental impacts of tourists have been shown to increase with use (Sun and Walsh 1998), it is pressing for Icelandic tourism operators and authorities that management protocols are developed to strike a mutually beneficial balance between nature conservation and tourism (Brandl *et al.* 2011).

Figure 1.3. *International arrivals to Iceland from 1949 to 2014. Based on data from The Icelandic Tourist Board (2014).*

1.4. The Thingvellir National Park

Thingvellir National Park (TNP) in southwest Iceland is a UNESCO world heritage site renowned for its history and nature (UNESCO 1994-2014). The site includes the location where the world's first parliament was established and where major decisions in Iceland history were taken. In addition, the geology of TNP is considered special because it is located at a tectonic plate boundary where the Hreppafleki and North American tectonic plates are drifting apart. The processes associated with the tectonic movements have created numerous geological features. The tectonic drift caused the creation of a rift valley, which eventually lead to the formation of Lake Thingvallavatn, the largest natural lake in Iceland, and fissures, some of which are freshwater filled (Einarsson 2008).

TNP is one of the most sought after tourist destination in Iceland (Óladóttir 2014) with 50% of international tourists in Iceland visiting the national park in 2014 (Sæþórsdóttir 2015), an estimate of 588.000 tourists (Elmarsdóttir and Ásbjörnsdóttir 2014). Since 2004, visitor numbers in TNP have increased by 77% (international travelers: 107%; Icelandic travelers: 19%). Discussions about the current and future development in relation to this increase have surfaced with concerns emerging on the potential impact of tourist traffic, especially due to trampling on vegetation (Elmarsdóttir and Ásbjörnsdóttir 2014).

The groundwater fissures of TNP open into the groundwater aquifer (Einarsson 2008), resulting in great visibility valued by divers and snorkelers from around the world (Ólafsdóttir 2010). Diving is now allowed in two fissures, the in-lake Davíðsgjá fissure, located roughly 300 meters off the shore of Lake Thingvallavatn, and the more accessible Silfra (Stjórnartíðindi 2013a). Dive and snorkeling entrees into the Silfra groundwater fissure have increased drastically in the last few years and predictions on the number of entrees into Silfra by the National Park have been underestimated in past years. For example in March 2013, a 1.000 kr. entrance fee was established for divers and snorkelers. The TNP´s operating budget estimated 6-8000 entrees to the fissure during 2013 but in the 10-month period from March 2013 (when detailed registration of diver numbers commenced) to the end of December the same year 11.983 divers and snorkelers entered the fissure. In 2014, 19.597 entrees were confirmed (data from Þingvallaþjóðgarður 2015).

Numerous examples exist in the literature surrounding instances where divers and snorkelers cause disturbances in aquatic environments, especially in marine systems (*see*: Wong 2002; Abidin and Mohamed 2014) and to a lesser extent freshwater (Humphreys *et al.* 1999; Teresa *et al*. 2011). However, ecological consequences of the increased traffic within Silfra are unknown. Much of the dive and snorkeling traffic in Silfra takes place during the sub-arctic spring-bloom months from May to June (data from Þingvallaþjóðgarður. 2013, 2014), when algal growth is at its peak. Divers with years of experience have noted a visual decay in algal cover in Silfra, while other fissures in the area have remained intact (Ólafsdóttir J.H.; Sigurþórsson D.; Ramsey D., personal communication). However, ecological decay in Silfra is debated, as other experienced Silfra divers do not claim to have witnessed such decay (Skúlason B., personal communication). This justifies the need for a quantitative assessment of potential diver-related disturbances in the Silfra freshwater ecosystem.

1.5. Objectives

This thesis aims to evaluate the presence of diver-related ecological disturbances in Silfra, the mechanisms behind diver-related disturbances and to propose management protocols for the sustainable use of Silfra as a dive-site. To evaluate potential diver-related disturbances in Silfra, a twofold objective is presented in this thesis:

- Chapter 1 will assess ecological disturbance in Silfra by analyzing algal biomass and zoobenthic diversity, both by comparing Silfra to a fissure without dive tourism, and by comparing areas within Silfra that are subject to different levels of dive-use.

- Chapter 2 will investigate mechanisms behind diver-related disturbance in Silfra by observing diver behavior underwater in relation to algal removal and sediment raising, and assess diver characteristics that may cause greater incidence of disturbance.

In order to propose management protocols surrounding the use of Silfra as a dive-site, the following objective is presented:

- Chapter 3 will present management protocols and options for the sustainable dive tourism in Silfra by taking into account the interests of stakeholders surrounding the use of Silfra as a dive-site.

1.6. Research questions:

From the objectives above, three general research questions are presented:

- Chapter 1: Are there differences in zoobenthic diversity and biomass 1) between a fissure where diving is allowed and a fissure where diving is prohibited, and 2) within areas in Silfra that are subject to different levels of dive-use?
- Chapter 2: What are the mechanisms behind diver-related disturbances in Silfra, and are there any diver characteristics that cause an increased likelihood of disturbance?
- Chapter 3: How can diving in Silfra be managed with regards to sustainable development, so that it becomes minimally destructive while still serving the interests of major stakeholders?

Chapter 1: Assessing ecological disturbance in the Silfra groundwater fissure.

1.1. Introduction

The total volume of water reserves on earth is about 1.4 billion km^3 (Shiklomanov 1993). Most of the water is saline (97.5%) while the rest is fresh. The amount of freshwater readily available for ecosystems is less than 1% of all water resources. This is contained in the atmosphere, organisms and freshwater habitats (Shiklomanov 1993). The importance of freshwater is vast, as it sustains all terrestrial and freshwater life. Humans alone now use around 10% of the renewable freshwater supply available (Sarukhán *et al.* 2005) and despite our dependence on freshwater, future human impact on water quality and biodiversity is inevitable (Dodds 2002). Humans have severely damaged the freshwater habitat by destruction, pollution, exploitation, overfishing, climate change, flow modifications and the introduction of invasive species (Dudgeon *et al.* 2005). Although knowledge on global freshwater biodiversity is incomplete, potentially resulting in underestimated species losses, the highest proportion of threatened species on earth belong to taxonomic groups that directly rely on freshwater habitats (Dudgeon 2005; Sarukhán *et al.* 2005) possibly resulting in freshwaters being the most endangered ecosystems in the biosphere (Dudgeon *et al.* 2005).

Freshwater ecosystems can be classified into lotic (habitats with flowing waters) and lentic (habitats with non-flowing waters) systems (Dodds 2002). Organisms in freshwater ecosystems are commonly adapted to the predictable changes present in their ecosystems, such as variations in light climate, temperature and dissolved oxygen, and therefore, disturbance is usually caused by unpredictable events that can modify conditions beyond normal fluctuations (Resh *et al.* 1988). These events are diverse, and their impacts depend on the disturbance intensity, frequency and extent (Resh *et al.* 1988). Two hypotheses have attempted to explain the interactions of these that affect species diversity. According to the Intermediate disturbance hypothesis (IDH) and the dynamic equilibrium model (DEM) disturbance can act as a structural force to ecological assemblages. The IDH suggests that disturbance at intermediate frequency or intensity causes the greatest ecological diversity (Connell 1978) as it gives rise to the coexistence of competitive dominants and rapid colonizers. The DEM on the other hand, suggests that disturbance, in conjunction with competition and production act together to modify diversity. That way, the amount of disturbance needed to sustain the highest diversity will depend on growth rates and competitive displacement. When these rates are high, a strong disturbance is needed to counter competitive exclusion while at lower rates, a weaker disturbance will suffice to inhibit competitive exclusion, sustaining high diversity (Huston 1979). The manner in which diversity is defined within the hypotheses also differs as the IDH is primarily concerned with species richness, while in the DEM diversity is defined as species richness and Pielou´s evenness index (Huston 1979).

Thingvellir National Park (TNP) in southwest Iceland is located at a tectonic plate boundary where the Mid-Atlantic Ridge is being driven apart, causing the formation of a rift valley. The tectonic drift has caused the cracking of the crust parallel to the rift valley, creating a large amount of rift valley fissures (Sæmundsson 2002). Some fissures are open into the groundwater aquifer (Sæmundsson 2002) and are therefore groundwater filled. For these, the main source of groundwater are the Þórisjökull and Langjökull glaciers, located in the central west highlands of Iceland, 35 and 40 km north-east of the rift valley in question, respectively. The flow path for this water, from the glaciers to TNP, is through porous lava, allowing for a steady flow of groundwater to the valley (Sigurðsson and Sigbjarnarson 2011). A large part of the rift valley extends below the aquifer, creating the Lake Thingvallavatn. Three main groundwater streams, the Miðfells, Hrafnagjár, and Almannagjár streams contribute groundwater to the lake. Underground channels within these streams provide an inflow of 75-80 m^3/s into the lake while the inflow from surface bound fissures has been estimated around 5-10 m^3/s. The greatest inflow from surface bound fissures comes from the Silfra fissure, which transports groundwater directly into Lake Thingvallavatn (Sigurðsson and Sigbjarnarson 2011).

Although the ecosystems of the groundwater fissures in TNP have not been systematically studied, ecosystems in Lake Thingvallavatn have been extensively researched (*see* Jónasson and Hersteinsson 2011). In the lake, plant life consist largely of diatoms that are present throughout the photic zone. Other plant life varies with depth. The littoral zone is abundant with *Ulothrix* sp. during the springtime. Growing amongst those are diatoms that bloom in late summer, after the *Ulothrix* have declined in abundance. At around 1m depth, where ice does not inhibit algal growth in winter, the cyanobacteria *Nostoc* are present and can survive throughout the year. At 2-10 m Cladophora spp. dominate and from 10-22m Chlorophyta in conjunction with diatoms take over (Jónsson 2011). Vertebrate life consists of fish species and Lake Thingvallavatn is especially known for its four morphs of Arctic charr (*Salvelinus alpinus*) (Sandlund *et al.* 1987): the large benthivorous (LB-) and small benthivorous (SB-) charr, and the pelagic planktivorous (PL-) and piscivorous (PI-) charr (Magnusson and Ferguson 1987; Sandlund *et al.* 1992). Additionally, within Lake Thingvallavatn, both lava and mud substrates are found, supporting two morphs of the threespine stickleback (*Gasterosterous aculeatus*). The lava morph specializes as chironomid eaters while the mud morph feed more on crustaceans (Kristjánsson *et al.* 2002). The Brown trout (*Salmo trutta*) is also present in the lake (Malmquist and Sturlaugsson 2002).

The submerged groundwater fissures in TNP are difficult to classify as they exhibit characteristics of both rheocrene (lotic) and/or limnocrene (lentic) (Springer and Stevens 2008) spring environments. Temperatures in the fissures remain relatively stable, varying from 2-4 °C throughout the year (Ólafsdóttir. M.Sc. thesis in prep.). However, a large seasonal variation is present in irradiance levels due to the high latitude (64°15) of TNP. As a consequence a spring bloom is present, inducing the highest levels of primary production in the spring/summer months from May-June (Adalsteinsson and Jónasson 2011). No quantitative algal sampling has been done in TNP fissures although Cyanobacteria, diatoms and *Tetraspora cylindrica* have been observed by the author. In addition, no quantitative analysis of fishes in the groundwater fissures has been done, although the small benthivorous morph of the Arctic charr has been seen in there, justifying its Icelandic name "Gjáarmurta" (*e. fissure fish*). Other morphs of Arctic charr have also been seen, especially at nighttime feeding, or in a resting state (Ólafsdóttir J.H., personal communication). In 2004 and 2006 Svavarsson and Kristjánsson described new species of groundwater amphipods (*Crymostigius thingvallensis* and *Crangonyx islandicus*) that are endemic to Iceland. The former has been found in springs in the TNP area, and in Arctic charr stomachs in Herðubreiðarlindir springs NE Iceland, while the latter has been caught in TNP springs and numerous spring sites around Iceland (Svavarsson and Kristjánsson 2004, 2006). Most recently in 2013, Ólafsdóttir (M.Sc thesis in prep.) found *Crangonyx islandicus* in a underground groundwater fissure in TNP demonstrating that these underground amphipods inhabit parts of TNP´s groundwater fissures. However, the ecology of these animals is unknown but as is common with other underground dwellers, they may to some extent rely on nutrients from outside the cave habitat (Dodds 2002) although some evidence suggests that the groundwater amphipods feed on chemotrophic bacteria (Kornobis 2011; Pálsson S., personal communication). Biodiversity in groundwater fissure ecosystems in Iceland are currently being studied (Ólafsdóttir. M.Sc.

thesis in prep.) but the interconnectedness of hydrology, nutrient flow and species dispersal demands further research in TNP fissures, especially surrounding endemic and possible undiscovered species.

Several individuals active in the Icelandic dive community have noted a visual decay in algal abundance in Silfra (Ólafsdóttir J.H.; Sigurþórsson D.; Ramsey D., personal communication). No systematic measurements have been done to evaluate this but as diving traffic has dramatically increased in Silfra, specifically in the high season during the algal spring bloom, the possibility exists for diver-related disturbances to impact algal covers and species diversity in Silfra. Numerous examples exist in the literature attributing the level of dive-use to ecological damage, although especially in coral reefs (*for review see* Wong 2002; Abidin and Mohamed 2014) but also in kelp forests (Schaeffer and Foster 1998). Riegl and Velimirov (1991) showed that frequently dived areas had higher rates of coral tissue loss, algal overgrowth and coral breaking. Dixon *et al.* (1993) indicated that heavily dived sites had significantly decreased coral cover, and that biological diversity was highest at sites of intermediate disturbance, as predicted by the IDH. High diver numbers have been shown to negatively impact the coral cover and increase the amount of dead coral (Tratalos and Austin 2001). In their 2008 study, Hasler and Ott concluded that diving has a major effect on coral reefs. Although Luna *et al.* (2009) showed that diving can cause algal removal and Schaeffer and Foster (1998) concluded that diving can detach blades off kelp, diver impacts on benthic algal covers and the potential resuspension of organic matter are predominantly unknown. Diver-related disturbances in freshwater systems have not been much researched (*but see*, Humphreys *et al.* 1999; Teresa *et al.* 2011).

1.1.2. Objectives and hypotheses:

Disturbance has been defined as a force that can impact biomass, species composition and species diversity (Grime 1977; Connell 1978; Huston 1979; Rykiel 1985; Pickett and White 1985). The objectives of this study were to assess the presence of diver-related disturbance in Silfra. To do this, 1) Silfra was compared to Flosagjá, a fissure where diving is prohibited, with regards to algal biomass and zoobenthic diversity, 2) regions within Silfra that were subject to different levels of dive-use were compared with regards to algal biomass and zoobenthic diversity, and 3) suspended organic matter in Silfra's water column was assessed in the morning before divers entered the fissure and at mid-day when diving was at its peak.

An increase in dive traffic can result in diver-related disturbances, affecting the ecosystems where diving is pursued (Hawkings and Roberts 1992a; Tratalos and Austin 2001; Milazzo *et al*. 2002; Hasler and Ott 2008). Due to the recent increase in Silfra dive traffic I predict that:

1) As a result of diver-related disturbance that exceeds high diversity levels as predicted by the IDH and the DEM, zoobenthic diversity (measured by taxa richness, species PEI and the Shannon diversity index) is less in Silfra than in Flosagjá.
2) As a result of diver detachment of algae on Silfra´s vertical substrate, dry algal biomass is less in Silfra than in Flosagjá.
3) Areas in Silfra that are subject to high levels of dive-use have lesser algal biomass and zoobenthic diversity than those of lower use.
4) As there is higher dive-traffic at mid-day than morning in Silfra the biomass of suspended organic matter in Silfra´s water-column is lesser in the morning than mid-day.

1.2. Materials and methods

1.2.1. Study site

This study focuses on Thingvellir National Park (TNP) (Figure 1.2.1, 1.2.2) and two fissures within it: Silfra and Flosagjá (Figure 1.2.2, Figure 1.2.3). TNP is located in southwest Iceland, at a rift valley where the Mid-Atlantic ridge is being driven apart. As a result of this, Lake Thingvallavatn (Figure 1.2.2) has formed, in addition to groundwater fissures, such as Silfra and Flosagjá that are all individually unique.

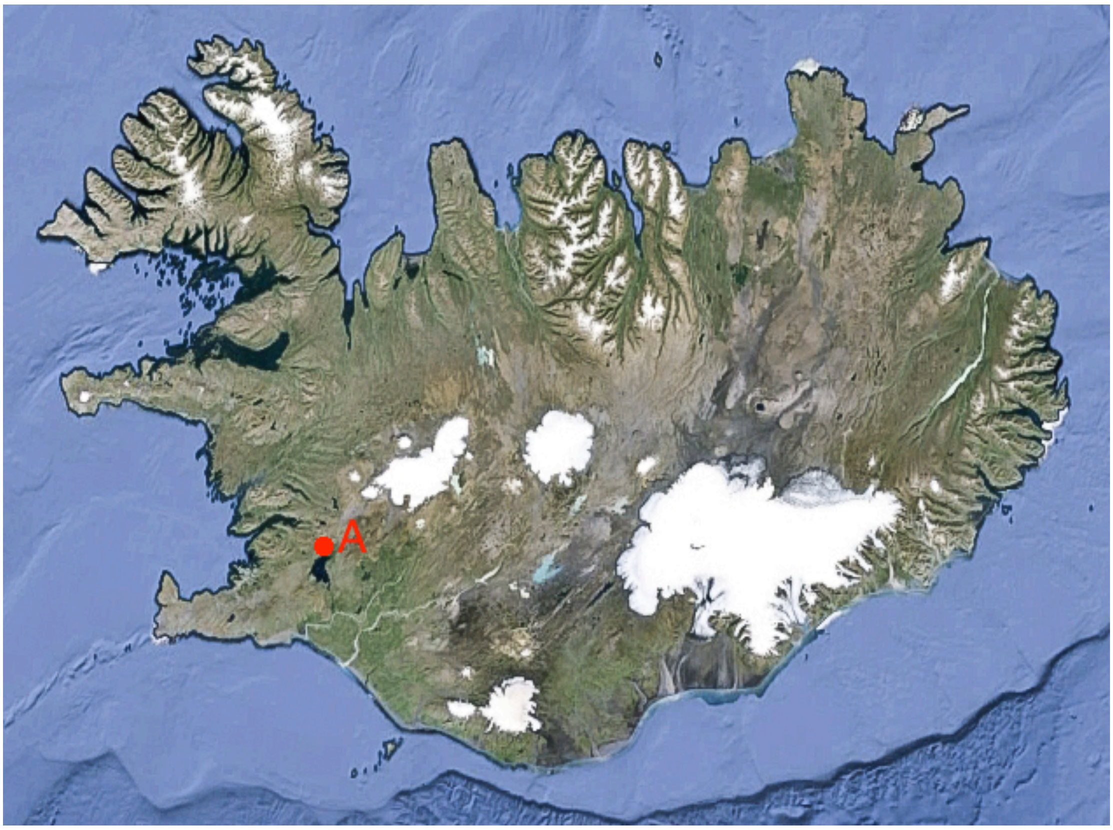

Figure 1.2.1. *Iceland and the Thingvellir National Park (A), located by Lake Thingvallavatn. Modified image retrieved from Google Earth (2015).*

Figure 1.2.2. *Lake Thingvallavatn in the Thingvellir National Park. The location of the groundwater fissures Silfra (A) and Flosagjá (B) is shown. Modified image retrieved from Google Earth (2015).*

Silfra

The Silfra (64°15´14 N, 21°07´05 V) (Figure 1.2.3 A) fissure parallels the Mid-Atlantic ridge. It is an opening into the groundwater aquifer and is freshwater-filled. The fissure measures 373m long at the surface, but has an underground part making its total length considerably longer. Of the entire surface length of Silfra, a 280m stretch is used for diving activities in typical dive-tours. Although mostly narrow (5-8m) Silfra varies in width, ranging from 3-20m. The fissure walls rise to a maximum of 3m above the water surface. At its deepest point, in an underground part, Silfra reaches 60m depth. The maximum depth in the part of the fissure open to the surface is 40m. A moderate current flows from North to South. Silfra connects to Lake Thingvallavatn, both at its northwest part and at its southernmost end, making it the only large fissure in TNP that connects from land to the lake.

Flosagjá

Flosagjá (64°15´46 N, 21°06´46 V) (Figures 1.2.3 B) parallels the Mid-Atlantic ridge and is freshwater-filled. In total, Flosagjá is around 770m in length, ranges from 4m to 20m in width and is generally wider than Silfra (mostly 10-15m). The fissure walls rise up to 18m above the water surface. At its deepest point, Flosagjá reaches 17m. Very low current is present within the fissure. Flosagjá does not directly connect to Lake Thingvallavatn like Silfra, although underground channels likely connect it to the lake. For this study, Flosagjá was determined as the best comparison site to Silfra, as all diving is prohibited there and also restricted by the difficulty of access, therefore no diver-related disturbances should occur there.

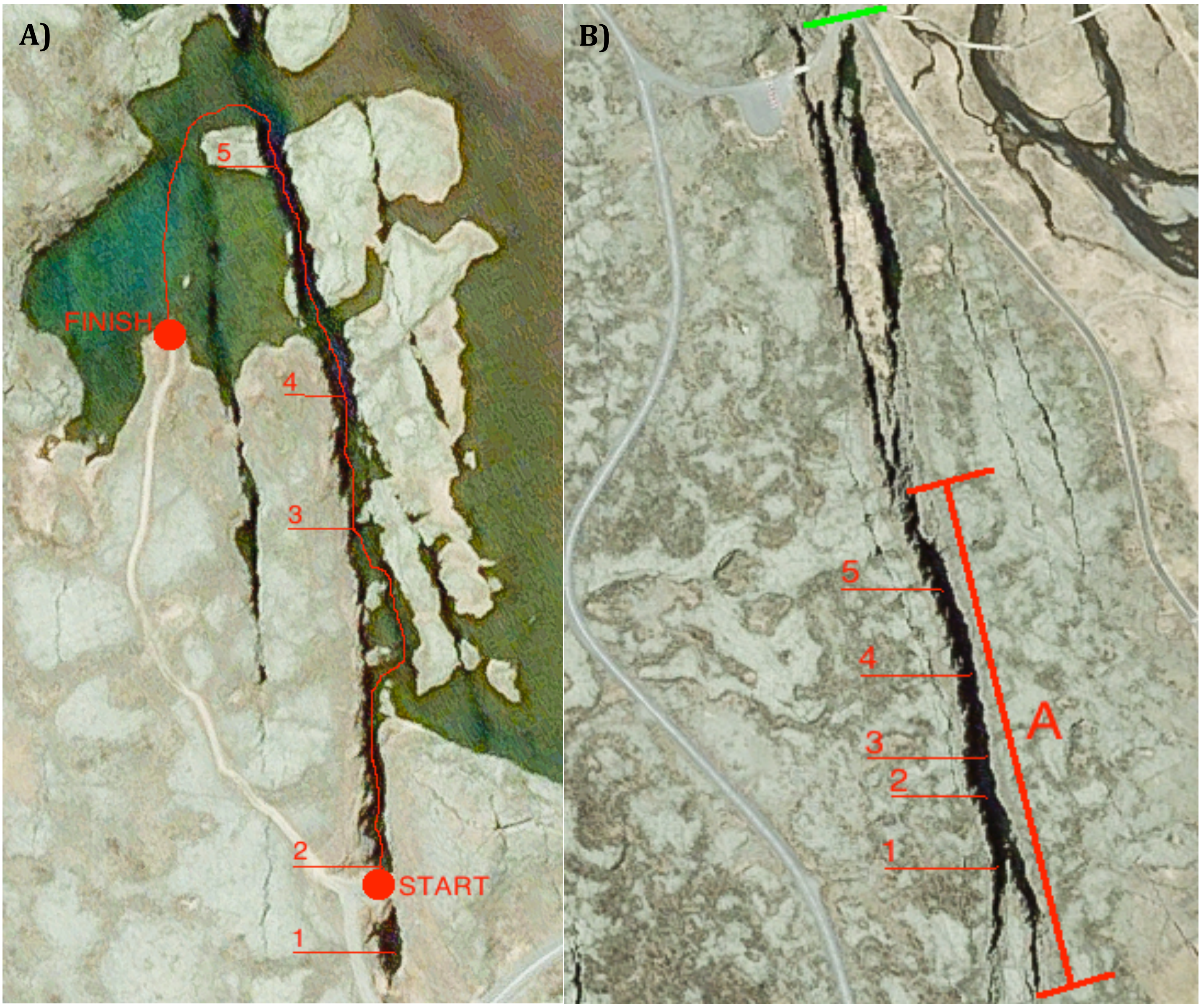

Figure 1.2.3. *A) The groundwater fissure Silfra in Thingvellir National Park. The start and finish locations and the line of travel for typical dive-tours are marked. All zoobenthic diversity sampling (also used for algal biomass), suspended organic matter and chla measurements took place along the line of travel at vertical transects (1-5).* ***B)*** *The groundwater fissure Flosagjá in Thingvellir National Park. The area marked as A on the image is where zoobenthic diversity sampling (also used for algal biomass), suspended organic matter and chla measurements took place along vertical transects (1-5). Flosagjá spans the entire length from the lower red horizontal line to the upper green horizontal line. Modified images retrieved from Google Earth (2015).*

Diving in Silfra in relation to sampling transects

In a typical Silfra dive, divers get into the water by transect two where they group together and perform a buoyancy check at around 0-3m depth. Next, they dive close to the surface before they reach a long shallow part (<1m depth). Subsequently divers approach transect three, where they also stay close to the surface. By the end of the shallow part, the fissure gets deeper and wider allowing the divers to dive deeper into the water. This continues past transect four and five where divers typically stay at around 4-10m depth

1.2.2. Sampling procedures

All sampling took place along transects in Silfra and Flosagjá (ABBREVIATIONS and EXPLANATIONS: Table 3, Table 4). Zoobenthic diversity and algal biomass were compared between Silfra and Flosagjá and sites in Silfra that are subject to different levels of dive-use (Table 1.2.1). The amount of suspended organic matter (SOM) was compared between morning and mid-day in Silfra and Flosagjá. This study was performed in conjunction with another study investigating biodiversity in Icelandic groundwater fissures (Ólafsdóttir. M.Sc. thesis in prep). Data collection and sorting of zoobenthic diversity samples were shared between the studies.

Zoobenthic diversity sampling

Zoobenthic samples were taken by SCUBA divers using a suction pump sampling system (Þorbjörnsson 2013) and PVC pipes for sediment core sampling.

In each fissure, imaginary transects were made with 10 m intervals spanning the entire length of the fissure. Subsequently five transects were randomly chosen for sampling. At each transect, three replicate samples were taken at 1m, and the bottom substrates of each transect (ABBREVIATIONS and EXPLANATIONS, p. 12). For this, the suction pump sampling system was used at vertical walls and horizontal rock bottom to remove all visible organic material within a $0.04m^2$ size quadrant. PVC pipes were used when acquiring core samples from the sediment at transect five bottom station in Silfra. Once collected, the samples were stored in ethanol. In a laboratory, all individuals were counted within each sample and classified to the lowest possible taxonomic rank.

Algal biomass on fissure substrates

After the sorting of zoobenthic diversity samples from Silfra and Flosagjá, all remaining material was preserved in ethanol. Subsequently, these samples were drained of liquid through a 30-micron sieve, leaving the remaining matter of the samples. The samples were put into trays, weighed and dried at 60°C until measured at constant weight. Next, the samples were left for cooling in a desiccator for ten minutes before being weighed to acquire dry-weight with four decimal numbers. The sample was then burned at 550 C° for two hours to remove all organic matter from the sample. Next the sample was cooled in a desiccator for ten minutes and weighed to four decimal numbers. The organic weight of each sample was calculated as the difference between the two weights, giving a measure of dry algal biomass (DAB).

Chl*a* and suspended organic matter

To assess the impact of diving on the resuspension of sediment and algal detachment, replicated sampling of suspended organic matter (SOM) in Silfra´s and Flosagjá´s water-column was performed in June and repeated in July 2015. Three transects from the original five were chosen in each fissure: transects two, four and five in Silfra and transects one, two and three in Flosagjá (Figure 1.2.3). At each transect, the samples were taken from an inflatable boat, the mid-way between the fissure´s walls, where a 4L water sampler (Woldco) was dropped down to 2m and 4m depth for sampling. The content was separated into three bottles (1L each) from each depth. Of those three bottles, 2L were used for Chl*a* analysis while 950ml were used for dry-mass and 50 ml stored for future phytoplankton classification. This sampling took place twice a each day, once in the morning, just prior to the start of diving operations, and at mid-day, when the fissure became heavily occupied by divers.

- Dry weight measurements: A 47mm glass microfiber filter (GE Healthcare Life Sciences) was weighted with four decimals. The weight acquired was subtracted from all following measurements. Next each sample (950 ml) was filtered. Subsequent procedures followed the dry-weight methods described above.
- Chl*a* analysis: In the field, bottles containing samples used for Chl*a* analysis were stored in black plastic bags. Those were brought to a laboratory where the 2L were filtered through a 47mm glass microfiber filter (GE Healthcare Life Sciences) and stored in 5ml ethanol in a cooler for 24 hours. Subsequently, the samples were put in a centrifuge (Hettich Rotanta type 3500) at 90000 RPM for five minutes, put into a 10x10 mm cuvette and the absorbance measured in a spectrophotometer (Hach DR 5000) at 665 and 700 nm. This was repeated after acidification with 0.1 N HCL which was used to break down Chl*a* into phaeophytins.

1.2.2. Numerical analysis

Numerical analysis were conducted in MICROSOFT EXCEL for Mac (2011), RSTUDIO for Mac (RSTUDIO. Version 0.98.1103. 2015) and CANOCO 5 for Windows (Microcomputer Power. 2012). Samples that were collected at the bottom station at transect five were omitted from all numerical analysis, because they were collected using different method than samples taken at other stations. A significance level of $p<0.05$ was used in all statistical tests.

Average taxa density was computed as the number of individuals/0.04m^2. Average Shannon diversity index (SDI) (Equation 1.2.1) and the Pielou´s evenness index (PEI) (Equation 1.2.2) were computed for each sampling station. For each station, the average dry algal biomass (DAB) was calculated (g/0.04m^2). Differences in the SDI, taxa richness and density, along with DAB was tested between Silfra and Flosagjá using the Wilcoxon test. The impacts of dive-use were assessed by the use of the dive-use index (Table 1.2.1), which was modeled with DAB, the SDI, richness, and PEI in a linear regression model, and tested using the Spearman Rho test. In addition, the dive-use index was included in taxa redundancy analysis (RDA) along with DAB and depth. The most common taxonomic groups in Silfra, in addition to species and taxa that exhibited a positive or negative correlation with the dive-use index in the RDA analysis, were included in a linear regression analysis and the correlation was tested with a Spearman Rho test. For the comparison of dry-weight of suspended organic matter and the absorption of Chl*a*, a Wilcoxon test was used.

The concentration of Chl*a* was calculated in (µg/l) according to Søndergaard and Riemann (1979) by the use of the following equation:

$$\text{Chl}a\ (\mu g/l) = 29.1*(Abs.(665_b - 750_b) - (665_a - 750_a)) * A/V$$

Chl*a: Concentration of* Chl*a in (µg/l)*
29.1: Absorbtion coefficient for Chl*a in ethanol (11.99) multiplied by factor of correction for acidification (2.43)*
665_b: Absorbance at a wavelength of 665 nm before acidification
750_b: Absorbance at a wavelength of 750 nm before acidification
665_a: Absorbance at a wavelength of 665 nm after acidification
750_b: Absorbance at a wavelength of 750 nm after acidification
A: Volume of ethanol used for the extraction of Chl*a (ml)*
V: Volume of filtered water (l)

To quantify dive-use at each station sampled in Silfra, a dive-use index (DUI) was constructed, using factors thought to influence the dive-use at each site: 1) distance between fissure walls (in meters), 2) level of diving (no dive-use: 0, very low dive-use: 1, low dive-use: 2, some dive-use: 3, intermediate dive-use: 4, high dive-use: 5), and 3) diver motion (swim-through=1, diving stationary=2) (Table 1.2.1.). The DUI was calculated by the use of the following equation:

$$Dive - use\ index = \left(\frac{Level\ of\ diving}{distance\ between\ fissure\ walls}\right) \cdot Dive\ motion$$

Table 1.2.1. *A description of diving at all transects and sampling sites in Silfra. The max depth, in addition to variables used for the calculation of the dive-use index (distance between fissure walls, level of diving, dive motion) are shown for each sampling site. The calculated dive-use index is also shown.*

Transect	Max depth	Sampling station	Distance between fissure walls	Level of diving**	Dive motion***	Level of dive-use index****
Transect 1	4m	1m	9m	0	N/A	0
		B	9m	0	N/A	0
Transect 2	10m	1m	6.5m	5	2	1.5385
		B	6.5m	1	1	0.1538
Transect 3	10m	1m	3.5m	5	1	1.4286
		B	3.5m	1	1	0.2857
Transect 4	9m	1m	8m	3	1	0.375
		B	8m	4	1	0.5
Transect 5	10m	1m	15m	2	1	0.1333

**B: Bottom sampling stations*
***No dive-use: 0, very low dive-use: 1, low dive-use: 2, some dive-use: 3, intermediate dive-use: 4, high dive-use: 5*
****Swim-through: 1, stationary: 2*
*****Level of dive-use index (see equation above)*

$$H' = -\sum_{i=1}^{S} p_i \ln p_i$$

Equation 1.2.1. *Equation for the Shannnon diversity index. H': Shannon diversity index, p_i:Proportion of individuals belonging to the i´th species, S: Species richness.*

$$E = \frac{H'}{H_{\max}}$$

Equation 1.2.2. *Equation for the Pielou´s PEI index. E: Pielou´s PEI index, H´: Shannon diversity index, H_{max}: ln(Species richness).*

1.3.Results

1.3.1. Zoobenthic diversity

The total number of individuals was greater in Flosagjá (n_{total}=1344) than Silfra (n_{total}=940) while total taxa richness was equal in Silfra ($n_{richness}$=22) and Flosagjá ($n_{richness}$=22). In Silfra, the highest richness and density was at the bottom station at transect four, while the highest PEI was at the bottom station at transect three and the 1m station at transect one and the highest SDI was at the bottom station at transect four. The lowest richness and density was at the 1m station at transect one, while the lowest PEI was at the 1m station at transect two and the lowest SDI at the 1m station at transect one (Table 1.3.1). In Flosagjá, the highest richness and density was at the bottom station at transect five and the highest PEI and SDI at the bottom station at transect four. The lowest richness, density and PEI was found at the 1m station at transect two, while the lowest SDI was encountered at the 1m station at transect one and the 1m station at transect two (Table 1.3.1). Tables 1.3.2 and 1.3.3 show the mean densities (number of individuals/0.04m^2) of zoobenthos in Silfra and Flosagjá, respectively.

Table 1.3.1. *Average taxa richness and density (individuals/0.04m^2), with standard deviation, and the Pielou's evenness index (PEI) and the Shannon diversity index (SDI) at all stations (1m: 1m stations, B: bottom stations) at transects 1-5 in the groundwater fissures Silfra and Flosagjá in Thingvellir National Park.*

	Transect	**1**		**2**		**3**		**4**		**5**	
	Depth	**1m**	**B**	**1m**	**B**	**1m**	**B**	**1m**	**B**	**1m**	**B**
Silfra	Richness	2.0±0.8	4.7±0.9	4.3±0.5	5.0±2.9	5.3±0.5	5±0.8	5.0±2.2	9.3±1.9	6.7±1.7	N/A
	Density	6±3.6	34±10	57±14	19±13	31±3.3	10±4	54±29	67±22	35±14	N/A
	PEI	0.9	0.7	0.5	0.7	0.6	0.9	0.6	0.8	0.8	N/A
	SDI	0.5	1.1	0.8	1.0	1.2	1.4	1.1	1.8	1.5	N/A
Flosagjá	Richness	5±1.4	8.3±1.2	4.7±0.5	6.7±2.4	6.3±1.9	8±2.2	7±0	9.3±2.4	7.7±4	9.7±3.4
	Density	34±8.7	54±8.7	16±4.8	41±6.4	56±9.1	47±6.1	40±8.9	47±4.7	50±8.6	63±8.9
	PEI	0.6	0.6	0.7	0.7	0.7	0.8	0.7	0.9	0.7	0.8
	SDI	1.1	1.6	1.1	1.4	1.3	1.7	1.5	2.0	1.4	1,7

Taxa richness differed significantly between Silfra and Flosagjá (Wilcoxon: p=0.03) while PEI, the SDI and taxa density did not differ significantly between the fissures (Wilcoxon: p=0.90, p=0.08, p=0.29 respectively). The SDI in Silfra increased significantly with proximity to its Southern connection to Lake Thingvallavatn (Spearman Rho: p=0, R=1). In Flosagjá the SDI increased insignificantly with proximity to Lake Thingvallavatn (Spearman Rho: p=0.1, R=0.8) (Figure 1.3.1, Figure 1.3.2).

Table 1.3.2. *Mean densities (individuals/0.04m²) and standard deviation of taxonomic groups at all stations (1m: 1 m stations, B:bottom stations) at transects 1-5 (see ABBREVIATIONS AND EXPLANATIONS, p.11) in the groundwater fissure Silfra in the Thingvellir National Park.*

	1		**2**		**3**		**4**		**5**
	1m	**B**	**1m**	**B**	**1m**	**B**	**1m**	**B**	**1m**
Chironomidae									
Arctopelopia sp.	0	0	0	0	0	0	0	0	0
Chaetocladius vitellinus group	0	0	0	1±0	0	0	0	0	4.5±2.5
Cricotopus tibialis group	0	0	0	0	0	0	0	0	0
Diamesa bertrami	0	1±0	0	0	0	0	0	0	0
Diamesa zernyi group	0	14±8.6	40±7.8	5±0	14±2.1	2.5±0.5	29±17	18±8.6	14±4.2
Eukiefferiella minor	0	8.7±6.6	11±5.7	5.5±1.5	10±5.4	0	12±16	17±6.2	4.7±3.1
Macropelopia sp.	0	0	0	0	0	0	0	0	0
Metriocnemus obscuripes	0	0	0	0	0	0	0	0	0
Micropsectra sp.	0	0	0	0	1±0	0	0	4±1	1.5±0.5
Orthocladius frigidus	4±0	9±1.6	3.7±0.5	13±1.5	7±0	0	6±0.8	9.7±4.6	5±5
Orthocladius oblidens	0	0	0	0	0	0	1±0	3±0	1±0
Rheocricotopus cf. effusus	0	0	0	1±0	0	0	0	0	1±0
Thienemaniella sp.	0	0	0	1±0	0	0	0	0	0
Cladocera									
Acroperus harpae	0	0	0	0	0	3±2	0	1±0	0
Alona affinis	0	0	0	0	0	0	0	3±0	0
Alona quadrangularis	1±0	0	0	0	1±0	2±1	1±0	2±0	1±0
Alona werestschagini	0	0	0	0	0	0	0	0	0
Chydorus cf. sphaericus	0	0	0	0	0	2±0	0	0	0
Iliocryptus sordidus	0	1±0	0	0	0	0	0	0	0
Macrothrix hirsuticornis	0	0	0	0	0	4±0	0	1±0	0
Ostracoda									
Cyclocypris ovum	0	0	0	0	0	0	0	0	0
Cypria opthalmica	0	0	0	0	0	0	0	0	0
Cypridoidea sp.	7±0	0	0	1±0	5±0	1±0	11±0	4±4	0
Fabaeformiscandona sp.	0	0	0	0	0	0	1±0	0	4±0
Limnocytherine sanctipatricii	0	0	0	0	0	0	0	0	0
Potamocypris zschokkei	0	0	0	0	0	0	0	0	0
Other groups									
Acarina	0	0	3±0	1±0	0	1±0	1±0	3.5±0.5	0
Coleoptera	0	0	0	0	0	0	0	0	0
Collembola	0	0	0	0	0	1±0	0	0	0
Copepoda	2±0.8	1±0	0	1±0	1.5±0.5	0	0	7±2.8	7±4
Empididae	0	0	0	0	1±0	0	0	0	0
Gastropoda	0	0	0	0	0	0	0	0	0
Hydra	0	0	0	0	0	0	0	0	0
Plecoptera	0	0	0	0	1±0	0	0	0	0
Trichoptera	0	0	1.5±0.5	2±0	0	3±0	0	2±0	0

Table 1.3.3. *Mean densities (individuals/0.04m²) and standard deviation of taxonomic groups at all stations (1m: 1 m stations, B:bottom stations) at transects 1-5 (see ABBREVIATIONS AND EXPLANATIONS, p. 11) in the groundwater fissure Flosagjá in the Thingvellir National Park.*

	1		**2**		**3**		**4**		**5**	
	1m	**B**	**1m**	**B**	**1m**	**B**	**1m**	**B**	**1m**	**B**
Chironomidae										
Arctopelopia sp.	0	0	0	0	0	0	0	0	0	0
Chaetocladius vitellinus group	0	0	0	0	0	0	0	0	0	0
Cricotopus tibialis group	4±3	6±4.3	1.7±0.5	6±14	5±4	0	3±0	2±0	1±0	1.3±0.5
Diamesa bertrami	0	0	0	0	0	0	0	0	0	0
Diamesa zernyi group	24±11	10±3.3	2.7±1.2	13±5.7	17±12	7.3±1.9	15±13	9.3±6.5	26±1	4.7±4.5
Eukiefferiella minor	3.5±2.5	5±2.4	1.5±0.5	5.5±1.5	6±4.5	4±0	2±0	3±2	2±0	3±2
Macropelopia sp.	0	0	0	0	0	1±0	0	0	0	0
Metriocnemus obscuripes	0	0	0	0	0	0	0	0	0	0
Micropsectra sp.	0	0	0	0	0	0	0	0	1±0	2±0
Orthocladius frigidus	11±4.1	4±10	10±7.1	15±6	20±4	17±9.6	15±12	8.7±5.4	14±7.5	4.7±1.2
Orthocladius oblidens	0	0	0	1±0	0	3±0	0	4.7±3.9	1.5±0.5	2.5±0.5
Rheocricotopus cf. effusus	0	0	0	2±0	1±0	0	0	0	0	0
Thienemaniella sp.	0	0	0	2±0	0	0	0	0	0	0
Cladocera										
Acroperus harpae	0	2±0	0	0	0	11±0	0	1.5±0.5	1±0	1±0
Alona affinis	0	2±0	0	0	0	6±0	1±0	1±0	0	3.5±1.5
Alona quadrangularis	0	1±0	0	0	0	4±0	0	0	0	0
Alona werestschagini	2±0	1.7±0.5	1±0	0	18±0	5±4	1±0	3±2.2	2.3±1.2	9.7±7.4
Chydorus cf. sphaericus	1±0	1±0	0	2±0	1±0	6±0	2.7±1.7	2.7±1.2	5±3	35±4
Iliocryptus sordidus	0	0	0	0	0	0	0	0	0	0
Macrothrix hirsuticornis	0	0	0	0	0	4±0	0	0	0	0
Ostracoda										
Cyclocypris ovum	0	0	0	0	0	0	0	0	0	0
Cypria opthalmica	0	0	0	0	0	0	0	0	0	0
Cypridoidea sp.	1±0	1±0	0	1±0	2±0	2.5±0.5	1±0	13±1.5	3±1	10±0
Fabaeformiscandona sp.	0	1±0	0	0	0	0	0	1±0	0	1±0
Limnocytherine sanctipatricii	0	0	0	5±0	0	0	0	0	0	0
Potamocypris zschokkei	0	1±0	0	0	0	0	1±0	0	0	1±0
Other groups										
Acarina	2±0	0	1±0	1±0	2±1.4	1±0	1±0	6±0	2±0	5±0
Coleoptera	0	0	0	0	0	0	0	0	0	0
Collembola	1±0	0	0	0	0	0	0	0	0	0
Copepoda	1±0	1±0	0	0	2±0	3.7±1.7	4±2	5.5±1.5	11±11	5±4
Empididae	0	0	0	0	0	0	0	0	0	0
Gastropoda	0	0	0	0	0	0	0	0	0	0
Hydra	0	0	0	0	0	0	0	0	0	0
Plecoptera	0	0	0	0	0	0	0	0	0	0
Trichoptera	0	0	1±0	2±0	0	0	0	0	0	0

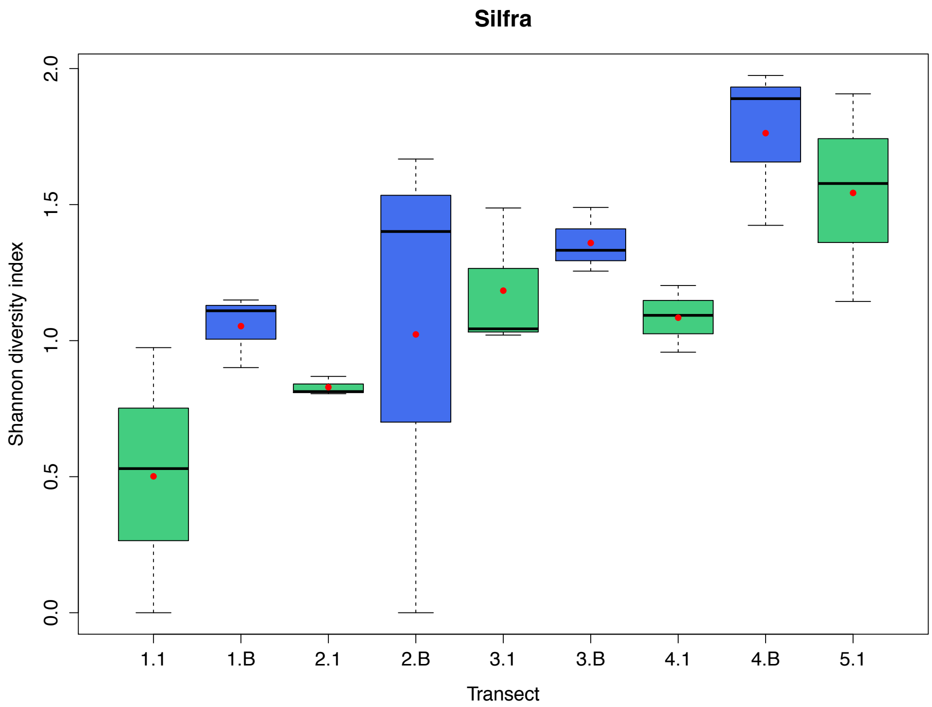

Figure 1.3.1. *Boxplots showing the Shannon diversity index calculated from samples taken at vertical substrates at transects (1-5) and sampling stations (1:1m, B: bottom) in the groundwater fissure Silfra in the Thingvellir National Park. Green boxplots each represent three samples from 1m stations while the blue boxplots each represent three samples from bottom stations. The 3rd (Q3) and 1st (Q1) quartiles are represented by the top and bottom lines of the boxes. The interquartile range (IQR) is the length of the boxes from top to bottom. The top whiskers represent Q3 + 1.5*IQR and the bottom whisker represent Q1-1.5*IQR. Red dots indicate mean values, black lines indicate median values.*

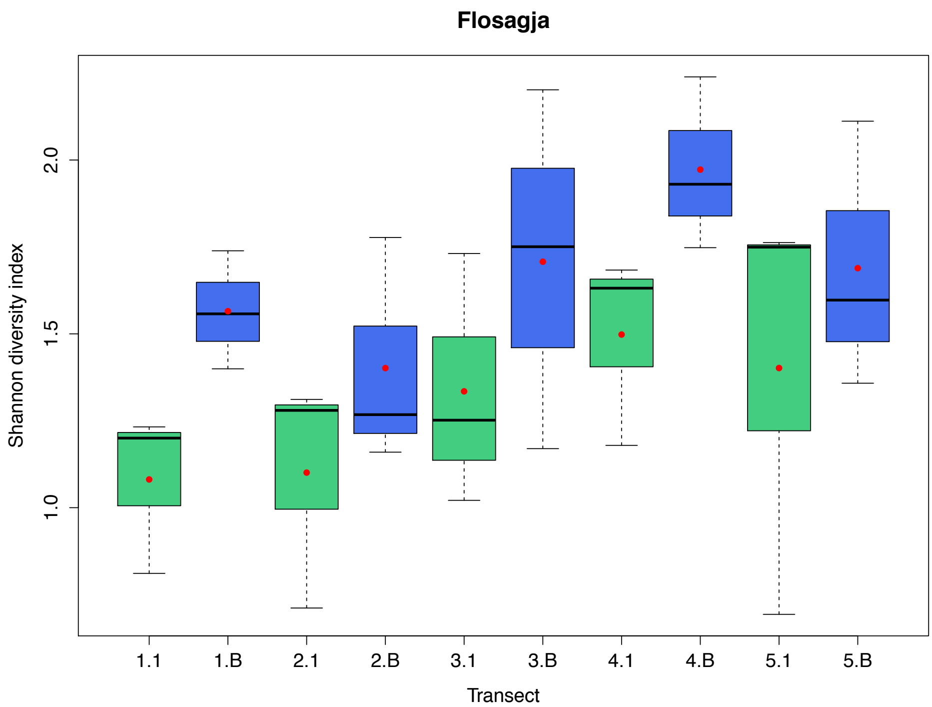

Figure 1.3.2. *Boxplots showing the Shannon diversity index calculated from samples taken at vertical substrates at transects (1-5) and sampling stations (1:1m, B:bottom) in the groundwater fissure Flosagjá in Thingvellir National Park. Green boxplots each represent three samples from 1m stations while the blue boxplots each represent three samples from bottom stations. The 3rd (Q3) and 1st (Q1) quartiles are represented by the top and bottom lines of the boxes. The interquartile range (IQR) is the length of the boxes from top to bottom. The top whiskers represent Q3 + 1.5*IQR and the bottom whisker represent Q1-1.5*IQR. Red dots indicate mean values, horizontal black lines indicate median values.*

1.3.2. Dry algal biomass

Dry algal biomass (DAB) (g/0.04m^2) was acquired from zoobenthic diversity samples. Values were significantly lower (Wilcoxon: p<0.001) in Silfra (mean=0.1200±0.165 g/0.04m^2) than in Flosagjá (mean=0.2937±0.086 g/0.04m^2) (Table 1.3.2).

Table 1.3.2. *Mean dry algal biomass (DAB) (g/0.04m^2) and standard deviation (SD) from samples taken at vertical substrates at transects (1-5) and sampling stations (1:1m, B: bottom) in the groundwater fissures Silfra and Flosagjá in the Thingvellir National Park.*

	Transect	1		2		3		4		5	
	Depth	**1m**	**B**	**1m**	**B**	**1m**	**B**	**1m**	**B**	**1m**	**B**
Silfra	Mean	0.3002	0.1077	0.0195	0.1509	0.0997	0.0576	0.0574	0.0641	0.1305	N/A
	SD	0.03481	0.0270	0.0119	0.0191	0.0128	0.0445	0.0212	0.0259	0.0462	N/A
Flosagjá	Mean	0.2791	0.2792	0.3748	0.1500	0.4715	0.2953	0.3733	0.1966	0.3638	0.1538
	SD	0.1911	0.0828	0.1101	0.0633	0.2225	0.1248	0.0458	0.1412	0.1576	0.0329

In Silfra at 1m depth, the highest DAB values were measured at transect one while the lowest were measured at transect two. Bottom samples contained the highest DAB at transect two and the lowest at transect three (Figure 1.3.3). In Flosagjá, the highest DAB at 1m were measured at transect three and the lowest at transect one. In the bottom samples, the highest DAB was measured at transect three and the lowest at transect two (Figure 1.3.4). The amount of DAB at the 1m stations and the bottom stations differed significantly in Flosagjá (Wilcoxon: p=0.03) while the difference was insignificant in Silfra (Wilcoxon: p=0.90).

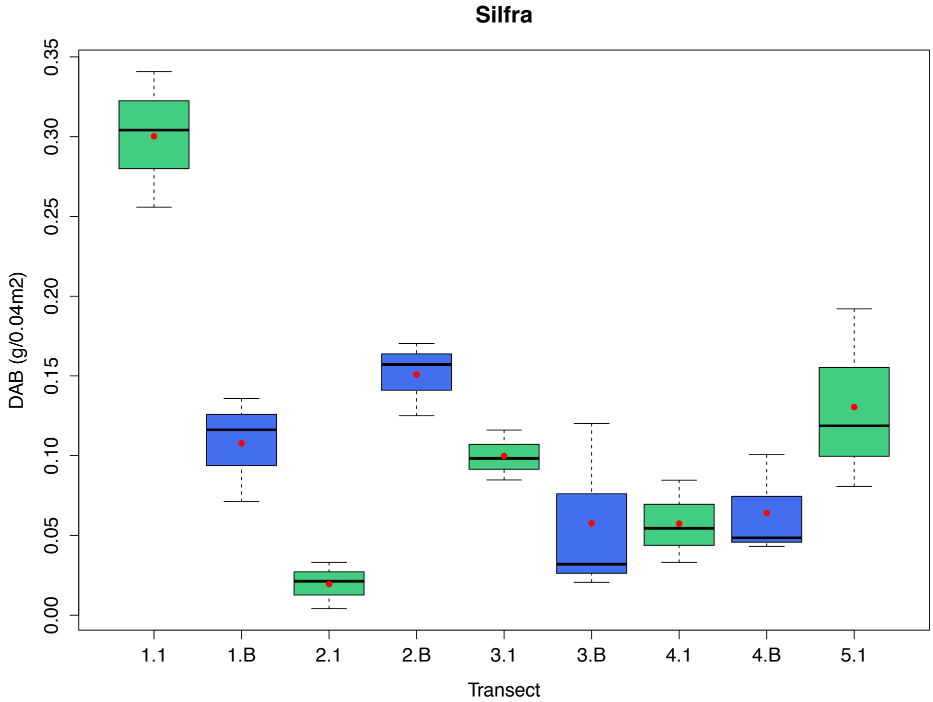

Figure 1.3.3. *Boxplots showing dry algal biomass (DAB) (g/0.04m^2) from samples taken at vertical substrates at transects (1-5) and sampling stations (1:1m, B: bottom) in the groundwater fissure Silfra in Thingvellir National Park, Green boxplots each represent three samples from 1m stations while blue boxplots each represent three samples from bottom stations. The 3rd (Q3) and 1st (Q1) quartiles are represented by the top and bottom lines of the boxes. The interquartile range (IQR) is the length of the boxes from top to bottom. The top whiskers represent Q3 + 1.5*IQR and the bottom whisker represent Q1-1.5*IQR. Red dots indicate mean values, horizontal black lines indicate median values.*

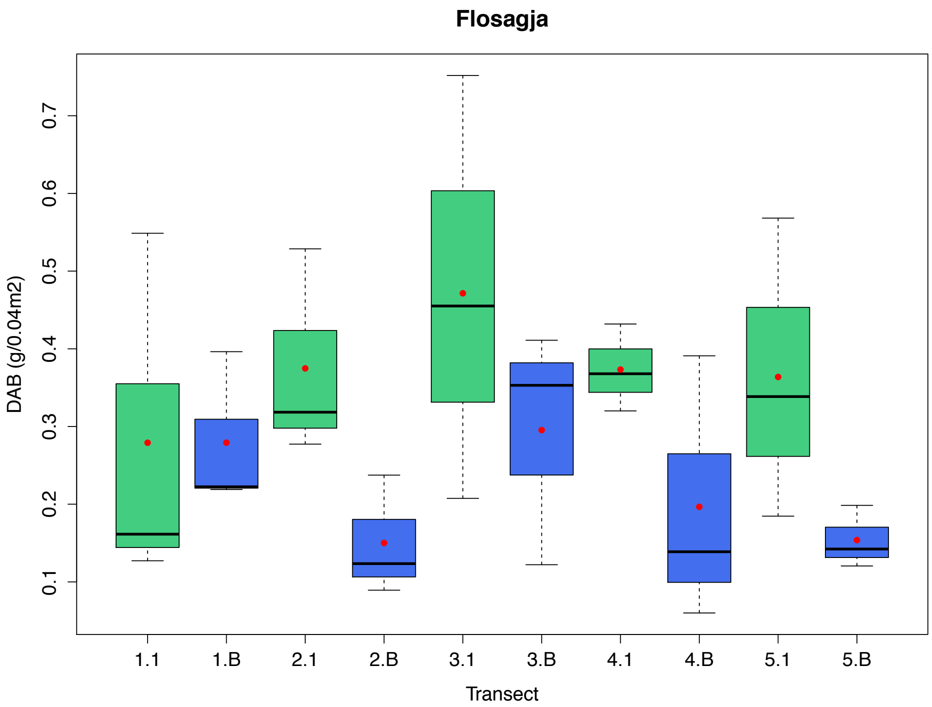

Figure 1.3.4. Figure 1.3.3. *Boxplots showing dry algal biomass (DAB) (g/0.04m^2) from samples taken at vertical substrates at transects (1-5) and sampling stations (1:1m, B: bottom) in the groundwater fissure Flosagjá in Thingvellir National Park, Green boxplots each represent three samples from 1m stations while blue boxplots each represent three samples from bottom stations. The 3rd (Q3) and 1st (Q1) quartiles are represented by the top and bottom lines of the boxes. The interquartile range (IQR) is the length of the boxes from top to bottom. The top whiskers represent Q3 + 1.5*IQR and the bottom whisker represent Q1-1.5*IQR. Red dots indicate mean values, horizontal black lines indicate median values.*

1.3.3. Impacts of dive-use in Silfra

A significant negative correlation was found between the DUI and algal biomass (Figure 1.3.5) (Spearman Rho: p=0.02). No correlation was found between the DUI and SDI and richness (Figures 1.3.6 and 1.3.7) (Spearman Rho: p=0.59, p=0.56, respectively) while a negative correlation was found between DUI and PEI, although the relationship was insignificant (Figure 1.3.8) (Spearman Rho: p=0.11).

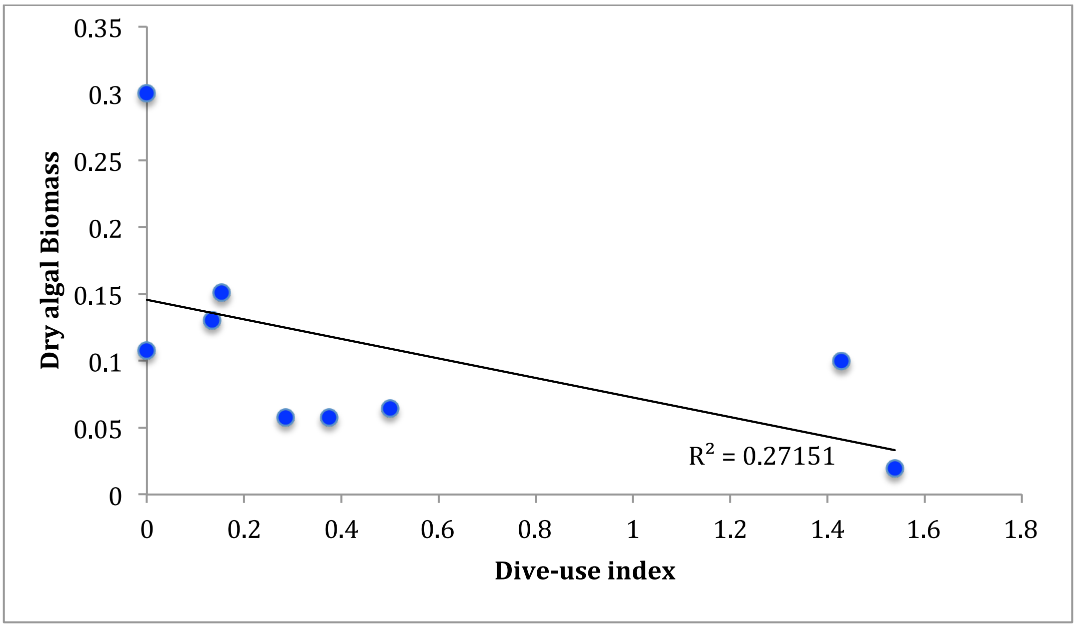

Figure 1.3.5. *Linear regression, including the coefficient of determination (R^2), showing the correlation between dry algal biomass measured from samples taken at vertical transects in the Silfra groundwater fissure in the Thingvellir National Park (Y-axis) and the dive-use index calculated for each sampling site (X-axis).*

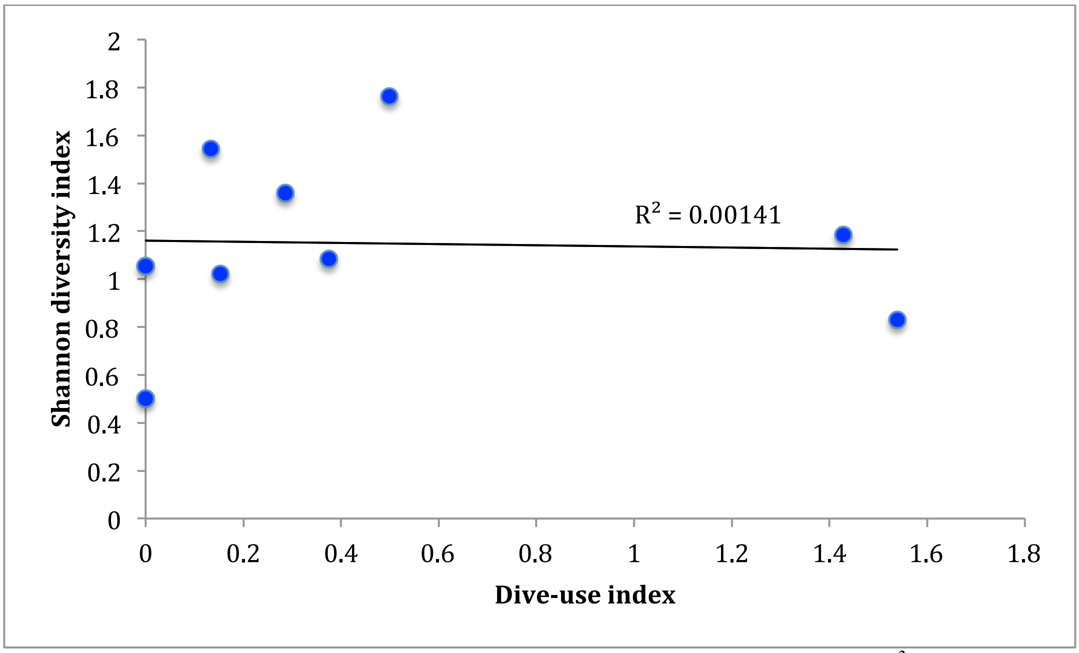

Figure 1.3.5. *Linear regression, including the coefficient of determination (R^2), showing the correlation between the Shannon diversity index, calculated from samples taken at sites at vertical transects in the Silfra groundwater fissure in the Thingvellir National Park (Y-axis) and the dive-use index calculated for each sampling site (X-axis).*

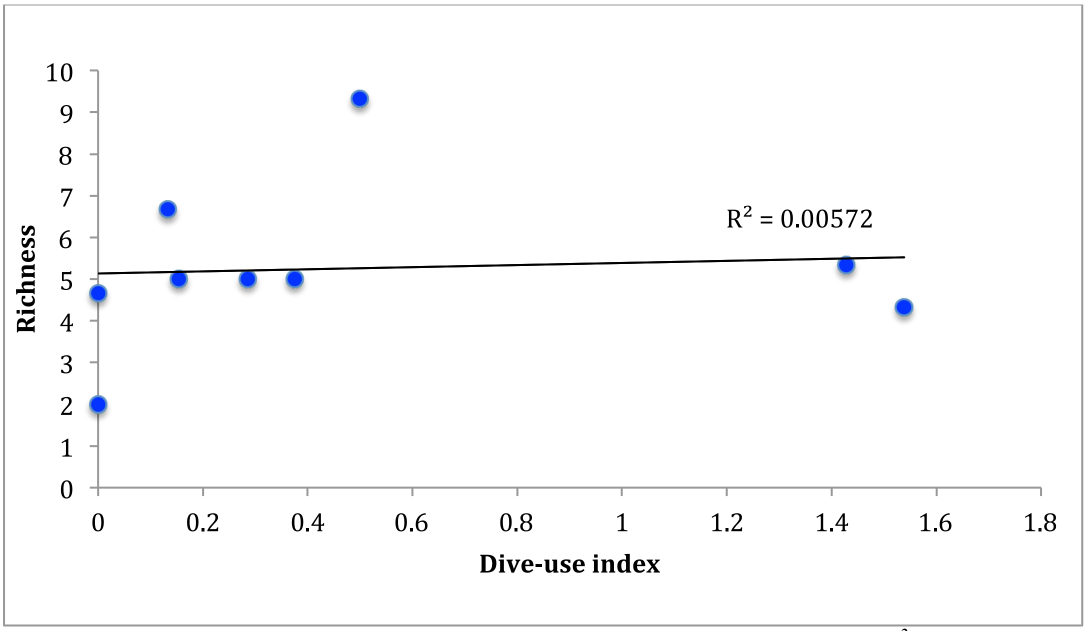

Figure 1.3.6. *Linear regression, including the coefficient of determination (R^2), showing the correlation between taxa richness, acquired from samples taken at sites at vertical transects in the Silfra groundwater fissure in the Thingvellir National Park (Y-axis) and the dive-use index calculated for each sampling site (X-axis).*

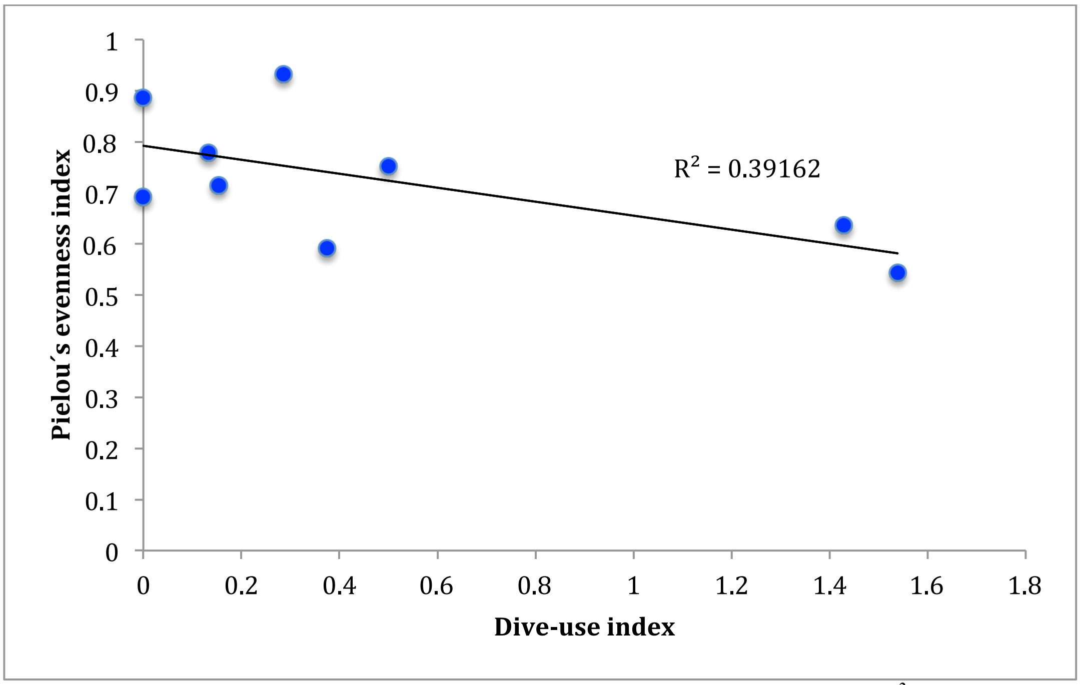

Figure 1.3.7*. Linear regression, including the coefficient of determination (R^2), showing the correlation between taxa Pielou´s evenness index, calculated from samples taken at sites at vertical transects in the Silfra groundwater fissure in the Thingvellir National Park (Y-axis) and the dive-use index calculated for each sampling site (X-axis).*

To more closely inspect the relationship between the DUI, algal biomass and substrate taxa composition, a redundancy analysis (RDA) was conducted for Silfra. In the RDA, the first axis (RDA1) explained 25.0% of the composition, the second axis 8.3%, and the third axis (RDA3) explained 3.4% of the taxa composition (Figure 1.3.7). When looking at the explanatory variables, DAB explained 23.4% of the taxa composition, the DUI explained 9.5% of the composition and depth explained 8.3% of the composition. However, none of these variables significantly explained patterns in assemblages (DAB: p=0.07, DUI: p=0.42, depth: p=0.79).

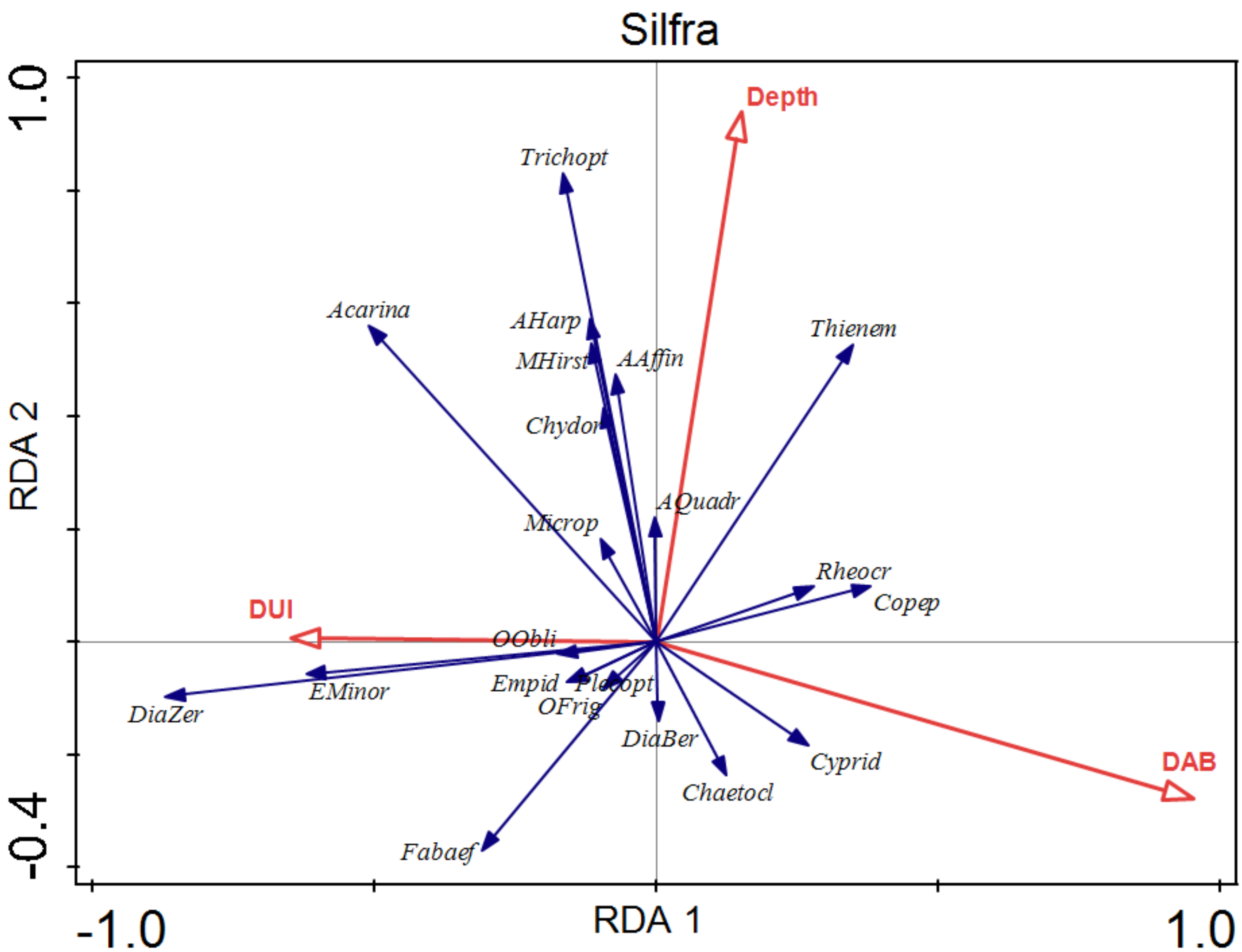

Figure 1.3.8. *An RDA ordination diagram of the composition of taxa (see ABBREVIATIONS and EXPLANATIONS, p. 12 for taxa names) from samples taken at sites at vertical transects in the Silfra groundwater fissure in the Thingvellir National Park as blue arrows and the relationship of explanatory variables (DUI: the dive-use index calculated for each site, Depth, DAB: dry-algal biomass measured at each site) as red arrows.*

In Silfra, a linear regression analysis was conducted on the most common taxa (Cladocera, Chironomidae, Copepoda, Ostracoda) and the DUI. Of the most common taxa, Chironomidae exhibited the strongest correlation with the DUI, although the relationship was insignificant (p=0.12), while Cladocerans, Copepods and Ostracods did not show a correlation the with dive-use index (p=0.63, p=0.58, p=0.8m respectively) (Figure 1.3.8).

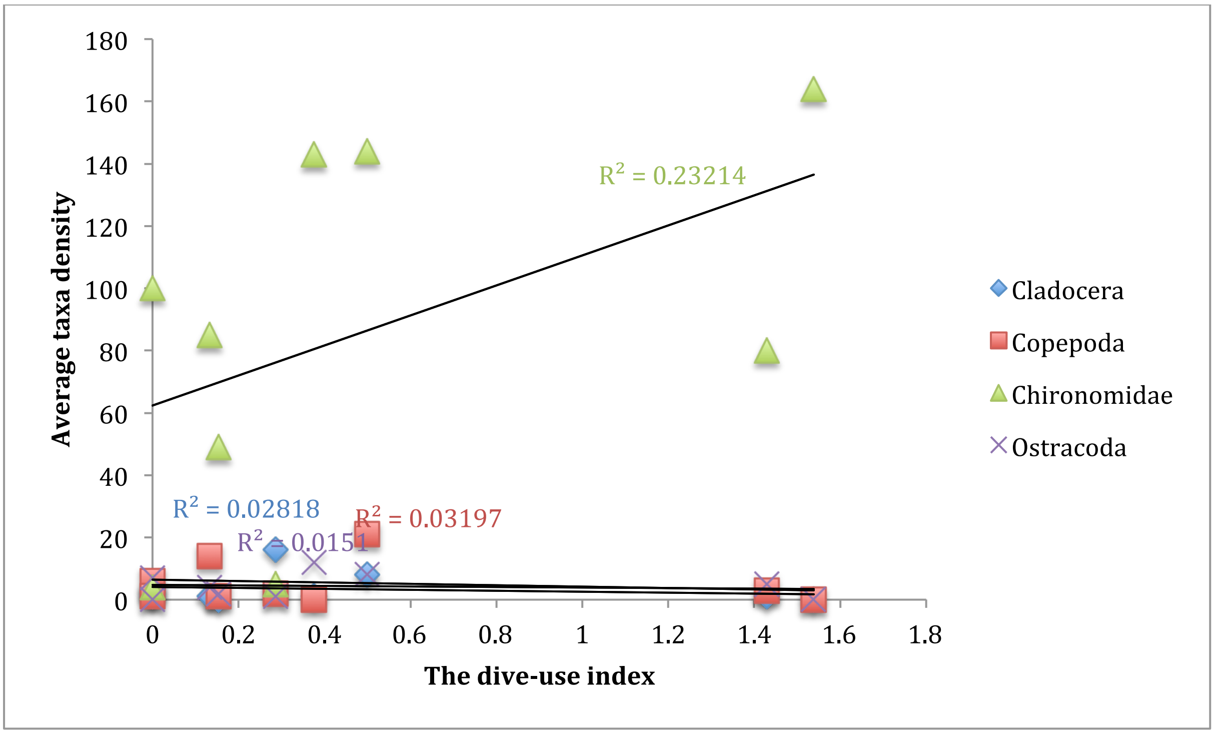

Figure 1.3.9. *Linear regression, including the coefficients of determination (R^2), showing the correlation between the average taxa density (individuals/0.04m^2) of major taxa (Cladocera, Copepoda, Chironomidae, Ostracoda) encountered in samples taken at sites at vertical transects in the Silfra groundwater fissure in the Thingvellir National Park and the dive-use index.*

To acquire further details, species and taxa densities that appeared positively or negatively correlated with the DUI in the RDA analysis were used in a linear regression model with the DUI. There, *Diamesa zernyi* and *Eukiefferiella minor* correlated positively with the DUI although the relationships were insignificant (Spearman Rho: p=0.10, p=0.06, respectively), while *Orthocladius oblidens* did not correlate with the DUI (Spearman Rho: p=0.78) (Figure 1.3.9). For species and taxa that were inversely correlated with the DUI in the RDA analysis, (*Rheocricotopus cf. effusus*, *Cypridoidea* sp. and Copepods) none were correlated with the DUI in the linear regression model (Spearman Rho: p=0.41, p=0.82, p=0.58, respectively) (Figure 1.3.9.1).

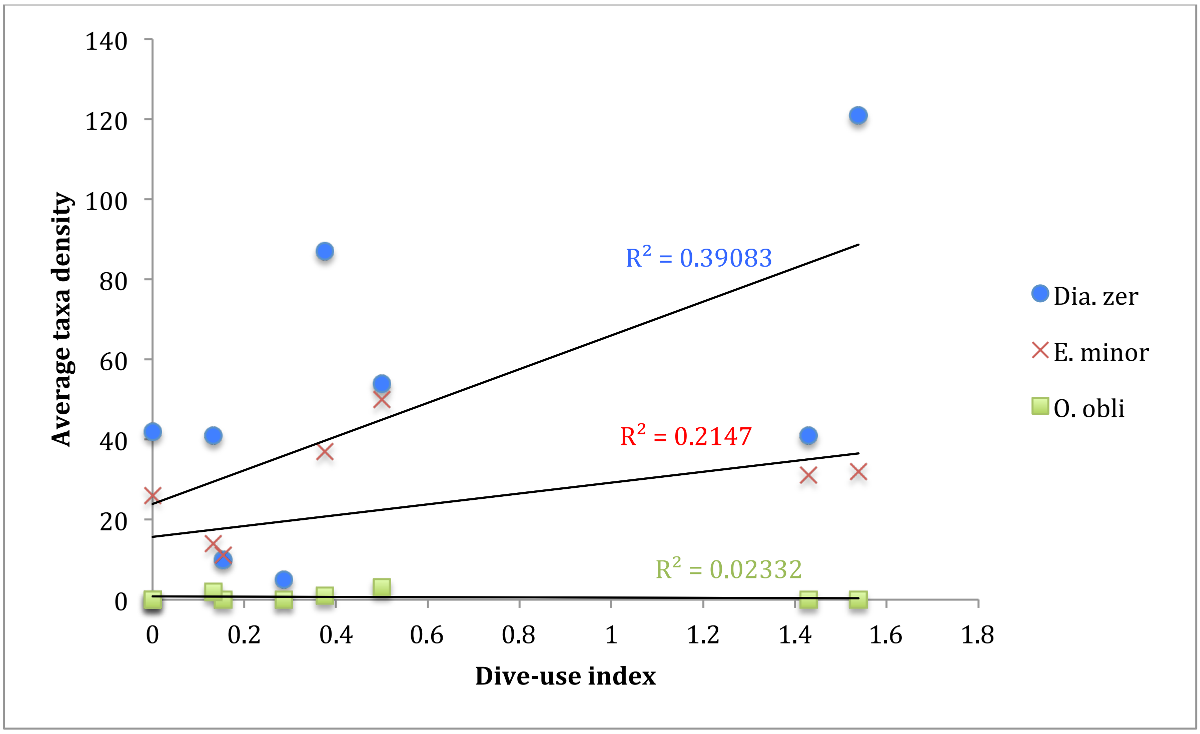

Figure 1.3.9.1. *Linear regression, including the coefficient of determination (R^2), for taxa that exhibited a positive correlation with the dive-use index (see pp. 27-28) in an RDA analysis for the groundwater fissure Silfra. The figure shows the correlation between the average density (individuals/0.04m^2) of Dia. zer, E. minor and O.obli (ABBREVIATIONS AND EXPLANATIONS p. 12) and the dive-use index.*

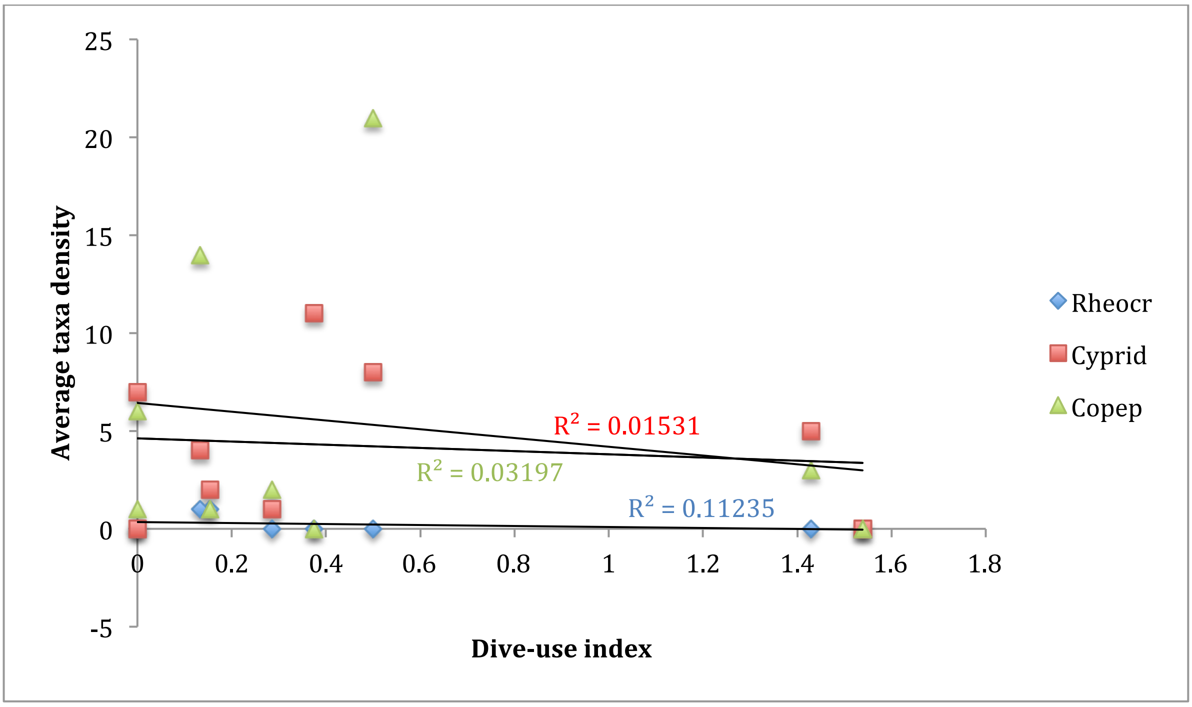

Figure 1.3.9.2. *Linear regression, including the coefficient of determination (R^2), for taxa that exhibited a negative correlation with the dive-use index in an RDA analysis for Silfra. The figure shows the correlation between the average density (individuals/0.04m^2) of Rheocr, Cyprid and Copepods (ABBREVIATIONS AND EXPLANATIONS p. 12) and the dive-use index.*

1.3.4. Chl*a* and suspended organic matter

For Chl*a,* only data from June is presented. Samples taken in July could not be analyzed, because there was a defect in the spectrophotometer utilized. The June chl*a* values did not differ significantly between fissures or between morning and mid-day samples (Table 1.3.4).

In June, the dry-organic weight of SOM obtained from samples taken in the morning and at mid-day did not differ significantly in Silfra or Flosagjá (Table 1.3.5). In July, there was a significant difference for Silfra but not for Flosagjá (Table 1.3.6).

Table 1.3.4. *Chl a (µg/l) in a 2L water sample taken in June at two depths, twice a day in Silfra and Flosagjá. The samples were taken from transects 2,4,5 in Silfra and 1,2,3 in Flosagjá.*

June	**Transect 2/1**		**Transect 4/2**		**Transect 5/3**		**p-value**
	2m	**4m**	**2m**	**4m**	**2m**	**4m**	
Silfra morning	0	0.0728	0	0	0.1455	0	p=0.79
Silfra mid-day	0.0726	0.0729	0	0	0	0.0728	
Flosagjá morning	0.0735	0	0.0786	0	-0.0728	0.0728	p=0.32
Flosagjá mid-day	0	-0.0728	0.0728	0	-0.0786	0.0728	

Table 1.3.5. *Dry-organic weight (g/950mL) of SOM from a water sample taken in June at two depths, twice a day in Silfra and Flosagjá. The samples were taken from transects 2,4,5 in Silfra and 1,2,3 in Flosagjá.*

June	**Transect 2/1**		**Transect 4/2**		**Transect 5/3**		**p-value**
	2m	**4m**	**2m**	**4m**	**2m**	**4m**	
Silfra morning	0.0004	0.0002	0.0006	0.0003	0.0002	0.0003	p=0.26
Silfra mid-day	0.0001	0.0002	0.0001	0	0.0005	0.0004	
Flosagjá morning	0.0003	0.0001	0.0001	-0.0001	0.0002	0.0004	p=1.0
Flosagjá mid-day	0.0001	0	0.0004	0.0002	0.0002	0.0001	

Table 1.3.6. *Dry-organic weight (g/950mL) of SOM from a water sample taken in July at two depths, twice a day in Silfra and Flosagjá. The samples were taken from transects 2,4,5 in Silfra and 1,2,3 in Flosagjá.*

July	**Transect 2/1**		**Transect 4/2**		**Transect 5/3**		**p-value**
	2m	**4m**	**2m**	**4m**	**2m**	**4m**	
Silfra morning	0	0	0	0	0.0001	0.0002	p=0.007
Silfra mid-day	0.0002	0.0003	0.0005	0.0005	0.0002	0.0004	
Flosagjá morning	0.0003	0.0007	-0.0002	0	0.0005	0.0004	p=1.0
Flosagjá mid-day	0.0002	0.0004	0.0001	0.0005	0.0004	0.0001	

1.4. Discussions

1.4.1. Zoobenthic diversity

The Shannon diversity index and the Pielou´s evenness index did not differ significantly between Silfra and Flosagjá. However, taxa richness was significantly greater in Flosagjá than Silfra, which is interesting, especially because Silfra´s connection to Lake Thingvallavatn could help increase richness in Silfra, by facilitating dispersal of taxa that spend their entire life-cycle in water into the fissure. This can indicate that diving may contribute to a reduction in richness within Silfra. To further evaluate the potential impacts of diving activities on zoobenthic diversity, I compared diversity at areas within Silfra that are subject to different levels of dive-use. That comparison indicates that the PEI may be compromised with increasing dive-use. As predicted by the intermediate disturbance hypothesis (IDH) diversity (defined as richness) is highest at intermediate disturbance. It is possible that zoobenthic diversity in Silfra is either preceding or succeeding the high diversity levels at intermediate disturbance. If heavily used sites are past the high diversity levels at intermediate disturbance, opportunities for species that are adapted to disturbance can emerge. The results demonstrate some support for this, with indications of a negative correlation between the DUI and PEI, and a positive correlation between the DUI and the density of the Chironomidae taxon, where the clearest relationship was seen with the species *Eukiefferiella minor* and the group *Diamesa zernyi.* The relationship of the latter with DUI is particularly interesting as *Diamesa zernyi* is common in madicolous habitats (Hrafnsdóttir 2005). Currents generated by diver fins and hands may imitate conditions present in madicolous habitats, allowing for this group to flourish in heavily dived sites. Further disturbance in Silfra of increasing intensity, frequency and extent may gradually reduce PEI by eventually restricting growth to species that are tolerant to diver-related disturbance. However, further investigations are needed to assess how Silfra´s community reacts to diver-related disturbances. Future studies should quantitatively monitor Silfra´s zoobenthic diversity for any progressions in community assemblages that can occur as a result of increasing dive-use.

1.4.2. Dry algal biomass

Comparisons of DAB between Silfra and Flosagjá revealed a significant difference as hypothesized. This difference may provide evidence that Silfra is experiencing algal decay as a result of diving. For a further analysis, areas within the fissures were also compared. In Flosagjá, DAB was significantly lower at the bottom stations than at the 1m stations, likely due to a reduction in irradiance with depth. However, this was not the case in Silfra, which may be explained by potential diver-induced algal detachment at shallower sites in the fissure. This was supported by the linear regression model showing a significant negative correlation between the DUI and DAB. This trend is especially relevant at transect one and two. At the first transect, no diving takes place, and its 1m station contained the highest biomass of all sampled stations in Silfra. At the second transect, divers enter the fissure, group together and prepare themselves for their dive, typically at around 4-0m depth. Generally, the divers move around extensively during this process, likely increasing the likelihood of disturbance. Therefore, it is unsurprising that the 1m station at this transect contained the lowest DAB of all sampled stations within Silfra. The bottom however, where divers usually do not descend to, had greater dry algal biomass than the 1m station, resulting in this being the only transect where such a clear trend is seen between depths. This is consistent with studies from coral reef dive sites, where the start of the dive site has been shown to be subject to the highest diver-related disturbance (Barker and Roberts 2004; Hasler and Ott 2008). To investigate this further, future monitoring of algal biomass in Silfra should take place in addition to studies on the ecological impacts of algal decay.

1.4.3. Suspended organic matter

In Silfra, low dive traffic occurs early morning, as most divers enter the fissure at mid-day. My results demonstrate significantly lower SOM values in the morning than mid-day in June in Silfra. Although this can indicate that divers increase the amount of SOM in the Silfra´s water-column, both SOM and chl*a* values were extremely low in all samples. As a result, these results need to be taken with a grain of salt. Nevertheless, detached algae were observed in the fissures throughout the sampling period, especially in Silfra´s water-column when divers and snorkelers were present within the fissure. Most of the observed algae were quite large in size, some floated on the surface, while other parts sunk to the bottom or remained suspended mid-way in the water-column. The low values measured for SOM and Chl*a* suggest that the 4L water sampler utilized is too small to capture this large material. However, other methods can be used to capture the larger pieces of detached algae. For a quantitative analysis, a large plankton net could be used. This should be considered for future studies with the objective of acquiring a representative quantification of SOM levels within Silfra. Deeper sampling should also take place, as divers in Silfra dive well below 4m depth at numerous occasions, where they can cause algal detachment.

1.4.4. Further ecosystem impacts

As discussed previously, the two main hypotheses that act to explain how ecological disturbance can shape diversity levels are the intermediate disturbance hypothesis (IDH) and the dynamic equilibrium model (DEM). In Silfra, environmental conditions are relatively stable although predictable seasonal irradiance fluctuations occur. However, with the development of diving in Silfra, an unpredictable disturbance factor has been introduced. In a certain manner, this can be viewed as an introduction of an invasive species into the fissure ecosystem. It can be assumed that post diving ecological development in Silfra will follow patterns predicted by either the IDH or the DEM. Applying the IDH to Silfra, increasing frequencies or intensities of diver-related disturbances should increase diversity until disturbance becomes too great to allow for algal and zoobenthic recovery. My results indicate that algal biomass may be decreasing, especially at high-use dive sites. In addition, PEI appears to decrease with the DUI, while richness and the SDI are not affected. This may suggest that taxonomic groups that are tolerant to disturbance can dominate heavily disturbed areas within Silfra, without leading to a decrease in taxa richness. However, a future increase in diver-related disturbances may surpass the ability of some species to recover from disturbance, which could cause a reduction in richness. This could initiate a trend towards ecological thresholds controlled by biotic interactions. Nonetheless, diversity increased with proximity to Lake Thingvallavatn, suggesting that the Silfra´s connectivity to the lake may prevent ecological thresholds from occurring, by the input of colonists, which can hasten post-disturbance recovery. If that is the case, Silfra may be a good option for dive-tourism in the TNP area. However, much is left open for investigation and the impacts of diving on community assemblages in Silfra need to be further investigated.

Chapter 2: Mechanisms behind SCUBA diver disturbance in the Silfra groundwater fissure.

2.1. Introduction

Anthropogenic disturbances resulting from recreational activities are well documented in many ecosystems (Hammitt et al. 1998). Tourism has increased the spread of alien species (Sarukhán *et al.* 2005) and caused physical impact on ecosystem structures (Wong 2002). In aquatic systems, recreational disturbance has been addressed in lentic (Dokulil 2014), lotic (Hadwen *et al*. 2006) and coastal environments (Davenport and Davenport 2006). In marine ecosystems, impact by SCUBA diving is well documented, such as in kelp forests (Schaeffer and Foster 1998) and on coral reefs (Riegl and Velimirov 1991; Hawkings and Roberts 1992a; Hawkings *et al.* 1999; Tratalos and Austin 2001; Milazzo *et al.* 2002; Barker and Roberts 2004; Hasler and Ott 2008; Luna *et al.* 2009; Abidin and Mohamed 2014). It has been demonstrated that SCUBA diving can have a significant impact on coral cover in areas that are subject to high levels of use (Tratalos and Austin 2001) and that areas that experience relatively low levels of use can still be affected (Hawkings *et al.* 1999).

Diver-related disturbances on aquatic ecosystems can occur as a result of diver underwater behavior, such as through "trampling, holding, kneeling or standing on benthic organisms" (Hawkings and Roberts 1992a. p. 171). Milazzo *et al.* (2002) attributed anthropogenic diving disturbance to the physical contact of life forms by diver fins, body and SCUBA equipment and Luna *et al.* (2009) further acknowledged this by observing the highest number of diver contacts through the flapping of fins, followed by diver contacts and equipment contacts. Divers carrying photographic equipment can cause more damage than others (Rouphael and Inglis 1995; Luna *et al.* 2009) and the maintenance of proper buoyancy control has been demonstrated to be critical to minimize impacts on corals (Medio *et al.* 1997).

Evidence from popular coral reef dive sites shows that management protocols are important for the sustainable use of the reefs (Hawkings and Roberts 1992b; Ott and Hasler 2008; Luna *et al.* 2009). The objective of management needs to be considered (Hawkings *et al.* 1999), then the disturbance factors must be determined (Rouphael and Inglis 2001; Hobbs 2002). To ensure successful management of dive-sites, assessment of the consequences of diver behavior (Rouphael and Inglis 1995; Walters and Samways 2001; Barker and Roberts 2004; Luna *et al.* 2009; Musa *et al.* 2010) and the effect of the increased number of divers (Riegl and Velimirov 1991; Tratalos and Austin 2001; Hasler and Ott 2008) should be addressed.

The Silfra groundwater fissure in Thingvellir National Park (TNP) is different from coral reefs in numerous ways. Damage may not be as visible in Silfra, as no life forms can be broken. However, as Luna *et al.* (2009) demonstrated, disturbance can also occur as a result of sediment raising and the removal of algae. In chapter 1, I found evidence that algal biomass may be decreasing and that zoobenthic community assemblages may be affected, as a result of diver-related disturbances. If dive-traffic continues to increase in Silfra, it remains unknown how the ecosystem will react to such changes. To prevent unwanted consequences of dive traffic in Silfra, the potential disturbance factors must be evaluated before specific management protocols can be proposed.

2.1.2. Objectives and hypotheses:

Previous studies have shown that diver gender (Luna *et al.* 2009; Rouphael and Inglis 2001), experience (Walters and Samways 2001; Luna *et al.* 2009), perception of damage (Luna *et al.* 2009) and the reception of a pre-dive briefing on the ecological consequences of diving (Luna *et al.* 2009) can affect diver-related underwater disturbances. On the other hand, diver dive-certification level has not been shown to affect diver-related disturbance (Barker and Roberts 2004; Luna *et al.* 2009) and the impact of perceived challenge level of a dive has not been previously researched.

The objectives of this chapter are to: 1) determine the mechanisms behind SCUBA diver-related disturbances and the resulting consequences and 2) determine how SCUBA diver characteristics may affect diver-related disturbances in Silfra, by testing the following predictions:

1) Gender: Female divers disturb less than male divers.
2) Experience: Divers that are highly experienced (>100 dives and/or logged dry-suit dives) cause less disturbance than those less experienced.
3) Certification: Divers that are highly certified (Certification 2 and/or dry-suit certification) do not disturb less than those with lower certifications.
4) Damage perception: Divers that perceive diver-related ecological damage in freshwater systems cause less disturbance than those who don´t.
5) Diver briefing: Divers that received a briefing on the environmental impacts of diving disturb less than those who didn´t receive such a briefing.
6) Perceived dive challenge level: Divers that consider the dive in Silfra easy (1-5 on a scale from 1-10) disturb less than those who think it is challenging

2.2. Materials and methods

2.2.1. Study site

Of the entire surface length of Silfra, 280m are used for diving. During commercial dive tours conducted in Silfra over recent years customers have seldom been guided below the 18 m depth mark. This was further restricted in 2013 when the director of TNP and the Icelandic Maritime Administration banned all diving below 18 meters to reduce the risk of accidents occurring in the deeper parts of the fissure (Stjórnartíðindi 2013b).

Figure 2.2.1 shows a typical dive profile in Silfra in addition to the two locations where divers were recorded:

- Loc. 1 is the start of the dive where the walls are algal covered and narrow.
- Loc. 2 has wider walls that are algal covered, but a sediment bottom is also present, which the divers pass over.

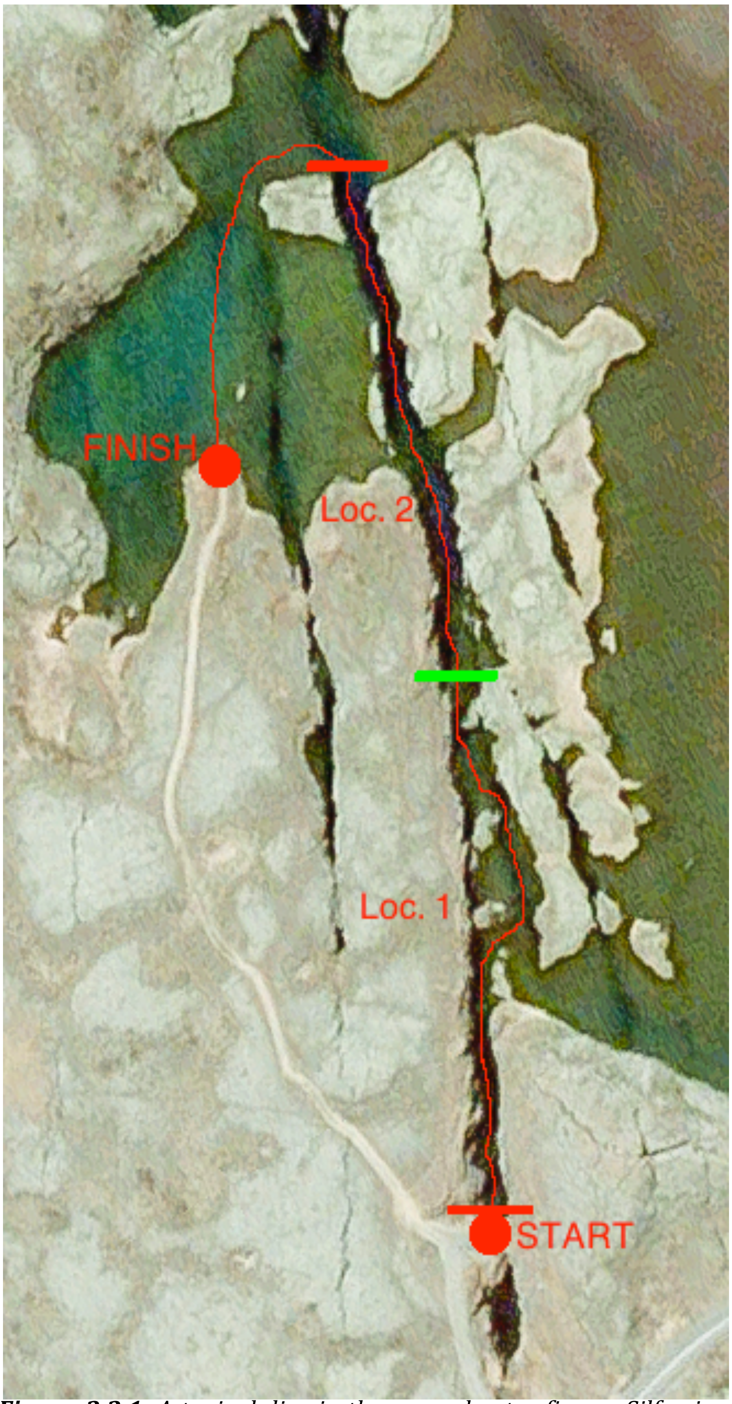

Figure 2.2.1. *A typical dive in the groundwater fissure Silfra in the Thingvellir National Park is shown (red line). Dive start and finish locations are displayed in addition to the locations were divers were recorded for underwater disturbance (Loc. 1: Lowest horizontal red bar to green red bar, Loc. 2: Horizontal green bar to topmost horizontal red bar). Modified image retrieved from Google Earth (2015).*

2.2.2. Execution

Customers in commercial dive tours were recorded at two locations (Figure 2.2.1) during their dives in Silfra. After their dives, recorded divers were asked to fill out a questionnaire sheet. An assessment of the mechanisms behind diver-related disturbances was conducted over a period of five days in early September 2014. A total number of 35 divers were recorded in this study. The recorded divers were customers from 11 dive tours from all five tour companies operating dive-tours in Silfra as of fall 2014. The number of customers varied per group, but was three on average (min=2, max=4). Prior to all dives, SCUBA tanks of recorded divers were labeled with colored tape. This labeling was done to distinguish between divers and for simplification when divers were questionnaired after the dive. Once the group was prepared for diving, the observer followed the group into the fissure. Recording began once the divers were submerged in the water and started their dive. Each diver was recorded, using a JVC GC-WP10 HD recording camera, either from behind or above at a distance of approximately five meters for five minutes. After the recording of the first diver in the group was finished, recording of the next diver was immediately commenced, and so forth. This continued until the dive was completed. The videos were analyzed and the mechanisms behind each diver-related disturbance and the resulting ecological consequences noted:

- Mechanisms of disturbances were noted as an effect of contact or current generated by the diver´s fins, hands, equipment or body
- The severity of all disturbances was classified into:
    - 1) Minimal disturbances (Figure 1 and 3 – appendix 1)
    - 2) Severe disturbances (Figure 2 and 4 – appendix 1)
- Ecological consequences of diver-related disturbances were classified into
    - 1) Algal removal
    - 2) Raising of sediment

In Silfra, seven characteristics were thought to possibly impact diver underwater disturbance (*see* predictions; Table 2.2.1). After the dive, each recorded diver was given a questionnaire to answer (Figure 5a, 5b – appendix 1). The questionnaire contained questions designed to acquire information to determine which characteristics (Table 2.2.1) might affect diver underwater disturbance.

***Table 2.2.1**. Characteristics determined to potentially affect diver underwater behavior and associated disturbances (see predictions) in the Silfra groundwater fissure in the Thingvellir National Park.*

Characteristics that may affect diver underwater behavior
1. Gender
2. Experience (# of logged dives, # logged dry-suit dives)
3. Level of diving certification
4. Perception of diving damage
5. Briefing on diver impacts on the environment
6. Perceived difficulty the dive in Silfra

2.2.3. Numerical analysis

Numerical analysis was conducted in MICROSOFT EXCEL for Mac (2011), and RSTUDIO (RSTUDIO. Version 0.98.1103. 2015). A disturbance index was created for each diver. Each minimal disturbance was given a score of =1 while each severe disturbance was assigned a score of =2. Three separate indexes were calculated for every recorded diver:

1) Algal disturbance index: A sum of minimal and severe algal disturbance scores throughout the five-minute recording period.
2) Sediment disturbance index: A sum of minimal and severe sediment disturbance scores throughout the five-minute recording period.
3) Total disturbance index: A sum of all algal and sediment disturbance scores throughout the five-minute recording period.

To evaluate how diver characteristics affect diver-related disturbances, groups of divers attributing different characteristics were compared using a Wilcoxon test (significance level of $p<0.05$) as follows:

1) Gender:
    - Male and female
2) Experience:
    - Divers with <100 logged dives and divers with >100 dives.
    - Divers with 0 dry-suit dives and Divers with >0 dry-suit dives.
3) Certification:
    - Beginner and advanced.
4) Damage perception:
    - Divers that thought diving could damage freshwater ecosystems and divers that did not know or did not think diving could damage freshwater ecosystems.
5) Briefing:
    - Divers that received a briefing on potential diver-related damage prior to their dive and divers that did not receive such a briefing.

The Spearman´s Rho test (significance level of $p<0.05$) was used to attribute the perceived difficulty of the dive to disturbance.

2.3. Results

2.3.1. Mechanisms behind diver-related disturbances

All disturbance events were classified based on origin (contacts or currents), type (hands, fins, equipment and body), severity (1=minimal, 2=severe) and consequences (algal removal, raising of sediment). The total number of disturbance events was 373 and for the five minute observation period 10.7 disturbance events (SD=7.46) occurred on average. In total, 91.4% of the 35-recorded divers caused at least one disturbance, with an average of 2.11 disturbances/diver/minute. Most of the disturbance events occurred by diver-generated current (N=222, mean=6.3, SD=6.70) (Table 2.3.1). Disturbances by divers direct contact with the algal cover or sediment were fewer (N=151, mean=4.3, SD=3.51) (Table 2.3.2).

In total 310 (Mean=8.9, SD=7.76) disturbance events caused by diver fins were observed, 50 were caused by hands (Mean=1.4, SD=2.73), seven by equipment (Mean=0.2, SD=0.62), and six by divers body (Mean=0.17, SD=0.51).

Table 2.3.1. *Total number, mean and standard deviation (SD) of recorded underwater disturbances caused by diver–generated currents in the groundwater fissure Silfra in Thingvellir National Park.*

	N	Mean	SD
Hands	2	0.1	0.23
Fins	220	6.3	6.74
Equipment	0	0	0
Body	0	0	0

Table 2.3.2. *Total number, mean and standard deviation (SD) of recorded underwater disturbances caused by diver-generated contacts in the groundwater fissure Silfra in Thingvellir National Park.*

	N	Mean	SD
Hands	48	1.4	2.70
Fins	90	2.6	2.97
Equipment	7	0.2	0.70
Body	6	0.2	0.51

2.3.2. Consequences of disturbances

Minimal algal removal and severe sediment raising were the most frequent consequences of diver disturbance (Table 2.3.3). Disturbances by hands and fins through contacts and currents generated the highest number of disturbances, causing both minimal and severe consequences. Disturbance by hands was mostly caused by contact, producing minimal algal disturbances. Hand-generated current disturbances and disturbances by hands causing the raising of sediment were less frequent (Figure 2.3.1, Figure 2.3.2). Disturbance by the flapping of fins mostly produced severe sediment disturbance by current, but also caused a high number of minimal and severe algal disturbance by contacts and currents, severe sediment disturbance by contacts and minimal sediment disturbance by currents (Figures 2.3.1, 2.3.2).

Table 2.3.3. *The total number, mean and standard deviation of observed consequences (algal removal and sediment raising) of diver-related disturbances in the groundwater fissure Silfra in Thingvellir National Park.*

	N	Mean	SD
Algal removal 1	144	4.1	4.58
Algal removal 2	86	2.5	6.42
Sediment raising 1	21	0.6	1.25
Sediment raising 2	122	3.5	5.80

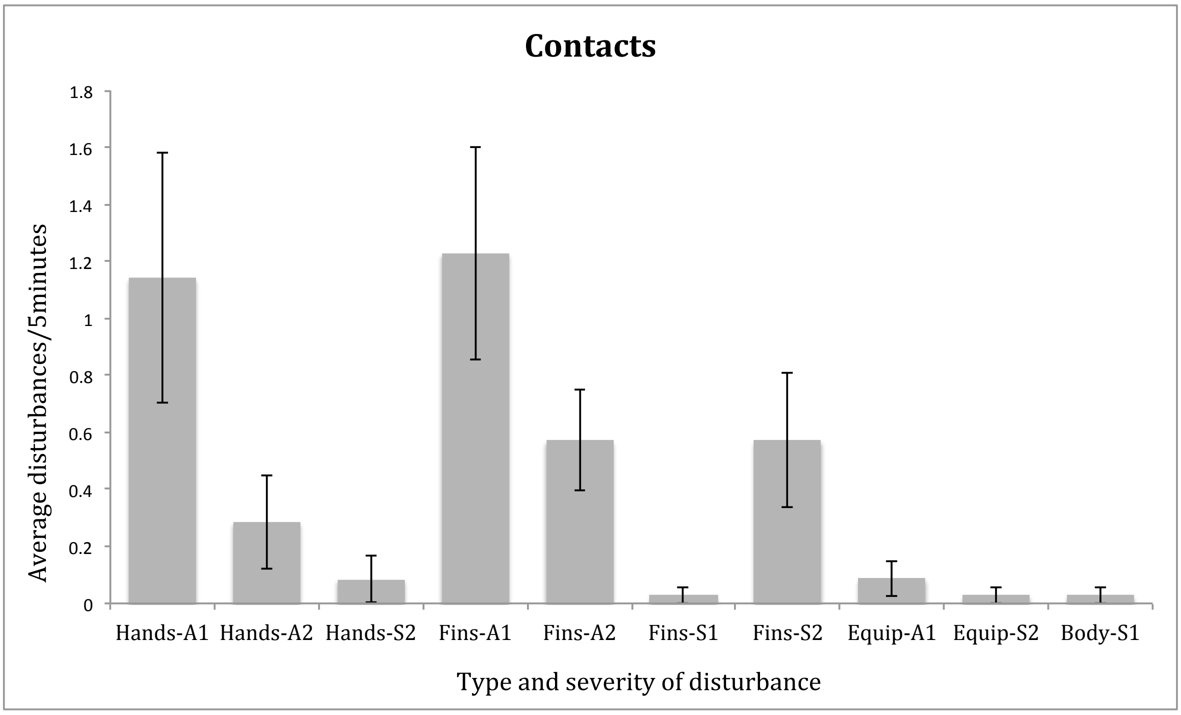

Figure 2.3.1. *The average number of recorded disturbances generated through contacts by type (hands, fins, equipment and body), in a study on the mechanisms behind diver-related disturbances in the groundwater fissure Silfra, with one standard error. A1, and A2 represent minimal and severe algal disturbance, respectively. S1 and S2 represent minimal and severe sediment raising, respectively (see APPENDIX 1).*

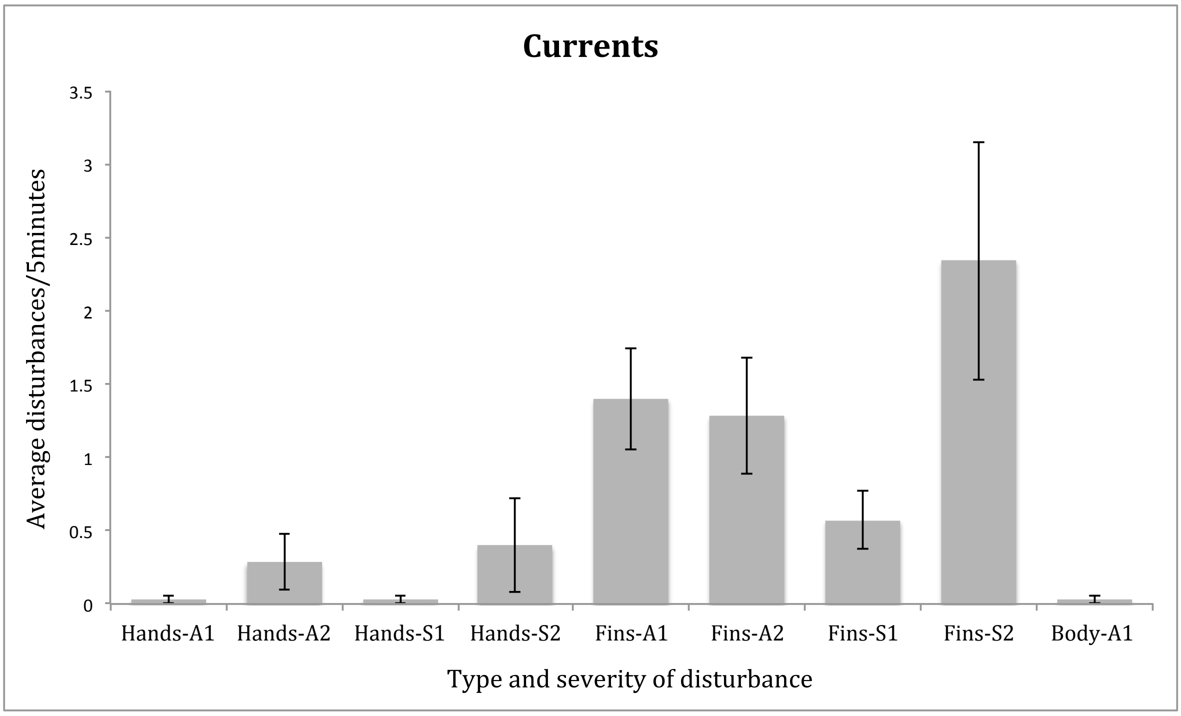

Figure 2.3.2. *The average number of disturbances caused by current generated by type (hands, fins and body), in a study on the mechanisms behind diver-related disturbances in the groundwater fissure Silfra, with one standard error. A1, and A2 represent minimal and severe algal disturbance, respectively. S1 and S2 represent minimal and severe sediment raising, respectively (see APPENDIX 1).*

2.3.3. Diver questionnaire

All the 35 recorded divers answered the questionnaire. Of all individuals, ranging from 24 to 63 years old, 34.3% were female and 65.7% were male. Roughly half (48.6%) had basic dive training while 51.4% had advanced training. Few (28.6%) had dry-suit certificates while 42.9% had logged at least one dry-suit dive. Of all the divers 28.6% had logged more than 100 dives and 5.7% had logged at least one dive in Silfra. Most divers (62.9%) believed that divers could cause damage to freshwater ecosystems, while 14.3 % did not believe so, and 22.9% did not know if divers could cause damage. Pre-dive briefing on the potential diver-related damage in Silfra was received by 74.3% of the divers. On a difficulty scale from 1-10, where one is the easiest and ten the hardest, 60% believed that the dive was easy (1-5) while 40% of the divers believed the dive in Silfra was difficult (6-10).

No significant differences were found when comparing characteristics that were thought to affect diver disturbance, except the location in which the divers were recorded (Table 2.3.4). Sediment disturbance was significantly greater at loc.2 than loc.1 while algal disturbance was significantly greater at loc.1 than loc.2 (Table 2.3.4).

Table 2.3.4. *Diver characteristics (gender, certification, experience, perceived damage, reception of briefing and perceived dive difficulty) predicted to affect diver underwater disturbance (see ABBREVIATIONS and EXPLANATIONS, p. 12). Disturbance indexes were created for sediment and algal disturbances, which summed together formed the total disturbance index. The total number of divers attributed to each characteristic, sum of disturbance indexes from all divers attributed to each characteristic, mean disturbance index and standard deviation are shown. P-values are also shown for statistical tests between groups of divers attributed to each characteristic. The Wilcoxon test was used between all groups except the difficulty of the dive, where the Spearman Rho test was used. Significant values (p<0.05) are shown in red.*

		Sediment disturbance index				**Algal disturbance index**				**Total disturbance index**			
	N	**Sum**	**Mean**	**SD**	**P val.**	**Sum**	**Sum**	**SD**	**P val.**	**Sum**	**Mean**	**SD**	**P val.**
Male	23	192	8.3	14.04	p=0.60	225	9.8	7.31	p=0.21	417	18.1	13.89	p=0.44
Female	12	73	6.1	8.82		91	7.6	9.25		164	13.7	10.33	
Cert. 1	**17**	**148**	**8.7**	**14.49**	**p=0.66**	**146**	**8.6**	**8.44**	**p=0.52**	**294**	**17.3**	**15.10**	**p=0.95**
Cert. 2	**18**	**117**	**6.5**	**10.27**		**170**	**9.4**	**7.73**		**287**	**15.9**	**10.49**	
Cert. DS+	10	90	9.0	10.14	p=0.42	81	8.1	6.67	p=0.90	171	17.1	10.45	p=0.57
Cert.DS-	25	175	7.0	13.35		235	9.4	8.57		410	16.4	13.83	
>100 dives	**10**	**79**	**7.9**	**9.86**	**p=0.88**	**56**	**5.6**	**4.57**	**p=0.25**	**135**	**13.5**	**8.61**	**p=0.53**
<100 dives	**25**	**186**	**7.4**	**13.47**		**260**	**10.4**	**8.76**		**446**	**17.8**	**14.14**	
DS logged+	15	112	7.5	9.6	p=0.55	102	6.8	6.35	p=0.25	214	14.3	9.91	p=0.57
DS logged-	20	153	7.7	14.43		214	10.7	8.83		367	18.4	14.54	
Damage+	**22**	**188**	**8.5**	**14.03**	**p=0.94**	**199**	**9.0**	**7.53**	**p=0.76**	**387**	**17.6**	**14.02**	**p=0.77**
Damage-	**13**	**77**	**5.9**	**9.30**		**117**	**9**	**8.97**		**194**	**14.9**	**10.70**	
Briefing+	26	208	8.0	13.18	p=0.93	234	9	8.26	p=0.11	442	17.0	13.64	p=0.81
Briefing -	9	57	6.3	10.41		82	9.1	7.59		139	15.4	10.65	
Difficulty	**35**				**p=0.13**				**p=0.83**				**p=0.14**
Loc. 1	20	7	0.4	1.31	p<0.001	266	13.3	7.81	p<0.01	273	13.7	8.22	p=0.27
Loc.2	**15**	**258**	**17.2**	**14.24**		**50**	**3.3**	**3.84**		**308**	**20.5**	**16.56**	

2.4. Discussions

2.4.1. Diver-related disturbances

Observing diver underwater behavior and the associated disturbances can be an important step for the sustainable development of dive-sites. Information obtained in this way can help managers to identify characteristics that can pose diver-related threats to dive-site ecology and develop ways to minimize them (Rouphael and Inglis 2001).

In this study, 35 customers from commercial dive-tours in Silfra were observed and the origin and severity of their underwater disturbances noted. The results indicate that divers caused algal removal and sediment raising in Silfra, and less than 10% of divers managed to dive through the five-minute observation period without causing a single disturbance. This is similar to ratios presented in studies on diver-related disturbances in marine systems, such as in coral reefs, where the majority of observed divers have been found to cause at least some disturbance (Rouphael and Inglis 2001; Barker and Roberts 2004; Uyarra and Côté. 2007; Luna *et al.* 2009). Fins caused the most frequent and severe disturbances, which is in accordance with studies from coral reef dive-sites (Rouphael and Inglis 1995; Walters and Samways 2001; Barker and Roberts 2004; Luna *et al.* 2009). Fins act as propellers for a diver and as a consequence, are moved quickly through the water. This makes them prone to disturbing the surroundings, either by contacting organisms or by generating a current, resulting in the detachment of algae and the raising of sediment. Previous studies on diver-related disturbances in marine systems have not addressed the importance of fin-generated currents, perhaps because these currents may not be strong enough to apply substantial forces to coral reefs. In Silfra however, this was the most frequent mechanism of diver-related disturbance, and caused severe disturbances to algae and the sediment. In addition to fin disturbances, the observed divers also frequently used their hands, contacting the substrate to improve their underwater buoyancy control. This resulted in algal disturbances by contact, but as hands do not generate a strong current, they did not cause many current-caused disturbances.

The consequences of each damaging event were further classified. Minimal algal disturbances occur where the algae is lightly detached or moved. The consequences of such events may not be large since neighboring organisms can rapidly re-colonize the affected area. Severe algal disturbances occur where large algal covers are removed off the substrate. This could result in a more time-consuming recovery for neighboring organisms (Matthaei *et al.* 1996). For sediment disturbances, minimal sediment raising causes the formation of a slight sediment cloud, in which organic matter can be resuspended and inhabiting organisms disturbed. Severe sediment disturbance causes the formation of a large sediment cloud, resuspending a greater amount of organic matter and disturbing zoobenthos. When it settles, the sediment can cover algae and other organisms, which can inhibit their accessibility to nutrients, oxygen and light (Schallenberg and Burns 2004).

As an average dive in Silfra lasts approximately 38 minutes, it can be estimated that each diver will on average cause 81 disturbance events, consisting of 50 algal removals and 31 sediment raising events. A group of four customers will on average cause 324 disturbance events, of which 181 would be classified as severe disturbances and 143 as minimal disturbances. Although each individual diver may only cause relatively small disturbances, the cumulative consequences of multiple divers a day throughout the year can cause consistent damages to Silfra ecology, that may exceed the self-restoring capacity of its ecosystem, gradually morphing its community structure (*see* chapter 1).

2.4.2. Characteristics behind diver-related disturbances

None of the presented predictions were supported in my study, and hence, it is impossible to state which diver characteristics lead to increased disturbance while diving in Silfra. However, a comparison of mean numbers, indicated that the diver characteristics hypothesized to lead to a higher disturbance generally did so. Therefore, future studies should observe a greater number of divers, which might help find any existing significant differences.

The only significant differences identified in this study were between algal and sediment disturbances at the locations where the divers were observed. This is unsurprising, as algal cover is extensive at loc.1, with sediment bottoms barely present, resulting in a higher number of algal disturbances than sediment disturbances. Loc.1 also has narrow sections that are challenging as careful maneuvering is needed to minimize disturbance of the algal covered walls. Loc.2 however, consists of wider areas that have algal covers in addition to large areas with sediment bottoms, explaining the higher number of sediment disturbances observed there.

2.4.3. Final remarks

Evidence presented in the previous chapter, showed that areas subject to high dive-use in Silfra have less algal biomass and may have different zoobenthic composition than low-use areas. In this chapter, I have demonstrated how divers can cause this, both by detaching algae that may contribute to a reduction in algal biomass, and by raising sediment, that may bury organisms.

Diver-related disturbances in Silfra vary by frequency and severity. Activity peaks in the summer months from May-August, where the most disturbance will be expected. A threshold in the number of entrees could minimize disturbances, which would be especially important during the algal spring bloom (May-June). In addition, as fin-generated currents are the primary disturbance causing factor in Silfra, divers should be briefed on the importance of careful fin maneuvering to minimize disturbances. This could include adopting different fin techniques depending on the area within Silfra. In shallow and wide areas, the frog kick would be advised, as it generates a current accumulating to the sides and will therefore lessen the damage to the horizontal substrate. In narrow but deep areas, the scissor kick would be advised as it generates a downward current, lessening any damage to the vertical substrate.

Future studies should carry out further observations of diver disturbances in Silfra. A greater sample size (>35 observed divers) is advised as it could help acquire indications on which diver characteristics can relate to diver-related disturbance. In addition, the impacts of snorkelers should be studied as snorkeler entrances are frequent in Silfra and they may pose threats to the shallower habitats within the fissure. Furthermore, the ecological impacts of algal removal and sediment raising should be thoroughly analyzed so that the consequences of diver-related disturbances can be better known.

Chapter 3: Perception of stakeholders on the future use of Silfra as a dive site.

3.1. Introduction

Sustainability is utilized to adapt the interests of environmental protection, economic growth and social equality into the management of resources (Bringezu and Bleischwitz 2009). Nature-based tourism, which involves interactions and/or appreciation of natural environments, is increasing across the world (Balmford *et al.* 2009). Consequently the implementation of sustainability guidelines for natural tourist resources becomes ever more important, as they are the central reason nature-based tourism can exist (Kuenzi and McNeely 2008).

The management of tourist destinations depends on the nature of the tourism involved. Sensitive natural areas may need stricter management protocols than sites that are more tolerant to higher levels of disturbance (Eagles *et al.* 2002). The emergence of sustainable tourism and ecotourism has allowed for attempts in managing tourism so that it does not become destructive for the environment (Hughes 2002; Cater 2002).

Tourists visit natural areas for numerous purposes, such as wildlife watching, engaging in recreational activities, or to acquire a wilderness experience (Nyaupane *et al.* 2004). As a result, the development of nature-based tourism should address the importance of protecting the nature that tourists come to experience. For this to be achieved, the promoted environment needs protection. At the same time, the number of tourists as well as infrastructure requires managing to ensure that the quality of the tourism experience is not compromised (Lime and Stankey 1971). The concept of carrying capacity is an approach to manage the number of tourists visiting a destination, so that the environmental, social and economical basis of the destination are not compromised (Castellani and Sala 2012). As a result, environmental, social and economical factors act as components in tourism carrying capacity (Coccossis *et al.* 2002). Tourism carrying capacity has been defined as a "maximum number of tourists that sojourn in a specific area and use its contents in a way that does not induce unacceptable and irreversible change in the environmental, social, cultural and economic structure of the destination nor does it decrease the quality of tourist experience." (Jovicic and Dragin 2008, p. 6). In Thingvellir National Park (TNP), no carrying capacity has been established, although the rapid increase in tourism has degraded the national park´s environment (Elmarsdóttir and Ásbjörnsdóttir 2014) that tourists come to experience (Íslandsstofa. 2013a). Few management protocols have been put into action to control the process, without which a further increase in TNP tourism is worrisome (Elmarsdóttir and Ásbjörnsdóttir 2014).

Dive-related tourism in the TNP has also increased drastically, especially in the Silfra groundwater fissure, which received just below 20.000 entrees in 2014 (data from Þingvallaþjóðgarður. 2015). Dive tourism in Silfra takes place in a natural setting and within a national park, and therefore can be classified as nature-based tourism. As such, management protocols, not only to minimize environmental damage, but also to maximize economic growth and the quality of the offered tourism, must be proposed so that dive-tourism within the fissure can be sustainably managed. In 2013, a fee was initiated for the entrance into Silfra with the purpose to fund management and infrastructure for diving in the fissure. In 2015, a B.Sc. thesis on the management of diving in Silfra proposed that management surrounding the use of Silfra as a dive-site should establish a threshold on the number of diver and snorkeling entrees, and that dive-tour companies should auction to be one of three operating in Silfra (Sigurjónsdóttir, 2015).

In chapter 1 and 2, I provided evidence that dive-tourism can degrade the underwater ecosystem of the Silfra groundwater fissure. However, it is unknown how dive tourists, guides, operators and the TNP authorities perceive the current and future dive tourism in Silfra. Knowledge of such perceptions is important for the sustainable management of the fissure, which should take into account the interests of all stakeholders (UNWTO 2005). Here, I collect and analyze the interests of all stakeholders surrounding the current and future use of Silfra as a dive-site. By questioning the TNP authorities, dive operators, guides and dive-tour customers, I create the basis for protocols that can be implemented for the sustainable use of Silfra as a tourist destination.

3.2. Materials and methods

3.2.1. Study site

In Thingvellir National Park (TNP), southwest Iceland, diving is only allowed in two fissures: Silfra and the Davíðsgjá fissures. Silfra is Iceland´s most popular dive-site, located close to the center of TNP. Davíðsgjá is located in the Lake Thingvallavatn, next to a breeding site for the large-benthivorus morph of Arctic charr (*Salvelinus alpinus*) (Kristjánsson B.K., personal communication), but it receives much lesser traffic than Silfra, mostly due to poorer access. In 2013, the TNP and the Icelandic Maritime Administration updated rules regarding diving in Silfra, prohibiting diving below 18m and in caves, and that a group could only enter after the previous group had passed a certain point in the fissure (Stjórnartíðindi 2013b). This reduced in-water crowding, but has caused the formation of queues on hectic days, where fully geared divers need to wait prior to entering Silfra.

3.2.2. Execution

Stakeholders for the dive tourism in the Silfra groundwater fissure were determined as 1) the executive members of TNP, hereby refereed to as park officials 2) operators of dive companies in Silfra, 3) dive guides in Silfra and 4) customers on dive-tours.

Interviewing was chosen as the best method to questionnaire park officials as there were only four major individuals: the Director and the interpretive officer of the park, the park´s project manager and the executive staff member for Silfra during the summer 2015 (Figure 1 – appendix 2). Written questionnaires were used to sample opinions of the other stakeholders, as they were more abundant. The questionnaires were distributed to the operators of all major dive companies running diving tours in Silfra as of summer 2015 (n=6, Figure 2 – appendix 2), dive guides (n=10, Figure 3 – appendix 2), and customers after their dives (n=61, Figure 4 – appendix 2).

Questions addressed in the questionnaire and interviews were designed to gain insights into the different perceptions of stakeholders for the operation and management of dive tourism in the Silfra fissure on the following topics:

- Factors that influence tourist´s decisions to dive in Silfra and operators to operate there,
- The willingness amongst stakeholders to have more fissures opened for diving
- The appropriateness of waiting times to enter Silfra.
- Opinions on the current and increasing number of divers and snorkelers in Silfra.

3.2.3. Analysis

Interviews were analyzed through inductive coding so that answers from each relevant question could be extracted. Descriptive statistics were compiled on questionnaire data using MICROSOFT EXCEL for Mac (Microsoft, 2011). For customers' reasons to visit Silfra, (question 1 on customer questionnaire sheets - Figure 4, appendix 2), an importance index was calculated to determine which factor, dry-suit diving, geology, biology or visibility, was considered most important. The same was done for guides and operators (questions 1 on guide- and operator questionnaire sheets - Figure 3 and 4 - appendix 2). The index was calculated as follows:

$$Importance\ index = \left(\frac{((nA * 4) + (nB * 3) + (nC * 2) + (nD * 1))}{10}\right) * \left(\frac{nCustomers}{(nA + nB + nC + nD)}\right)$$

Importance of factors where 1=the most important factor and 4 the least important factor: A=importance 1, B= importance 2, C= importance 3, D=importance 4.

3.3. Results and discussions

3.3.1. Diving motivations

Results indicate that customers visit Silfra for its unique geology first and visibility second (Table 3.3.1). Reputation may have initiated this, as Silfra has been named in numerous dive-magazines and websites as one of the world´s best dive sites providing stellar visibility between the tectonic plates (Time magazine 2005; Hood 2005; Sulit 2014; Diveadvisor. [No year]; Mike. 2015). Guides considered visibility the most important and geology the second most important factor for their client´s decision to dive in Silfra (Table 3.3.1). Operators mostly focused on marketing the visibility first and geology or biology of Silfra second (Table 3.3.1). Customers did not consider biology an important factor in their decision to visit Silfra, suggesting that even if a biological decay is occurring in the fissure, it will unlikely affect the popularity of Silfra. Guides agreed with this and ranked biology as the least important factor for their clients decision to dive in Silfra. In contrast, the operators ranked biology equally to geology, suggesting that they perceive biology as a more important factor than customers and guides and use it to a certain extent in their marketing. Put another way, a decline in biological diversity would not be of equal concern to all of these stakeholders.

Table 3.3.1. *Importance indexes of dry-suit diving, geology, biology and visibility (see materials and methods) for customers (stated reasons for visiting Silfra), guides (perceptions on their clients reasons´ to visit Silfra) and operators (stated aspects of marketing diving in Silfra) in the Silfra groundwater fissure in Thingvellir National Park. The higher the index, the greater the importance.*

Factor	Customer imp. index	Guides imp. index	Operator imp. index
Dry-suit diving	11.8	14.03	11.18
Geology	20.7	19.52	15.25
Biology	12.4	8.54	15.25
Visibility	17.8	23.18	23.38

The majority of customers (80%) said they would like to dive in the currently closed fissures in TNP. The guides exhibited similar attitudes, as 90.1% stated that they were willing to guide dive tours in the currently closed fissures. Furthermore, 100% of the company operators wanted to operate in these closed fissures. Opening more fissures for diving is entirely dependent on the national park´s willingness to do so, but since all three stakeholder groups are in favor of this, park managers may experience pressure to comply in the near future. However, TNP officials all stated that they would not, under any conditions, be willing to open other fissures for diving. The director of TNP stated the following three reasons for keeping other fissures closed: 1) safety, as evacuation in hard-to-access fissures would be difficult in the case of an accident, 2) to protect the original image of the area so that guests can experience freedom and peacefulness, and 3) diving may impact life in and around the fissures due to increased traffic.

Both guides and operators specifically mentioned that they would like to see more fissures opened especially if one was open for divers only and the other for snorkelers only so that traffic could be better managed. As one operator said:

Dominantly snorkelers need to be controlled. They cause the most damage. They spit their gum into the water, they throw coins into Silfra, also trash (cameras, fins) and nobody picks that up, except one dive company, once a year. Snorkelers pull onto rocks, plants, moss and pull it into the water. If a fissure would be opened only for snorkeling and Silfra would only be available to diving, it would fix the problem. It would need to be better managed and policed. My issue is protecting the place.

The above comment illustrates the importance of considering the different kinds of diving activities in the park, and the role that specific policies or management rules can have in sustainable tourism management. The comment also highlights the connections of traffic, increasing diver numbers, and negative impacts while at the same time offering a plausible solution for protection. Below, I discuss issues of traffic and perceived stakeholder improvements to infrastructure surrounding the use of Silfra as a dive-site.

3.3.1. Diving experiences: Traffic and infrastructure

As introduced in chapter 1, without intervention by national park management policies, the vast increase in Silfra visitor numbers over the last few years is likely to continue. Although most customers (88%), stated that they were content with what they perceived as the current snorkeler and diver numbers in Silfra, 92% also affirmed that they would not like to see a further increase. As the following questionnaire comments illustrate, they identified the uniqueness of the dive while recognizing that Silfra poses an important business opportunity for locals, but were also wary of further increase in dive numbers:

It is very impressive to be able to dive in this area. However, it would feel more exclusive if there weren't so many other divers/snorkelers.

More divers=more tourism, but too many divers would affect the unique experience. Absolutely amazing dive.

Too many people.

The guides agreed with this, with 73% happy with the number of divers and snorkelers, while none would like to see an increase. One guide suggested the following:

There should be a maximum amount of people we can take in the water a day.

On the other hand, most operators (66%) were unhappy with the current number of divers/snorkelers and did not want an increase in numbers. The findings above suggests that customer numbers may be reaching a threshold in terms of social capacity, in which additional visitors may constrain the quality of the customer experience. This is in accordance with other studies that have shown that by increasing visitor numbers, quality may decrease (Keane 1996; Hall and Page 2014)

Much in the same way, customers were satisfied with wait times (82%), while guides felt the wait times were too long (100%). Customers that needed to wait prior to entering Silfra had to wait for a perceived average of 11 minutes (SD=8.22, min=2, max=30), but the waiting time was not considered inappropriate by most, as highlighted by the following comment:

> *Great dive. Even though we had to wait it was for the best because we didn´t see the other group when we were in the water.*

All guides stated that the waiting times were inappropriate. Guides may consider the wait for entry to be unprofessional, while customers do not yet think much of it and are instead focused on the experience itself. However, if waiting times increase it may shift this opinion of customers, because standing in heavy and warm dive-gear is strenuous.

As for the park officials' perception of the number of Silfra divers and snorkelers, the director of the national park specified that as long as the right infrastructure is in place then the current numbers of divers and snorkelers in Silfra were not a problem, except for the visual disturbance that is associated with increased vehicle traffic around Silfra. Nevertheless, the director also suggested that increasing numbers might compromise customer experience. The interpretive officer of TNP considered the current numbers too high, with the disturbance on a small and important sector of the national park too great. The TNP project manager and the executive staff member for Silfra both stated that the dive companies need to consider how increased numbers may affect their customer experience while the national park needs to consider how the area around and in Silfra can be protected. All interviewees recognized the need to manage diver numbers and limit the number of operators, as is similar to what was suggested in the B.Sc. thesis by Sigurjónsdóttir (2015).

Comments from customers, guides and operators suggested that infrastructure improvements to the dive experience itself was a more pressing concern than limiting diver and snorkeler numbers. Customers and guides suggested constructing a better in-water entrance such as a platform, and having a changing room. This is understandable as it would make the dive more comfortable for customers and improve the guide´s working environment. Several operators suggested enhanced accessibility to the only other fissure open in TNP, Davíðsgjá, which is 300m off shore of the Lake Thingvallavatn, as is underlined by the following comments:

> *We think that improved access to the Davíðsgjá fissure might solve many problems.*
>
> *We would like an eco-friendly dive-park in Lake Thingvallavatn, for example by Davíðsgjá.*

Davíðsgjá fissure is open to traffic, but its location 300m off shore of Lake Thingvallavatn may act to limit the number of divers entering the fissure. Increased access to Davíðsgjá might help spread vehicle-, pedestrian- and dive-traffic away from Silfra and the center of TNP. This might also help lessen ecological disturbances in Silfra. However, an environmental impact assessment should be conducted before constructing enhanced access to the fissure, especially as Davíðsgjá is located next to a breeding site for the large-benthivorus morph of Arctic charr (Kristjánsson B.K., personal communication).

3.4 Conclusions and recommendations

In the discussion above I have examined the different perceptions of stakeholders surrounding the use of Silfra as a dive-site. The source of income of diving in Silfra is the customers themselves, and their perceptions need consideration. Most customers stated that they were willing to dive in the currently closed TNP fissures. However, the National Park officials stated that no more fissures would be opened. Most customers said that they were happy with the current number of divers and snorkelers in Silfra, but a similar proportion also said that they would not like to see an increase in numbers. Although most customers considered waiting times appropriate, increased numbers of divers and snorkelers might intensify future waiting times beyond appropriate points, limiting the quality of the tourism experience. This suggests that numbers of divers and snorkelers in Silfra may be approaching Silfra´s social carrying capacity.

Some dive operators thought that further infrastructure around the currently open Davíðsgjá fissure could help maintain the quality of customer experience. This could also help decrease diver-related ecological disturbances around and within Silfra. Additionally, this might lessen pedestrian and vehicle traffic around Silfra, reducing visual disturbance around the center of TNP. In light of the findings described above, I recommend the following actions:

1. An environmental impact assessment for diving in Davíðsgjá fissure is advised. This should focus on assessing at potential diver-related impacts on the breeding of large-benthivorous Arctic charr. If potential diver-related impacts do not exceed sustainable limits, further marketing and use of Davíðsgjá fissure by dive companies is advised. In addition, added infrastructure around Davíðsgjá should be considered by the national park management, provided such development does not greatly impair the natural environment around the access to the fissure. This could help reduce traffic and ecological disturbance in Silfra.

2. Further increase in the number of divers and snorkelers in Silfra is not advised beyond 2015 numbers until future projects have established a carrying capacity for SCUBA diving and snorkeling in the fissure. In addition a daily limit of divers and snorkelers should be considered, both to reduce ecological disturbance and to maximize tourism quality.

4. Final conclusions

Results from this thesis suggest that diving in Silfra may approach the fissure´s ecological and social limits in the near future. In further detail, chapter 1 showed that diving appears to decrease algal biomass on Silfra´s substrate, and provided some indications that community assemblages may be affected through potential dominance of disturbance tolerant species. In chapter 2, I demonstrated the mechanisms behind diver-related disturbances and concluded that fin-generated current is a frequent cause of algal detachment and the raising of sediment. In chapter 3, I presented evidence that a social carrying capacity as a result of tourist dissatisfaction will approach quickly with increasing numbers of divers and snorkelers. The identified ecological and social impacts of diving in Silfra will probably be magnified with increasing numbers of entrees into the fissure, potentially threatening Silfra´s ecosystem and the activities of tourist operations in Silfra. Hence, great care must be taken in increasing the numbers of entrees into Silfra, so that the fissure´s ecosystem and the tourism experience can be preserved.

For tourism to be sustainable, it must take full responsibility of its current and future economic, social and environmental impacts. It must also address the needs of a wide range of stakeholders, including the environment, visitors, tourism operators, and host communities (UNWTO 2005). By striking the balance between environmental conservation, customer satisfaction and economic growth, sustainable tourism can be achieved in Silfra. To assist with achieving this balance, I recommend that the future number of divers and snorkelers in Silfra, does not exceed those for the year 2015. However, more research should be undertaken to fully understand the ecological and social thresholds of tourism in Silfra. Future studies should follow the recommendations below:

1) Explore the interconnectedness of ecosystems connecting to TNP groundwater fissures to create a basis for the potential ecological consequences of fissure diving in TNP.
2) Monitor the ecological impacts of diving and snorkeling in Silfra on species biomass, diversity and assess how diver-related disturbances can shape community assemblages in Silfra. Algae, invertebrates and fishes inhabiting the fissure should be included in this monitoring.
3) Attempt to determine which diver and snorkeler characteristics lead to high disturbances, by utilizing large sample sizes so that any significant disturbance characteristics can be encountered. This, in addition to recommendation 1 and 2 can help establish an ecological carrying capacity for diving and snorkeling in Silfra.
4) Monitor the perceptions of stakeholders surrounding the use of Silfra as a dive-site so that a social carrying capacity can be established.
5) Attempt to establish an economic carrying capacity by defining the extent of ecological, social, and infrastructure changes that fissure diving and snorkeling in TNP can sustain before adversely affecting activities and operations in Silfra.
6) Include the impacts of snorkeling in all future studies.

To achieve this, I recommend that the TNP and the dive operators work together to fund interdisciplinary monitoring projects with the aim of propositioning appropriate ecological, social and economic carrying capacities for fissure diving and snorkeling in TNP. For the national park, visitor fees for entering Silfra create a suitable fund for such projects. Determining appropriate carrying capacities for fissure diving in TNP is important as it helps maintain sustainable tourism from which all stakeholders benefit. To a broader extent I also recommend that such studies, integrating ecological, social and economical aspects, be undertaken in other nature-based tourist sites in Iceland. These interdisciplinary studies are especially important in light of the current development of the Icelandic tourist industry, which needs to consider how the nature-based tourism can maintain its future product value in Iceland.

5. Appendices

5.1. Appendix 1

Figure 1. *Removed algae as a consequence of minimal algal disturbance (A1). This is a result of diver contacting the algae directly or by the generation of a current which removes the algae.*

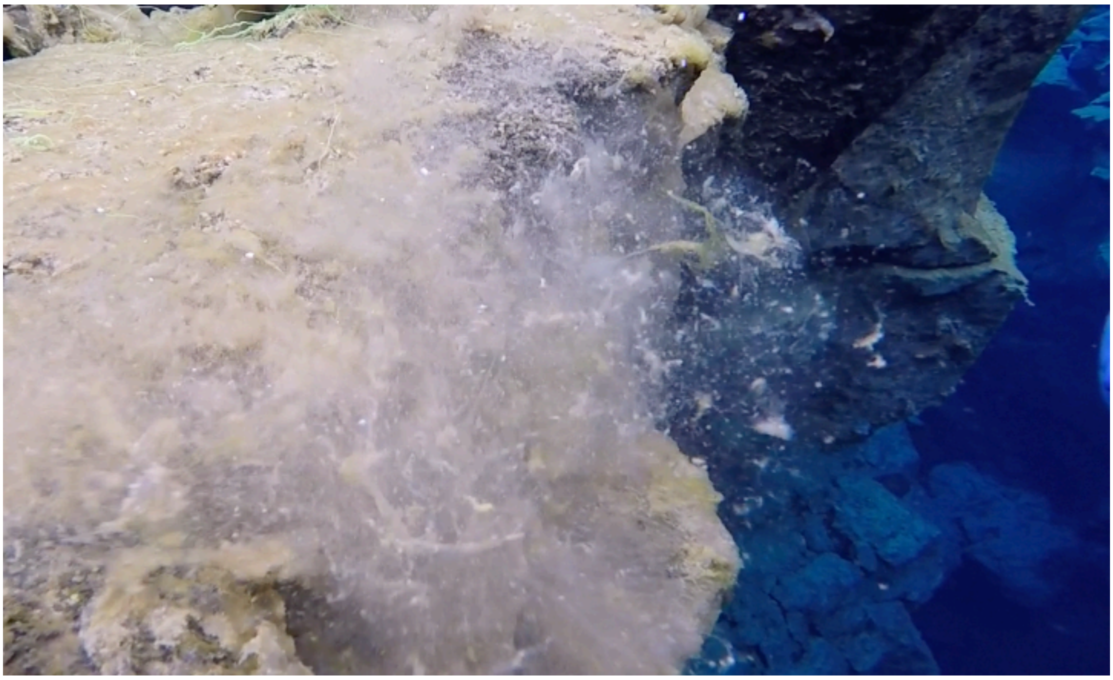

Figure 2. *Removed algae as a consequence of severe algal disturbance (A2). This is a result of diver contacting the algae directly or by the generation of a current which removes the algae.*

Figure 3. *The raising of sediment as a consequence of minimal sediment raising (S1). This is a result of diver contacting the sediment directly or by the generation of a current which raises the sediment.*

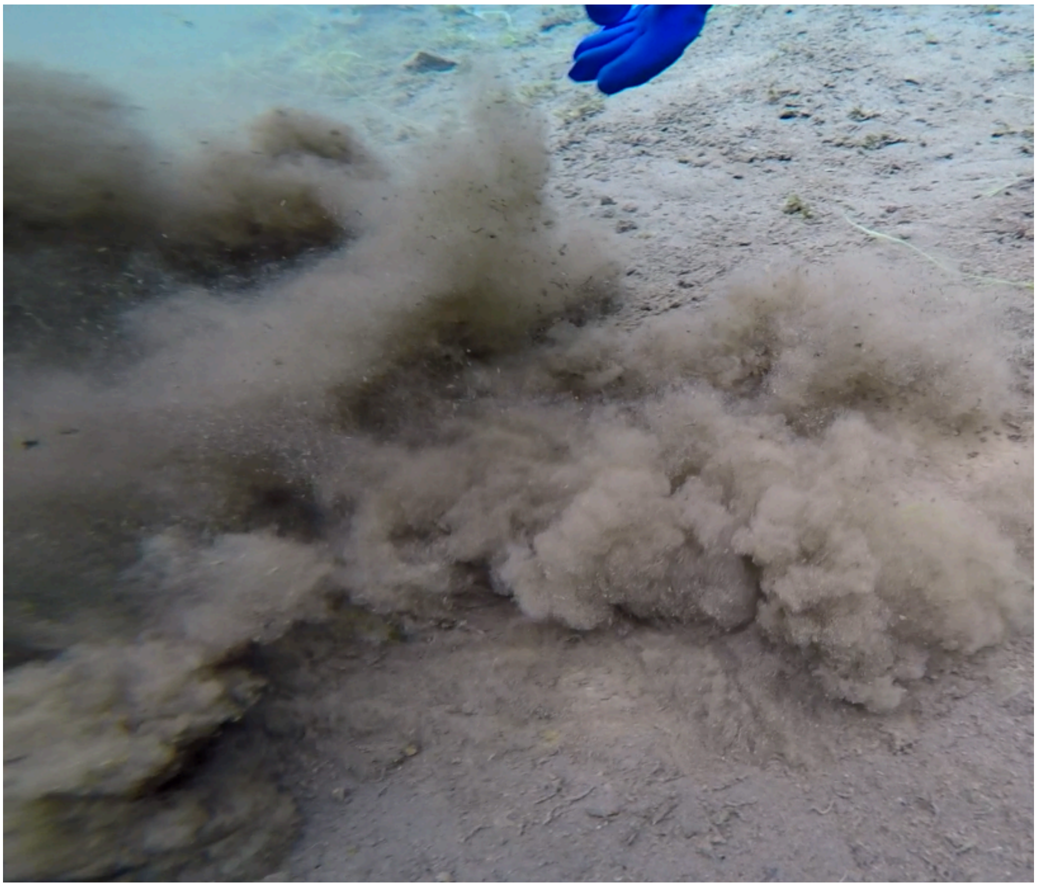

Figure 4. *The raising of sediment as a consequence of severe sediment raising (S2). This is a result of diver contacting the sediment directly or by the generation of a current which raises the sediment.*

Silfra diver survey

Part of an M.Sc. research at Hólar University College

1. Gender: Male______ Female______

2. Nationality: ___________________

3. Age: ______

4. Diving certifications acquired (mark all that apply):

- Beginner (Open water): _______
- Intermediate (Advanced, Rescue): _______
- Advanced (Dive Master, Instructor): _______
- Dry suit diver certified: _______
- Technical diver certified: _______

5. What is the total number of dives have you logged:

- <5 _______
- 6-10 _______
- 11-25 _______
- 26-50 _______
- 51-100 _______
- 101-200_______
- >200 _______

6. Prior to todays dive, how many dry-suit dives had you logged:

- 0 _______
- 1 _______
- 2-5 _______
- 6-10 _______
- 11-25 _______
- 26-50 _______
- 51-100 _______
- 101-200 _______
- >200 _______

7. Is this your first dive in Silfra?

- Yes:_____ No:______

Figure 5a. *A questionnaire, which was used to acquire a profile on divers that were recorded for diver-related disturbances in the groundwater fissure Silfra, Thingvellir National Park.*

8. Please name the dive shop you are diving with:____________________________

9. Do you think divers can cause damage to freshwater ecosystems?

- Yes: _______ No: _______ I don´t know: _______

10. Did you receive a briefing from your guide on the environmental aspects of diving in Silfra?

- Yes:_______No:_______

11. How deep did you go on your dive?

- _________ft _________m

12. Where 1 is the easiest and 10 is the hardest, how difficult did you consider your dive in Silfra to be? Please draw a circle around the answer.

1 2 3 4 5 6 7 8 9 10

13. Where 1 is the least enjoyable and 10 is the most enjoyable, how enjoyable did you consider your dive in Silfra to be? Please draw a circle around the answer.

1 2 3 4 5 6 7 8 9 10

Thank you for your time

Figure 5b. *A questionnaire, which was used to acquire a profile on divers that were recorded for diver-related disturbances in the groundwater fissure Silfra, Thingvellir National Park.*

5.2. Appendix 2

1. Why do you think divers like to visit Silfra?
2. Would you be willing to open the currently closed fissures in TNP for dive traffic?
3. Under which conditions, if any, would you be willing to open more fissures for diving?
4. Are you happy with the number of divers/snorkelers entering the fissure?
    a. Please explain your answer.
5. Would you be happy to see the numbers of divers/snorkelers increase in Silfra?

Figure 1*. Questions addressed in interviews to investigate the perception of the officials of of Thingvellir National Park surrounding the use of the groundwater fissure Silfra as a dive-site.*

Dive operations in Silfra – A survey
Part of a M.Sc. research at Hólar University College

Dive operators

1. **On a scale of 1-4 (1 being the most important and 4 the least) please rank the following aspects in <u>your marketing</u> for diving in Silfra.**
    - _____ Dry-suit diving
    - _____ Unique geology of the area
    - _____ Unique biology of the area
    - _____ Water visibility
2. **If presented with the opportunity, would you be willing to operate in the <u>currently closed</u> fissures of Þingvellir?**
    a. Yes____
    b. No____
3. **Are you happy with the number of divers/snorkelers entering Silfra?**
    a. Yes____
    b. No, there are too many____
    c. No, there are too few____
4. **Would you be happy to see the numbers of divers/snorkelers increase in Silfra?**
    a. Yes____
    b. No____
5. **Is there anything else you would like to add about diving in Silfra?**

____
____
____
____
____

Thank you for your time

-Jóhann Garðar Þorbjörnsson

Figure 2. *A questionnaire given to dive operators, operating in the groundwater fissure Silfra in Thingvellir National Park, to investigate their perceptions for the use of Silfra as a dive-site.*

Dive operations in Silfra – A survey
Part of an M.Sc. research at Hólar University College

Dive guides

1. **On a scale of 1-4 (1 being the most important and 4 the least) please rank the following aspects of your clients reasons to dive in Silfra.**

    _____ Dry-suit diving

    _____ Unique geology of the area

    _____ Unique biology of the area

    _____ Water visibility

2. **Would you be willing to guide dive tours into the <u>currently closed</u> freshwater fissures in Þingvellir?**
    a. Yes____
    b. No____
3. **Did you have to wait by the entrance point before entering Silfra?**
    a. Yes____*If so, how long?*_____minutes? *Do you* consider that waiting time appropriate for your customers? **Yes____No____**
    b. No____
4. **Are you happy with the number of divers/snorkelers entering the fissure?**
    a. Yes____ *If yes,* would you be happy to see the numbers of divers/snorkelers increase in Silfra? **Yes____No____**
    b. No, there are too few___
    c. No, there are too many____ *If too many*, do you think opening more fissures in Þingvellir would solve the problem? **Yes____No____**
5. **Is there anything you would like to add about guiding dive tours in Silfra?**

    ____

    ____

    ____

Thank you for your time

-Jóhann Garðar Þorbjörnsson

Figure3. *A questionnaire given to dive guides working in the groundwater fissure Silfra in the Thingvellir National Park, to investigate their, and their client´s perceptions, surrounding the use of Silfra as a dive-site.*

Dive operations in Silfra – A survey
Part of an M.Sc. research at Hólar University College

Customers

1. **On a scale of 1-4 (1 being the most important and 4 the least) please rank the following aspects of your decision to dive in Silfra.**

    _____ Dry-suit diving

    _____ Unique geology of the area

    _____ Unique biology of the area

    _____ Water visibility

2. **There are fissures in the Þingvellir National Park where diving is not permitted. Would you be willing to buy a guided dive tour into those <u>currently closed</u> fissures if they were opened?**
    a. Yes____
    b. No____
3. **Did you have to wait by the entrance point before entering the Silfra fissure?**
    a. Yes____*If so, how long?*_____minutes. *Do you* consider that waiting time appropriate? **Yes___No___**
    b. No____
4. **During your dive, were you happy with the number of divers/snorkelers around and in the fissure?**
    a. Yes____
    b. No, there were too many___
    c. No, there were too few____
5. **Would you be happy to see the numbers of divers/snorkelers increase in Silfra?**
    a. Yes____
    b. No____
6. **Is there anything else you would like to add about diving in Silfra?**

    ____

    ____

    ____

Thank you for your time

-Jóhann Garðar Þorbjörnsson

***Figure** 4. A questionnaire given to customers in commercial dive-tours in the groundwater fissure Silfra in Thingvellir National Park, to investigate their perceptions surrounding the use of Silfra as a dive-site.*

6. References

Abidin S.Z.Z. and Mohamed B. 2014. *A review of SCUBA Diving Impacts and Implication for Coral Reefs Conservation and Tourist Management*. SHS Web of Conferences, 12.

Adalsteinsson H. and Jónasson P.M. 2011. Plankton and conditions for life in the lake. In: Jónasson and Hersteinsson (eds.). *"A unique world evolving – Thingvallavatn – A World Heritage Site"* Opna Publishing, Reykjavík, pp. 150-162.

Alroy J. 2001. *A Multispecies Overkill Simulation of the End-Pleistocene Megafaunal Mass Extincion.* Science. 292:5523, pp. 1893-1896.

Balmford A., Beresford, J., Green J., Naidoo R., Walpole M., Manica A. 2009. *A Global Perspective on Trends in Nature-Based Tourism.* PLoS Biology, 7:6.

Barker N.H.L and Roberts C.M. 2004. *Scuba diver behavior and the management of diving impacts on coral reefs.* Biological Conservation, 120:4, pp. 481-489.

Barnosky A.D., Koch P.L. Feranec R.S., Wing S.L., Shabel A.B. 2004. *Assessing the Causes of Late Pleistocene Extinctions on the Continents.* Science, 306:5693, pp. 70-75.

Barnosky A.D., Hadly E.A., Bascompte J., Berlow E.L., Brown J.H., Fortelius M., Getz W.M., Harte J., Hastings A., Marquet P.A., Martinez N.D., Mooers A., Roopnarine P., Vermeij G., Williams J.W., Gillespie R., Kitzes J., Marshall C., Matzke N., Mindell D.P., Revilla E., Smith A.B. 2012. *Approaching a state shift in Earth´s biosphere*. Nature, 486:7401, pp. 52-58.

Barnosky A.D., Matzke N., Tomiya S., Wogan G.O.U., Swartz B., Quental T.B., Marshall C., McGuire J.L., Lindsey E.L., Maguire K.C., Mersey B., Ferrer E.A. 2011. *Has the Earth´s sixth mass extinction already arrived?* Nature, 471:7336, pp. 51-57.

Berry B.J.L. 1990. Urbanization. In: Turner II B.L. (ed.). *"The Earth as Transformed by Human Action: Global and Regional Changes in the Biosphere Over the Past 300 Years".* Cambridge University Press, pp. 103-120.

Bowman D.M.J.S and Murhpy B.P. 2010. Fire and biodiversiy. In: Sodhi N.S and Ehrlich P.R. (eds.). *"Conservation Biology for All."* Oxford University Press, pp. 163-180.

Brandl K., Baumgartner C., Birkett M., Dymak S., Price C., Protopapadakis P. 2011. *Sustainable Tourism and Nature Conservation. An Investment in our Future.* SURF nature project.

Bringezu S. and Bleischwitz R. 2009. *Sustainable Resource Management: Global Trends, Visions and Policies.* Greenleaf Publishing.

Buckley R. 2012. *Sustainable Tourism: Research and Reality.* Annals of Tourism Research, 39:2, pp. 528-546.
Burns, G. L., Macbeth, J., and Moore, S. 2011. *Should dingoes die? Principles for engaging ecocentric ethics in wildlife tourism management.* Journal of Ecotourism, 10:3, pp. 179-196.

CANOCO 5 for Windows. 2012. Microcomputer Power.

Castellani V and Sala S. 2012. Carrying capacity of tourism system: Assessment of environmental and management constraints towards sustainability. In: M.Kasimoglu (ed.). *"Visions for Global Tourism Industry: Creating and Sustaining Competitive Strategies."* Intech, pp. 295-316.

Cater E. 2002. Ecotourism: Theory and Practice. In: Lew A.A., Hall C. M. and Williams A.M. (eds.) *"A companion to Tourism."* Blackwell Publishing, pp. 484-497.

Ceballos G., Ehrlich P.R., Barnosky A. D. García A., Pringle R.M., Palmer T.M. 2015. *Accelerated modern human-induce species losses: Entering the sixth mass extinction.* Science Advances, 1:5.

Ceballos-Lascuráin H. 1993. *The IUCN Ecotourism Consultancy Programme*. México, DF, p. 4.

Coccossis H., Mexa A., Collovini A. 2002. *Defining, measuring and evaluating carrying capacity in European tourism destinations – Final Report.* European Commission.

Cochrane M.A. 2003. *Fire science for rainforests*. Nature. 421:6926, pp. 913-919.

Connell J.H. 1978. *Diversity in Tropical Rain Forests and Coral Reefs.* Science, 199:4335, pp. 1302-1310.

Crutzen P.J. 2006. The "Anthropocene". In: Ehlers E. and Krafft T. (eds.). *"earth system science in the anthropocene."* Springer, pp. 13-18.

Davenport J. and Davenport J.L. 2006. *The impact of tourism and personal leisure transport on coastal environments.* Estuarine, Coastal and Shelf Science, 67:1-2, pp. 290-292.

Dayton P.K. 1971. *Competition, Disturbance and Community Organization: The Provision and Subsequent Utilization of Space in a Rocky Intertidal Community.* Ecological monographs, 41:4, pp. 351-189.

Deane P.M. 1965. *The First Industrial Revolution.* Cambridge University Press.

Dirzo R., Young H.S., Galetti M., Ceballos G., Isaac N.J.B., Collen B. 2014. *Defaunation in the Anthropocene.* Science, 345:6195, pp. 401-406.

Dixon, J.A., Scura, L.F., van´t Hoff, T. 1993. *Meeting ecological and economic goals – marine parks in the Caribbean.* Ambio, 22:2-3, pp. 117-125.

Dodds W.K. 2002. *Freshwater Ecology: Concepts and Environmental Applications.* Academic Press.

Dokulil T.D. 2014. Environmental Impacts of Tourism on Lakes. In: Ansari A.A. and Gill S.S. (eds.). *"Eutrophication: Causes, Consequences and Control – Volume 2."* Springer Science and Buisness Media, pp. 81-88.

Dudgeon D., Arthington A.H., Gessner M.O., Kawabata Z., Knowler D.J., Lévêque C., Naiman R.J., Prieur-Richard A.H., Soto D., Stiassny M.L., Sullivan C.A. 2006. *Freshwater biodiversity: importance, threats, status and conservation challenges*. Biol. Rev, 81:2, pp. 163-182.

Eagles P.F.J., McCool S.F., Haynes C.D. 2002. *Sustainable Tourism in Protected Areas: Guidelines for Planning and Management.* IUCN.

Einarsson A., Stefánsdóttir G., Jóhannesson H., Ólafsson J.S., Gíslason G.M., Wakana I., Gudbergsson G., Gardarsson A. 2004. *The ecology of Lake Myvatn and the River Laxa: variation in time and space.* Aquatic Ecology, 38:2, pp. 317-348.

Einarsson P. 2008. *Plate boundaries, rifts and transforms in Iceland*. Jökull, 58 pp. 35-58.

Elmarsdóttir Á. and Ásbjörnsdóttir L. 2014. *Áhrif ferðamennsku á náttúrufar Þjóðgarðsins á Þingvöllum.* Náttúrufræðistofnun Íslands.

Sigurðsson F. and Sigbjarnarson G. 2011. Groundwater inflow. In: Jónasson P.M and Hersteinsson P. (eds.). *"A unique world evolving – Thingvallavatn – A World Heritage Site"* Opna Publishing, Reykjavík, pp. 124-139.

Gadgil P.D. and Bain J. 1999. *Vulnerability of planted forests to biotic and abiotic disturbances.* New Forests 17:1, 227–238.

Grime J. P. 1977. *Evidence for the existence of three primary strategies in plants and its relevance to ecological and evolutionary theory*. American Naturalist 111:982, pp. 1169-1194.

Grime J. P. 2001. *Plant Strategies, Vegetation Processes, and Ecosystem Properties.* John Wiley & Sons, New York.

Gössling S. 2000. *Sustainable tourism development in developing countries: some aspects of energy use*. Journal of Sustainable Tourism, 8:5, pp. 410-425

Hadwen W.L., Arthington A.H., Boon P.I., Lepesteur M., McComb A. 2006. *Rivers, Streams, Lakes and Estuaries: hot spots for cool recreation and tourism in Australia*. CRC for Sustainable Tourism.

Hall M.C. and Page S.J. 2014. *The geography of tourism and recreation: Environment , place and space.* Routledge, pp. 146-154.

Halpern B. S., Walbridge1 S., Selkoe1 K.A., Kappel1 C.V., Micheli F., D'Agrosa C., Bruno J.F., Casey K.S., Ebert C., Fox H.E., Fujita R., Heinemann D., Lenihan H.S., Madin E.M.P., Perry M.T., Selig E.R., Spalding M., Steneck R., Watson R. 2008. *A global map of human impact on marine ecosystems.* Science, 319:5865, pp. 948-952.

Hammitt W.E., Cole D.N., Monz C. 1998. *Wildland Recreation: Ecology and Management.* John Wiley and Sons, Inc.

Hasler H. and Ott J.A. 2008. *Diving down the reefs? Intensive diving tourism threatens the reefs of the northern Red Sea*. Marine Pollution Bulletin 56:10, pp. 1788-1794.

Hastings A. 2013. *Multiple Stable States and Regime Shifts in Ecological Systems.* Mathematics TODAY, pp 37-39.

Hawkings J.P. and Roberts C.M. 1992a. Effects of recreational SCUBA diving on fore-reef slope communities of coral reefs. Biological Conservation, 62:3, pp. 171-178.

Hawkings J.P. and Roberts C.M. 1992b. *Can Egypt´s Coral Reefs Support Ambitious Plans for Diving Tourism?* Proceedings of the Seventh International Coral Reef Symposium, Guam, 2, pp. 1007-1013.

Hawkings J.P. Roberts C.M., Van´t Hof T., De Meyer K., Tratalos J., Aldam C. 1999. *Effects of Recreational Scuba Diving on Caribbean Coral and Fish Communities.* Conservation Biology, 13:4, pp. 888-897.

Hobbs R.J. 2002. In: Perrow M.R. and Davy A.J. (eds.). *"The ecological context: a landscape perspective. In: Handbook of Ecological Restoration – Volume: Principles of restoration".* Cambridge University Press. pp. 24-45.

Hobbs R.J. and Harris J.A. 2002. *Restoration Ecology: Repairing the Earth´s Ecosystems in the New Millenium.* Restoration Ecology, 9:2, pp. 239-246.

Hobbs R.J. and Norton D.A. 1996. *Towards a Conceptual Framework for Restoration Ecology.* Restoration Ecology, 4:2, pp. 93-110.

Holling C.S. 1973. *Resilience and Stability of Ecological Systems.* Annual review of Ecology and Systematics, 4, pp. 1-23.

Hooke R. LeB. 2000. *On the history of humans as geomorphic agents.* Geology, 28:9, pp. 843-846.

Hrafnsdóttir T. 2005. Diptera 2 (Chironomidae). In: Gíslason G.M., Jónasson P.M., Ottósson J.G. *"The Zoology of Iceland".* Streenstrupia Zoological Museum, University of Copenhagen, 3:48b, pp. 1-169.

Hughes G. 2002. Tourism, Sustainability and Social Theory. In: Lew A.A., Hall C. M. and Williams A.M. *"A companion to Tourism*", Blackwell Publishing, pp. 498-509.

Humphreys W.F., Poole A., Eberhard S.M., Warren D. 1999. *Effects of research diving on the physio-chemical profile of Bundera Sinkhole, an anchialine rempied habitat at Cape Range, Western Australia.* Journal of the Royal Society of Western Australia, 82, pp. 99-108.

Huston M. 1979. *A General Hypothesis of Species Diversity*. American Naturalist, 113:1. pp. 81-101.

Huston M.A. 1994. *Biological diversity: the coexistence of species on changing landscapes.* Cambridge University Press, Cambridge, UK.

Íslandsstofa. 2013a. *Long-term strategy for the Icelandic tourism industry.* Íslandsstofa.

Íslandsstofa. 2013b. *Heildarúttekt á íslenskri ferðaþjónustu* - Útdráttur. Íslandsstofa.

Jónasson and Hersteinsson 2011. *A unique world evolving – Thingvallavatn – A World Heritage Site.* Opna Publishing, Reykjavík.

Jovicic D. and Dragin A. 2008. *The assessment of carrying capacity – A crucioal tool for managing tourism effects in tourist destinations.* Turizam, 12, pp. 4-11.

Jónsson G.S., Gunnarsson K., Jónasson P.M. 2011. Life on the lake bottom. In: Jónasson and Hersteinsson (eds.). *"A unique world evolving – Thingvallavatn – A World Heritage Site"* Opna Publishing, Reykjavík, pp. 163-179.

Kaplan H., Hill K., Lancaster J., Hurtado A.M. 2000. *A therory of human life history evolution: Diet, intelligence and longevity.* Evolutionary Anthropology: Issues, News, and Reviews, 9:4, pp. 156-185.

Keane 1996. *Sustaining quality in tourism destination: an economic model with an application.* Applied Economics, 28:12, pp. 1545-53.

Kiper T. 2013. *Role of Ecotourism in Sustainable Development.* In: Ozyavuz M. (ed.). "Advances in Landscape Arcitecture". InTech, pp. 773-802.

Svavarsson J. and Kristjánsson B.K. 2004. *Crymostygidae, a new family of subterranean freshwater gammaridean amphipods (Crustacea) recorded from subarctic Europe.* Journal of Natural History, 38:15, pp. 1881-1894.

Svavarsson J. and Kristjánsson B.K. 2006. *Crangonyx islandicus sp. nov., a subterranean freshwater amphipod (Crustacea, Amphipoda, Crangonyctidae) from springs in lava fields in Iceland.* Zootaxa, 1365, pp. 1-17.

Kristjánsson B.K., Skúlason S., Noakes D.L.G. 2002. *Morphological segregation of Icelandic threespine stickleback (Gasterosteus aculeatus L).* Biological Journal of the Limnean Society, 76:2, pp. 247-257.

Kornobis E. 2011. *Groundwater amphipods in Iceland: Population structure and phylogenetics*, PhD dissertation. Faculty of Science, University of Iceland, 166 pp.

Kuenzi C. and McNeely J. 2008. Nature-Based Tourism. In: Renn O., Walker K.D. *"Global Risk Governance".* International Risk Governance Council Bookseries, 1, pp. 155-178.

Lev-Yadun S., Gopher A., Abbo S. 2008. *The cradle of agriculture.* Science, 288: 5471, pp. 1602-1603.

Lewis L.A. and Berry L. 1988. The patterns of political change: relationships to the environment. In: Lewis L.A and Berry L. *"African Environments and Resources".* Routledge, pp. 71-112.

Lime D.W. and Stankey G.H. 1971. *Carrying Capacity: Maintaining outdoor recreation quality.* Forest Recreation Symposium Proceedings, pp. 174-184.

Luna B., Perez C.V., Sanchez-Lizaso J.L. 2009. *Benthic impacts of recreational divers in a Mediterranean Marine Protected area.* ICES Journal of Marine Science, 66:3, pp. 517-523.

Mairs K. A. 2007. *Islands and human impact: Under what circumstances do people put unsustainable demands on island environments? Evidence from the North Atlantic,* PhD dissertation. University of Edinburgh, pp. 398.

Malmquist H.J. and Sturlaugsson J. 2002. Urriði í Þingvallavatni. In: Jónasson P.M and Hersteinsson P. (eds.). "*Þingvallavatn – Undraheimur í mótun*." Mál og Menning, pp.197-202.

Martin P.S. 1984. Prehistoric Overkill. the Global Model. In: Martin P.S. and Klein R.G. *(eds.)."Quaternary Extinctions – A Prehistoric Revolution".* The University of Arizona Press, pp. 354-403.

Matthaei C., Uehlinger U., Meyer E., Frutiger A. 1996. *Recolonization by benthic invertebrates after experimental disturbance in a Swiss prealpine river.* Freshwater biology, 35:2, pp. 233-248.

May R.M. 1977. *Thresholds and breakpoints in ecosystems with a multiplicity of stable states.* Nature, 269:5628, pp. 471-477.

McDowell P.F., Webb III T., Bartlein P.J. 1990. *Long-Term Environmental Change. In: The Earth as Transformed by Human Action: Global and Regional Changes in the Biosphere Over the Last 300 Years.* Cambridge University Press.

Medio D., Ormond R. F. G. & Pearson M. 1997. *Effect of briefings on rates of damage to corals by SCUBA divers.* Biological Conservation, 79:1, pp. 91-95.

MICROSOFT EXCEL for Mac. 2011. Microsoft Corporation.

Milazzo M., Chemello R., Badalamenti F., Camarda R., Riggio S. 2002. *The impact of Human Recreational Activities in Marine Protected Areas: What Lessons Should Be Learnt in the Mediterranean Sea?* Marine Ecology 23:1, pp 280-290.

Monasterasky R. 2015. *Anthropocene: The human age.* Nature, 519, pp. 144-147.

Murrin J.M. 1997. Beneficiaries of Catastrophe: The English Colonies in America. In: Foner E. (ed.). "*The New American History*". Temple University Press, pp. 3-30.

Musa G., Tong S.W., Thinaranjeney T., Masoud A. 2010. *The influence of scuba divers´personality, experience and demographic profile on their underwater behavior.* Tourism in Marine Environments, 7:1, pp. 1-14.

Newsome D., Moore S.A., Dowling R.K. 2012. *Natural Area Tourism: Ecology, Impacts and Management.* Channel View Publications.

Nyaupane G.P. Morais D.B., Graefe A.R. 2004. *Nature Tourism Constraints: A Cross-Activity Comparison.* Annals of Tourism Research, 31:3, pp. 540-555.

Óladóttir Þ.O. 2014. *Ferðaþjónusta á Íslandi í tölum – Apríl 2014*. Ferðamálastofa.

Ólafsdóttir J.H. *Biological Diversity in Icelandic Groundwater Fissures.* M.Sc. thesis in prep.

Ólafsdóttir J. 2010. *Köfun á Íslandi – Öryggi og umgjörð,* B.Sc. thesis, Faculty of Life and Environmental Sciences, the University of Iceland, pp. 47.

Pickett S. T. A. and P. S. White P. S. 1985. Natural Disturbance and Patch Dynamics: An Introduction. In: Pickett S.T.A and White P.S. (eds.). "*The Ecology of Natural Disturbance and Patch Dynamics.*" Academic Press, pp. 3-13.

Resh V.H., Brown A.V., Covich A.P., Gurtz M.E., Li H.W., Minshall W., Reice S.R., Sheldon A.L., Wallace B., Wissmar R.C. 1988. *The Role of Disturbance in Stream Ecology.* Journal of the North American Benthological Society, 7:4, pp. 433-455.

Riegl B. and Velimirov B. 1991. *How many damaged corals in Red Sea reef systems? A quantitative questionnaire.* Hydrobiologia, 216:217, pp. 249–256.

Richmond R.H. 1993. *Coral Reefs: Present Problems and Future Concerns Resulting from Anthropogenic Disturbance.* American Zoologist, 33:6, pp. 524-536.

Rouphael A.B. and Inglis G.J. 2001. *"Take only photographs and leave only footprints"?: An experimental study of the impacts of underwater photographers on coral reef dive sites.* Biological Conservation, 100:3, pp. 281-287.

Rouphael T. and Inglis G. 1995. *The effects of qualified recreational scuba divers on coral reefs.* CRC Reef Research Centre Ltd. Technical Report No. 4., pp. 39.

RSTUDIO for Mac. Version 0.98.1103. Rstudio.

Rykiel JR. E.J. 1985. *Towards a definition of ecological disturbance.* Australian Journal of Ecology, 10:3, pp. 361-365.

Sander B. 2010. *The importance of education in ecotourism ventures: lessons from Rara Avis ecolodge, Costa Rica.* International Journal of Sustainable Society, 4:4, pp. 389 – 404.

Sandlund O.T., Jonsson B., Malmquist H.J., Gydemo R., Lindem T., Skúlason S., Snorrason S.S., Jónasson P.M. 1987. *Habitat use of arctic charr Salvelinus alpinus in Thingvallavatn, Iceland.* Evironmental Biology of Fishes, 20:4, pp. 263-274.

Sandlund O.T., Gunnarsson K., Jónasson P.M., Jonsson B., Lindem T., Magnússon K.P., Malmquist H.J., Sigurjónsdóttir H., Skúlason S., Snorrason S.S. 1992. *The arctic charr Salvelinus alpinus in Thingvallavatn.* Oikos, 64:½, pp. 305-251.

Sandom C., Faurby S., Sandel B., Svenning J.C. 2014. *Global late Quaternary megafauna extinctions linked to humans, not climate change.* Procedings of the Royal Society B, 281.

Sarukhán J., Whyte A. 2005. *Millennium Ecosystem Assessment - Ecosystems and Human Well-Being – Biodiversity Synthesis.* World Resources Institute, Washington, DC.

Schaeffer T.M. and Foster M.S.1998. *Diver disturbance in kelp forests. Research technical report.* Montery Bay National Marine Sanctuary.

Schallenberg M. and Burns C.W. 2004. *Effects of sediment resuspension on phytoplankton production: teasing apart the influences of light, nutrients and algal entrainment.* Freshwater biology, 49:2, pp. 143-159.

Shiklomanov I.A. 1993. *World Fresh Water Resources.* In: Peter H. Gleick (ed.). "*Water in Crises – A Guide to the World´s Fresh Water Resources".* Oxford University press, pp. 13-24.

Sigurjónsdóttir J.K. 2015. *Silfra í Þjóðgarðinum á Þingvöllum: Stjórnun takmarkaðrar auðlindar,* B.Sc. thesis. Landbúnaðarháskóli Íslands. Umhverfisdeild, pp. 45.

Sjoberg G. 1965. *The Origin and Evolution of Cities.* Scientific American, 213:3, pp. 54-63.

Sousa W.P. 1984. *The Role of Disturbance in Natural Communities*. Annual Review of Ecology and Systematics, 15, pp. 353-391.

Springer A.E. and Stevens L.E. 2008. *Spheres of discharge of springs.* Hydrogeology Journal, 17:1, pp. 83-93.

Sun D. and Walsh D. 1998. *Review of studies on environmental impacts and recreation in Australia.* Journal of Environmental Management, 53:4, pp. 323-38.

Sunlu U. 2003. Environmental impacts of tourism. In: Camarda D. and Grassini L. (eds.). *"Local resources and global trades: Environments and agriculture in the Mediterranean region".* CIHEAM, pp. 263-270.

Sæmundsson K. 2002. Jarðfræði Þingvallavatns og vatnasviðs þess. In: Jónasson P.M. and Hersteinsson P. (eds.). *"Þingvallavatn – Undraheimur í mótun".* Mál og Menning, pp. 40-63.

Sæþórsdóttir A.D. 2015. *Þolmörk ferðamanna á átta vinsælum ferðamannastöðum á Suður- og Vesturlandi sumarið 2014.* Ferðamálastofa.

Søndergaard M. and Riemann B. 1979. *Ferskvandsbiologiske analysemetoder.* Akademisk Forlag, pp. 227.

Teresa F.B., Romero R.M., Casatti L., Sabino J. 2011. *Fish as Indicators of Disturbance in Streams Used for snorkeling Activities in a Tourist Region.* Environmental Management 47:5, pp. 960-968.

Towner J. 1995. *What is tourism´s history?.* Tourism Management. 16:5, pp. 339-343.

Tratalos J.A. and Austin T.J. 2001. *Impacts of recreational SCUBA diving on coral communities of the Caribbean island of Grand Cayman.* Biological Conservation, 102:1, pp. 67-75.

UNWTO 2005. *Making tourism more sustainable – A guide for policy makers*. United Nations Environment Programme and World Tourism Organization.

UNWTO. 2015. *Tourism highlights 2015 Edition*. World Tourism Organization.

Uyarra and Côté. 2007. *The quest for cryptic creatures: Impacts of species-focused recreational diving on corals.* Biological Consevation, 136:1, pp.77-84.

Vitousek P.M., Mooney H.A., Lubchenco J., Melillo J.M. 1997. *Human Domination of Earth´s Ecosystems.* Science New Series, 277:5325, pp. 494-499.

Walker L.R. 2012. *The Biology of Disturbed Habitats*. Oxford University Press.

Walker L.R. and Willig M.R. 1999. An Introduction to Terrestrial Disturbances. In: Walker L.R. (ed.). *Ecosystems of Disturbed Ground.* ELSEVIER, pp. 1-5.

Walters R.D.M and Samways M.J. 2001. *Sustainable dive ecotourism on a South African coral reef.* Biodiversity and Conservation, 10:12, pp. 2167-2179.

Whisenant, S.G. 1999. *Repairing Damaged Wildlands: A process oriented, landscape-scale approach*. Cambridge University Press, Cambridge.

White P.S. 1979. *Pattern process and natural disturbance in vegetation*. The Botanical Reciew, 45:3, pp. 230-281.

White P.S. and Jentsch A. 2001. *The Search for Generality in Studies of Disturbance and Ecosystem Dynamics.* Progress in Botany, 62, pp. 399-450.

Wong P.P. 2004. Environmental Impacts of Tourism. In: Lew A.A., Hall C. M. and Williams A.M. (eds.). *"A companion to Tourism".* Blackwell Publishing, pp.450-461.

Wood M.E. 2002. *Ecotourism: Principles, Practices and Policies for Sustainability*. UNEP and The International Ecotourism Society.

WTTC. 2014. *Travel and Tourism Economic Impact.* World Travel and Tourism Council.

Þorbjörnsson J.G. 2013. *Comparison of two methods for sampling invertebrates on submerged vertical walls with diving*, B.Sc. thesis, Faculty of Life and Environmental Sciences, University of Iceland, pp. 26.

Zeder M. A. 2008. *Domestication and early agriculture in the Mediterranean Basin: Origins, diffusion, and impact.* PNAS, 105:33, pp. 11597-11604.

6.1. Other references:

Diveadvisor. [No year]. *6 dive sites to add to your scuba bucket list.* Retrieved 3. September 2015 at: http://diveadvisor.com/sub2o/6-dive-sites-to-add-to-your-scuba-bucket-list

Hood C. 2005. *Silfra – A dive between two continents*. Dive magazine. Syon publishing. Retrieved 3. September 2015 at: http://divemagazine.co.uk/go/2323-silfra-a-dive-between-two-continents

Mike. 2015. *World class dive sites – Silfra*. Divecompare. Retrieved 3. September 2015 at: https://www.divecompare.com/blog/world-class-dive-sites-silfra/

Sulit M. 2014. *8 cold water diving destinations*. Dive magazine. Syon publishing. Retrieved 3. September 2015 at: http://divemagazine.co.uk/go/6881-8-cold-water-diving-destinations

Stjórnartíðindi. 2013a. *Reglur um köfun í þjóðgarðinum á Þingvöllum (yfirborðs- og djúpköfun)*. Ministry of the Interior. Retrieved the 8. September 2015 from: http://www.stjornartidindi.is/Advert.aspx?ID=059300b6-d2b5-471d-a56a-9cbb761f331e

Stjórnartíðindi. 2013b. *Fyrirmæli vegna köfunar og yfirborðsköfunar í þjóðgarðinum á Þingvöllum.* Ministry of the Interior. Retrieved the 8. September 2015 from: http://www.stjornartidindi.is/Advert.aspx?ID=7eacc727-21a1-4bae-8971-ef794d6ad0e6

Time magazine. 2005. *Jurney to the center of the earth.* 2005. Vol 166:1.

UNESCO. 1994-2014. *United Nations UNESCO Worlds Heritage Center*. Retrieved the 12. November 2014 from http://whc.unesco.org/en/list/1152.