Riparian vegetation responses to hydropeaking

Experimental study on germination and performance of plants along rivers regulated by hydropower dams in northern Sweden

Emelie Fredriksson
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Abstract
Riparian vegetation is one of the most complex and abundant ecosystems in the world and it provides important ecosystem services. These services are affected by electricity production from hydropower dams. Hydropower accounts for 16% of the global electricity production and almost 50% in Sweden. One effect of hydropower is sub-daily fluctuations of water level caused by the turbines being turned on and off according to electricity demand. This is referred to as hydropeaking and has largely unknown effects on the fluvial ecosystem, and especially on the riparian vegetation. No studies have been made on the effects of hydropeaking on riparian vegetation. In this study, three native plants (Carex acuta, Betula pubescens and Salix phylicifolia x myrsinifolia) and one non-native plant (Helianthus annuus) were used as indicators (i.e., phytometers) for the effects of hydropeaking along two rivers from northern Sweden; one used for hydropower production and the other free flowing. From each of the four species, seedlings of two sizes and seeds were transplanted into five different river reaches and bank elevations along a hydropeaking gradient from none to high hydropeaking intensity. C. acuta and S. phylicifolia x myrsinifolia showed significant positive relationships to the hydropeaking gradient, likely due to their natural high tolerance to frequent inundation events. Therefore, they are suitable for restoration of river shores along reaches affected by hydropeaking. In contrast, B. pubescens was negatively related to the hydropeaking gradient, losing leaves and biomass with increasing hydropeaking intensities. It turned out to be the most sensitive species among the ones used in the experiment making it suitable as an indicator. H. annuus showed no response and therefore did not serve as impact indicator or for restoration. Germination for all native species was significantly lower along the reaches affected by hydropeaking which indicates a strong connection between hydropeaking and germination. These findings showed that recruitment becomes a bottleneck in riparian communities’ conservation along rivers affected by hydropeaking, and highlight the importance of mitigation actions focused on favoring riparian species seeds’ germination.

Keywords: Hydropeaking, riparian vegetation, germination, survival, performance, phytometer, restoration, mitigation
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1 Introduction

1.1 Hydropower production
Hydropower is seen as a clean renewable energy source with few carbon emissions on a global scale, and is still one of the major renewable energy sources worldwide. In 2007 about 16% of the total electricity production in the world came from hydropower (Bieri 2012). Globally, about two thirds of all freshwater systems with flowing water are used for hydropower production purposes (Jansson et al. 2000). On a local scale, hydropower plants cause large impacts on the fluvial hydrology and ecosystems. The exploitation of a river with hydropower dams implies multiple positive social changes, but a hydropower dam is a transversal barrier which traps sediments and modifies flows impacting habitats along the river downstream and in surrounding wetlands (Renöfält et al. 2010). Reservoirs are seldom operated sustainably; i.e. meeting the needs of society for power production, flood protection and water usage, and at the same time preserving the health of the river ecosystem in the long term (Jager and Smith 2008).

In Sweden, almost all large rivers are heavily modified for hydropower production purposes (except the Lule, Kalix, Torne, Pite and Vindeln Rivers), and hydropower accounts for almost half of the annual electricity production in Sweden (Renöfält et al. 2010). When the dams were built around the 1960s, little or no consideration of the ecological effects they might cause was taken. Most rivers in Sweden consist of a series of storage reservoirs in the mountain areas to the west with run-of-river impoundments towards the coastal areas to the east. Storage reservoirs are used to change the natural flow regime (of lowest flow in late summer and highest in spring) to the opposite, to be able to fit the higher energy demand during the cold winter months, using a large water storage capacity. Run-of-river impoundments are used to meet the short-term energy demand that varies over weeks and days, and usually lack large water-storage capacity (Pérez-Díaz and Wilhelmi 2010).

A hydropower dam affects the ecology of the river (Nilsson et al. 1991; Vehanen et al. 2005; Jager and Smith 2008; Renöfält et al. 2010; Bieri 2012). Generally, the biota suffers from disrupted migration and dispersal pathways, changed physical environment with new prerequisites, exotic species invasion (Renöfält et al. 2010), decreases in biomass and species richness (i.e., benthic invertebrates [Garcia de Jalon et al. 1994; Robertson et al. 2004; Bieri 2012]; fish [Robertson et al. 2004; Vehanen et al. 2005], and plants [Jansson et al. 2000]), and interruption of ecologically essential geomorphological processes (Jager and Smith 2008). These changes especially affect the riverine plant and animal community given their dependency on river hydrology (Jansson et al. 2000). Since the corridor function of rivers with hydropower dams installed is severely reduced, different methods of dispersal between species will likely either be favored or unfavored. In a study of eight different rivers in Sweden, Jansson et al. (2000) found that plant species richness and cover were lower in regulated rivers than in naturally flowing rivers.

1.2 Riparian vegetation
The riparian vegetation belt can be defined as the zone between the aquatic vegetation which is always inundated and the forest vegetation that is never inundated. The plants and animals in
the riparian zone are therefore adapted to endure and take advantage of periods of temporary inundation (Jansson et al. 2000). Healthy riparian vegetation provides many ecosystem services such as water supply, pollution reduction, habitat provisioning, or flood attenuation, among others (Jager and Smith 2008). Also from a conservationist perspective, riparian areas are valuable as they are among the most diverse and species rich ecosystems in the world. The deposition and removal of sediment, seeds and debris at flooding events creates a heterogenic and complex zonation of plants along the flooding gradient with different taxa adapted to different levels of inundation (Jansson et al. 2000). Floods favor seed and plant fragment dispersal, and create or remove habitats for their establishment. When and how long water is available is also essential for plant development and survival, and plant life cycles are synchronized to hydrological events. Since the riparian zone is shaped by the flow regime (i.e., magnitude, frequency, timing, duration, and rate of change of flows; Poff et al. 1997), a dam of any sort causes drastic changes to stream flows (added to the physical environment alterations), which have effects, most of them still unknown, on the plant and animal community.

1.3 Hydropeaking
The run-of-the-river power plants associated to storage reservoirs modulate the release of water through the turbines, which cause rapid and unnatural sub-daily flow and water-level fluctuations. These, often unpredictable flow and water-level changes (i.e. hydropeaking), modify the physical and chemical conditions of the river (Robertson et al. 2004), result in abrupt temperature changes (Carolli et al. 2012) as well as seepage erosion failures in the river banks and bars (Alvarez and Schmeeckle 2012). Bieri (2012) defined hydropeaking as “the sudden opening and closing of water releasing structures, i.e., turbines, which produces highly unsteady flow conditions in the river downstream of the power house outlet”. Natural short-term variations in flow (e.g., daily or sub-daily) are ultimately caused by variations in rates of precipitation, evapotranspiration, infiltration, and snowmelt which, together with watershed characteristics such as drainage area, slope and land uses, regulate daily and sub-daily water additions or losses (Lundquist and Cayan 2002; Archer and Newson 2002). Rivers subjected to hydropeaking usually show daily and sub-daily flow variations significantly higher than the ones that characterize free-flowing rivers, which can often be on the order of 10% of the mean daily flow (Lundquist and Cayan 2002; Schuster et al. 2008). Consequently, it is the assessment of short-term changes in river flow that is important for understanding the effects of hydropower generation dams through hydropeaking on riparian and aquatic species and communities.

The negative effects that dams have on ecosystems are relatively well studied (see section 1.1), but studies on the effects of hydropeaking are rare. Hydropeaking is included in many studies but not sorted out as an individual parameter. Focusing only on the effects of hydropeaking on the ecosystem, Bieri (2012) showed decreases in biomass and species richness of fish. No studies have been made specifically on how the riparian vegetation is affected by hydropeaking. A literature review by Bejarano et al. (2016) states that hydropeaking may have the following effects on riparian vegetation: fragmentation, native vegetation decline, shifts in species composition, and failure of recruitment processes that maintain the riparian populations.
1.3 Mitigation
The most generalized mitigation measure of hydropeaking impacts has been to rehabilitate the physical environment of the affected river stretch, while neglecting flow-regime related solutions (Van Looy et al. 2006). However, nowadays, the influence of flow management to uphold ecological health is becoming valued in the operation of reservoirs (Jager and Smith 2008). The most common flow-related mitigation effort to reduce the negative effects on the riverine ecosystem is a minimum flow-release constraint. This minimum is most often set as a lowest flow that still maintains downstream fish population (Jager and Smith 2008) and does not consider other riverine factors or taxa. Therefore, this is often not enough for maintaining ecological processes, which also depend on other components of the flow regime (Poff et al. 1997). A flow regime consisting of channel-shaping flows and not just of a constant optimal flow is recognized as the best guarantee of healthy fluvial ecosystems. In the Brisbane Declaration (2007) it is stated that: “Environmental flows describe the quantity, quality and timing of water flows required to sustain fresh-water and estuarine ecosystem and the human livelihoods and well-being that depend on these ecosystems”. Consequently, environmental flows (and not a bare minimum) should be considered when operating hydropower facilities. For example, Garcia de Jalon et al. (1994) suggested that mitigation effort to reduce the negative effects of hydropeaking in fish communities in Spain should include a minimum flow that is ecologically acceptable together with flow regimes similar to natural patterns.

In Sweden, the Swedish Environmental Code dictates that a minimum of 5% and maximum of 20% of the annual production value of a hydropower plant is set aside without compensation to minimum flow or other actions of ecological value. To know what actions actually have ecological value, experimental studies need to be done, as, sadly, these studies are largely lacking. Without this knowledge, the power companies have no incentive to decrease or adapt their power production for environmental reasons (Renöfält et al. 2010).

1.4 Climate change
A combination of global warming and other anthropogenic activities will directly affect the power production from freshwater systems all over the world. Already in a moderate climate-change scenario, severe changes in discharge with regional differences are expected. The general trends are towards a reduction of hydropower production potential by 25% in southern Europe (Lehnera et al. 2005), while in northern countries (such as Sweden), the gross power production capacity is expected to increase with the predicted increase in runoff and a flow regime that better suits the electricity demand (Renöfält et al. 2010). This change in flow regime also decreases the need for large storage reservoirs, creates opportunities for a higher release of water in reaches with low flows, and enables the allocation of more water to by-pass channels to open migrations pathways. But with an increasing human population size, the demand for energy, especially renewable energy, will likely increase when fossil energy sources are being faced out. Combinations of other renewable energy sources are necessary as complement to the hydropower production since building of new dams have a strong opposition in Sweden.

1.5 Aim
Many freshwater systems are affected by hydropower production worldwide. To guarantee that these ecosystems remain as natural as possible while continuing anthropogenic activities such as
hydropower production, it is essential to understand the processes underlying biological responses to hydropeaking and to identify the ecological thresholds above which the ecological impacts are irreversible. The main goal of this project is to investigate the responses of riparian vegetation to hydropeaking in order to propose management guidelines and restoration/mitigation measures which maximize ecological status and hydropower production. Specific questions addressed are: a) Is it possible to identify a threshold of hydropeaking intensity at which germination, performance, and survival of riparian species are irreversibly affected? b) Is germination, performance, and survival differently affected by hydropeaking depending on the plant species? c) Is any of the studied species an appropriate indicator (i.e., phytometers) of hydropeaking impact and/or useful in future restoration of sites affected by hydropeaking?

2 Method

2.1 Study area

The experiment was carried out along the Ume and Vindel Rivers within the Ume River Basin. The basin comprises 13776 km² + 12654 km² above their junction (Nilsson et al. 1991) and is located in the boreal zone, with a cold-temperate climate, in northern Sweden. The Ume River is strongly developed for hydroelectric power, whereas its main tributary, the Vindel River, is a free-flowing river, except for the last 10 km which are affected by a large reservoir located just downstream from the Ume-Vindel junction. Stream flows are naturally affected by ice during winter and snowmelt during spring, resulting in marked flow seasonality in the Vindel River. However, in the Ume River flows are annually stable but highly fluctuating at a day-scale as a result of the operation rules at hydropower plants. Nilsson et al. (1991) inventoried and described the Vindel River to have a distinctly zoned river margin of an herbaceous community closest to the water level, followed by shrub vegetation, and finally a forest community above the highest water line. Species on an average river bank are Carex juncella, Salix lapponum, Calluna vulgaris and Pinus sylverstris. Since the Ume River has had most of its former river margins moved during the hydroelectric development between 1951 and 1967 many areas do not show original riparian vegetation. The new river banks along the Ume River are described by Nilsson et al. (1991) as a thin line of vegetation without clear dominants near the highest water level. The species composition from top to bottom is Subularia aquatica, Sparganium spp., and Ranunculus reputans. Both rivers are about the same length and equally large, and historical documentation indicates that, previously to the regulation of the Ume River, riparian zone characteristics in terms of species composition and vegetation zonation were very similar to those described for the Vindel River (Nilsson et al. 1991). The experimental reaches along the Ume River were located upstream of the dam along the shores of the Harrsele, Bjurfors Övre, and Bålforsen reservoir lakes, and just downstream of the Tuggen dam. The experimental reach along the Vindel River was located upstream from the Vindeln village close to the Granåker gauging station (Figure 1).
Figure 1: Map of reaches along the Ume (regulated) and Vindel (free flowing) Rivers. Along the Ume River (to the left) the reaches from upstream to downstream are Bålforsen, Tuggen, Bjurfors Övre, and Harrsele. Along the Vindel River (to the right) is located the reach named Granåker.
2.2 Experimental design
During the summer of 2016, seeds and seedlings from selected riparian species were sown and transplanted in the five river reaches along three to five bank levels, representing a wide range of hydropoaking intensity. Four reaches characterized by low, medium, and high hydropoaking intensities were located in the Ume River, whereas one free-flowing reach was located in the Vindel River. Hydropoaking intensity of the reaches was based on a statistical comparative analysis of several hydrological metrics, calculated on hourly-flow series from the Ume and Vindel Rivers, assigned by Bejarano et al. (2016). Two to three planting sites per reach were selected, and seeds and seedlings were distributed within the sites along lines, which were parallel to the water edge and at different bank levels. Planting sites were 6 m wide but had variable depth according to the most frequently flooded area (i.e., minimum and maximum water levels), which was visually determined by the amplitude of the hydropoaking in the Ume River and by the winter minimum flows and spring floods in the Vindel River (Figure 2). There were up to five planting levels in the deepest sites and three in the shortest sites to assure enough separation between plants. The elevation of the planting lines was measured with a clinometer and a measuring rod to ensure similar elevation of lines among sites and between plants along the same line.

![Diagram of planting levels](image)

Figure 2: A plan view of a riparian planting site (two or three sites per reach).

A gradient of hydrological variables characterizing stream-flow fluctuation, such as inundation frequency and duration, was assumed to be associated to the planting levels, from frequent and long inundation events at the lowest level to virtually no inundation events at the highest. At the time of planting, one pressure logger (Rugged BaroTROLL 100 Data Logger, Amsele), which
recorded water level every 15 minutes, was installed at each site and was removed at the end of the experiment (dates are detailed in the following paragraph). The data from the pressure loggers were used to characterize the inundation events suffered by experimental plants growing along the banks. Additionally, selected river reaches are expected to reflect the dam operations which in turn affect bank inundation durations and frequencies (Bejarano et al. 2016). Pressure loggers are expected to show a gradient in the bank inundation characteristics from Harrsele (the highest hydropeaking intensity) to Granåker (the free flowing river, i.e. no hydropeaking).

*Carex acuta* (Ca), *Salix phylicifolia x myrsinifolia* (Spxm), *Betula pubescens* (Bp), and *Helianthus annus* (Ha) were selected for experiments. They represent dominant herbaceous or woody life forms on the river-bank elevation gradient: low-water level is represented by Ca, mid-water level by Spxm, and high-water level by Bp. As a generalist, and reported as a good plant indicator (i.e., phytometer; Dietrich et al., 2015), Ha was also included. To trigger germination, the seeds of Ca, Bp, and Ha were cold stratified during eight weeks. One portion of the seeds was sown in cassettes (i.e., two seeds in each cassette-pot) in a greenhouse (April 9 2015), whereas the remaining seeds were sown two months later (June 1 2015). The former seedlings were named “high” and the latter “small”. The purpose of the two sizes was to further examine if the effects hydropeaking affected younger seedlings differently from older and possible more resilient seedlings. When both seeds in the same cassette-pot germinated, the smallest was removed at an early stage. Before transplanting to the field sites the plants were slowly adjusted to outside conditions. Number of seedling individuals was determined by their availability (Table 1). Four 30-cm in-situ cuttings from Spxm were also transplanted to each level at each site. Replicates in a reach were the sum of the seedlings or cuttings planted at all sites within the same reach (Table 1). Transplantations were from June 28 2015 to July 5 2015 in the Ume River and from July 13 2015 to July 22 2015 in the Vindel River. Alive individuals from all species except for Spxm were harvested from August 23 2015 to August 25 2015 in the Ume River and on August 27 2015 in the Vindel River.

<table>
<thead>
<tr>
<th>Name of reach</th>
<th>Site (#)/Reach</th>
<th>Levels (#)/Site</th>
<th>Seedlings (#)/Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granåker</td>
<td>2</td>
<td>4</td>
<td>4 Cas, 2 Cah, 6 Bps, 6 Bph, 4 Has, 2 Hah, 4 Spxm</td>
</tr>
<tr>
<td>Bålforsen</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Bjurfors Övre</td>
<td>2</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Harrsele</td>
<td>3</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Tuggen</td>
<td>2</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

In addition to the seedlings, 15 Ca, Bp, and Ha, seeds were placed on each planting level under a 10x10cm fabric that was secured to the ground using six nails to avoid erosion (Figure 3).
2.3 Measured variables
Before allocation to the field sites, the number of leaves and the stem length of all seedlings were measured in the greenhouse. For *Ca* seedlings, which have no clear main stem but a bunch of leaves, the length of the longest leaf was measured instead. Additionally, for 20 representative replicates of each species and size (i.e., high and small); stem (leaf for *Ca*) and root length (only for small seedlings), and number of leaves were recorded and then dried at 60 °C to a stable weight. The biomass of stems, leaves, and roots was weighed in grams with an accuracy of at least two decimals. At each site, the original vegetation with roots was removed before planting. Twice during the growing season (i.e., after ~25 days and after ~50 days) the growth (i.e., number of leaves, stem length, and presence of new buds) and health status (i.e., color, softness and survival) of the seedlings and cuttings, and germination success of the seeds were recorded. In the laboratory, the soil was removed from the roots and the root length was measured. Afterwards, the seedlings were divided into stem, leaves and root, and the samples were dried in an oven at 60 °C to a stable weight. Then, they were weighed in grams using a scale with four-decimal precision for the small seedlings and a scale with two-decimal precision for the large seedlings.

2.4 Data analysis
Data analysis was performed in R (R Development Core Team 2011) except for the analysis of binomial data (germination, removal, and survival), which was performed in IBM SPSS 20 (Chicago SPSS, Inc.). I tested whether the change in numbers, length, and/or biomass of leaves, stem, and roots, along with resistance to erosion, survival and germinability for each plant individual was the result of the differing types and intensities of hydropeaking at each level and reach, and also whether there were differences among species and sizes. For this aim, and for response variables, group comparisons were carried out by using two-way ANOVA and Tukey HSD (parametric) when data were normally distributed, and Kruskal Wallis and Dunn’s test (non-parametric) when data were not. For binomial response variables, Chi-square test and contingency tables were done on their frequencies. Statistical analyses were done on the differences between the initial (i.e., before transplanting) and final (i.e., at or just after harvest) values for all biological continuous response variables. When there were no measurements for
each plant individual before transplanting to the field (i.e., the root measurements and below-and above-ground biomass), the initial value was either the mean of 20 samples from each species and size, or an estimation for each plant individual based on the measured biological variables, and by using equations derived from regressions on the 20 samples. Estimated initial values per plant individual were used when $R^2$ values were higher than 0.4, whereas mean values per species and size were selected when regressions showed $R^2$ values smaller than 0.4. Box and whisker plots were used to show results on continuous response variables while bar plots were used for the binomial response variables.

3 Results

3.1 Betula pubescens

Stem and root length, and stem and leaf biomass of $Bp$ small ($Bps$) seedlings were positively related to hydropeaking intensity along the intermediate bank elevations (levels 2 and 3; Table 2), showing a decreasing trend from the free-flowing reach (i.e. Granåker) to the highly regulated reaches (i.e. Harrsele and Tuggen) (Figure 4).

Table 2: Results from ANOVA for $Bps$ seedling variables showing significant differences among reaches at levels 3.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stem length</td>
<td>0.144</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Stem biomass</td>
<td>0.100</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Leaf biomass</td>
<td>0.059</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Root length</td>
<td>0.017</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Number of leaves</td>
<td>0.137</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

In general, along intermediate levels, stem, leaf, and root growth was observed (i.e., final values were higher than initial values) in plants located at the less impacted reaches, while no significant growth was found in plants along the most impacted reaches (Figure 4). There were no significant differences for these variables among reaches along the lowest and highest levels ($p > 0.05$). Along the lowest levels, for all reaches, stem length and biomass, leaf biomass, and root did not change regardless of differences hydropeaking intensity. No change was seen along the highest level for leaf biomass and root length, while increases in stem length and biomass were seen in all reaches. All plant individuals lost leaves during the season regardless of reach or their location in the riparian zone. A soft gradient of variable responses to hydropeaking intensity in the study reaches is seen in the figures; no mark thresholds can be drawn between reaches but a clear negative relationship between measured biological variable and hydropeaking intensity between reaches can be seen at the intermediate bank levels (2 and 3). This relationship cannot be found at the highest bank level (Figure 4).

Riparian vegetation is one of the most complex and abundant ecosystems in the world and it provides important ecosystem services. These services are affected by electricity production from hydropower dams. Hydropower accounts for 16% of the global electricity production and almost 50% in Sweden. One effect of hydropower is sub-daily fluctuations of water level caused by the turbines being turned on and off according to electricity demand. This is referred to as

3.1 Betula pubescens
hydropeaking and has largely unknown effects on the fluvial ecosystem, and especially on the riparian vegetation. No studies have been made on the effects of hydropeaking on riparian vegetation. In this study, three native plants (Carex acuta, Betula pubescens and Salix phylicifolia x myrsinifolia) and one non-native plant (Helianthus annuus) were used as indicators (i.e., phytometers) for the effects of hydropeaking along two rivers from northern Sweden; one used for hydropower production and the other free flowing. From each of the four species, seedlings of two sizes and seeds were transplanted into five different river reaches and bank elevations along a hydropeaking gradient from none to high hydropeaking intensity. C. acuta and S. phylicifolia x myrsinifolia showed significant positive relationships to the hydropeaking gradient, likely due to their natural high tolerance to frequent inundation events. Therefore, they are suitable for restoration of river shores along reaches affected by hydropeaking. In contrast, B. pubescens was negatively related to the hydropeaking gradient, losing leaves and biomass with increasing hydropeaking intensities. It turned out to be the most sensitive species among the ones used in the experiment making it suitable as an indicator. H. annuus showed no response and therefore did not serve as impact indicator or for restoration. Germination for all native species was significantly lower along the reaches affected by hydropeaking which indicates a strong connection between hydropeaking and germination. These findings showed that recruitment becomes a bottleneck in riparian communities' conservation along rivers affected by hydropeaking, and highlight the importance of mitigation actions focused on favoring riparian species seeds' germination.
Figure 4: Boxplots showing the change (g or cm) in four variables measured for Bps seedlings in the five reaches. Boxes consist of the 75 (upper line) and 25 (lower line) quartiles and the median (thick black line). The whiskers indicate the minimum and maximum values while the dots are outliers. Red line points out no change.

The between-level comparisons showed significant differences for all measured biological variables ($p < 0.05$), which increased with increasing bank elevation. There was no detectable change in length and biomass of stems and roots for plants growing at the lowest levels independent of reach, but with higher bank elevation positive responses of growth occurred. A threshold between the first and the second level was visually identified for all cases regardless of the reach (Figure 5).
Contrary to Bps seedlings, the stem length and biomass for high seedlings (Bph) did not show clear responses to hydropeaking intensities, among reaches or bank elevations (p > 0.05). However, number of leaves (p < 0.001), and leaf (p < 0.001) and root biomass (p < 0.001) differed significantly among reaches when comparing seedlings that grew up to level 3. In general, the number of leaves for Bph decreased at all levels and was significantly lower at the
lowest level compared to the other three (p = 0.009). *Bph* invested on root tissues, especially along less impacted reaches. Remaining biological variables measured did not show significant differences among levels (p > 0.05).

Mortality of *Bps* was significantly different among reaches and bank levels along regulated reaches (χ² = 55.23; CC¹ = 0.416; p < 0.001). Mortality was the highest in Tuggen, especially along the lowest bank levels, and almost negligible in Granåker (Figure 6a). Differences between reaches and levels were not significant for the high seedlings (data not shown). For both sizes, mortality also increased at the end of the season (Figure 6b).

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1 Contingency coefficient
Number of removed *Bps* was significantly higher along the most impacted reaches such as Harrsele, Tuggen, and B. Övre (Figure 6c), and within reaches, removal was higher along the lowest levels ($\chi^2 = 32.78; \text{CC} = 0.33; p < 0.001; \text{Figure 6d}$). No significant differences were found for the high seedlings. There were no removed plants along the free-flowing reach. Regardless of level, I found high mortality and plant removal along B. Övre (Figure 6c). Hence, independent on intensity, hydropeaking severely reduced the germination of *Bp*; less than 50% of the seeds germinated in the reaches affected by hydropeaking and germination occurred only along the two highest levels. In contrast, germination in the free-flowing reach was above 90% at all levels except for the uppermost level.

### 3.2 *Carex acuta*

In general, and opposite to *Bp*, leaf and root growth of *Ca* small (*Cas*) seedlings were positively related to hydropeaking intensity, though results were not statistically significant. There was a tendency for *Cas* seedlings to increase their length and biomass as intensity of hydropeaking increased at all reaches, and this became clearer the higher up the seedlings were located in the riparian zone (Figure 7) even though the results were not significant.

Except for number of leaves ($p < 0.001$), differences in leaf length and leaf and root biomass was not statistically different among reaches for *Ca* high (*Cah*) seedlings ($p > 0.05$). Number of leaves was lower at all reaches at the end of the season, but seedlings growing at the less impacted reaches (i.e., Granäker and Bälfsen) showed significantly fewer number of leaves than the ones growing at more impacted reaches at all levels except for the lowest level. Leaf length decreased in the same manner across all reaches and levels, while leaf and root biomass remained the same or slightly increased, respectively, for all reaches and levels.
Figure 7: Boxplots showing the change in leaf length and biomass of Cas seedlings at the different reaches. Boxes consist of the 75 (upper line) and 25 (lower line) quartiles and the median (thick black line). The whiskers indicate the minimum and maximum values while the dots are outliers. Red line points out no change.

Cas seedlings from level 1 at all reaches clearly showed significantly fewer and shorter leaves, shorter roots, and lower leaf and root biomass than those growing at higher levels (all p < 0.05). However, the high seedlings did not show significant trends for these variables at any level (all p > 0.05) (Figure 8).
Figure 8: Boxplots showing the change (cm, g or #) in three different variables for both Cas and Cah per level. Boxes consist of the 75 (upper line) and 25 (lower line) quartiles and the median (thick black line). The whiskers indicate the minimum and maximum values while the dots are outliers. Red line points out no change.

The frequencies of removed and alive Ca seedlings were not significantly different among levels or reaches, for small or high seedlings (p > 0.05). The number of removals was generally low; only a few occurrences in highly impacted reaches, and survival were very high in all reaches and
levels. I only found a slightly higher (although not statistically significant) mortality in level 4. Germination of Ca seeds was not statistically different among reaches and levels, although, in general, higher germination occurred under low hydropeaking intensities and with increasing bank level. For example, we found 100% germination along levels 1, 2 and 3 in Granåker, but no germination occurred at level 4 in this reach. Germination was between 50-60% in Harrsele along levels 0, 1 and 2 and reached 30% along levels 3 and 4. Further, a delayed response to hydropeaking for germination of Ca was also observed; most of the germination occurred at the end of the season (M3) (Figure 9).

Figure 9: Germination success (%) per reach and per level for both mid-season (M2) and at harvest time (M3) measurements for Ca seeds. Data shown are totals and not means.

3.3 Helianthus annuus
The biological variables measured for small seedlings of Ha (Has) showed two trends. On the one hand, stem and root length and biomass, and leaf biomass at levels 3 and 4 in Granåker and Tuggen were significantly lower (p < 0.05) than in the other reaches (Figure 10b). On the other hand, we found significant differences in the number of leaves at levels 2 and 3 between Granåker and the other reaches (L2: p < 0.001, L3: p = 0.040) (Figure 10a). Leaves were lost in seedlings growing along intermediate levels in all reaches except for Granåker; all seedlings lost leaves in similar amounts when they were at the lowest level and no leaves were lost when growing at the highest level.
Figure 10: Boxplots showing the change in leaf loss (a) and stem length (b) for Has along reaches affected by hydropeaking. Red line points out no change.

High seedlings of Ha (Hah) showed no significant relationships to hydropeaking intensity among reaches and levels except for number of leaves ($p < 0.001$) and leaf biomass ($p = 0.040$). No statistical conclusions can be drawn from the lowest level due to the low number of replicates (4) along with high mortality.

When combining all reaches to look at the differences among levels, I found a clear pattern of higher numbers and biomass of leaves, and length and biomass of roots and stems with increasing bank elevation for both seedling sizes (Figure 11).
Figure 11: Boxplots showing the change in variables measured for Ha small and high seedlings along bank elevations. Graphs show the increasing patterns for all variables and both seedling sizes with increasing bank level. Red line points out no change.

Survival for both Ha small and high seedlings was significantly different among reaches and levels (Ha small $\chi^2 = 57.53; \text{CC} = 0.58; p < 0.001$; Ha high $\chi^2 = 16.35; \text{CC} = 0.44; p < 0.001$). It was the lowest in the most impacted reach (i.e., Harrsele), specifically along the lowest levels, and the highest in the free-flowing reach (i.e., Granåker). According to results from the mid-season and late-season measurement, seedlings were very resilient to hydropeaking at the
beginning but the mortality rate increased toward the end of the season. There were no removals of Ha small and high at any level or reach except for a few in Harrsele. Germination of Ha seeds was not statistically different among reaches and levels, although, in general, germination patterns mirrored hydropoeaking intensity being higher along less impacted reaches. Germination was 100% at all levels in Granåker and Bälfsen, but within impacted reaches, it increased with increasing level (Figure 12). Germination of Ha seeds was fast, being germinated already at the first measurement in mid-season (M2) (Figure 12).

Figure 12: Ha germination success (%) among reaches (a) and levels (b) at mid-season measurement (M2) and late-measurement at harvest (M3). Data shown are totals and not means.

3.4 Salix phylicifolia x myrsinifolia
Number of leaves and stem length were the only analyzed variables for Salix phylicifolia x myrsinifolia (Spxm). At levels 2 and 3 in the free-flowing reach (i.e., Granåker; this species is usually found along free-flowing rivers), Spxm showed significantly higher number of leaves and longer stems (p < 0.05). In this reach, number of leaves and stem length also increased toward the end of the season, while it remained the same in the other reaches at these two intermediate bank levels. The lowest level showed no significant differences among reaches for these two variables, while in the highest level I found the highest stem growth and number of leaves along the most impacted reaches (Figure 13) (F = 6.18, p = 0.005).
The survival of *Spxm* was significantly different among reaches and levels ($\chi^2 = 29.43; \text{CC} = 0.38; p < 0.001$). It was low along the highest impacted reach and along the free-flowing reach, and similarly high for the other reaches. Within reaches, survival was usually low along the highest level. The rate of removal was generally very low at all reaches but was significantly different due to more frequent removal at the lowest levels of the highest impacted reach Harrsele ($\chi^2 = 41.92; \text{CC} = 0.44; p < 0.001$).

### 3.5 Data analysis

When comparing analyses carried out on mean and estimated starting values, the results were very similar so I conclude that means with a sample size of at least 20 is a reliable starting value for this kind of analysis.

### 4 Discussion

#### 4.1 Species responses to different hydropeaking intensities

*BP* is a native species to the studied area and it is usually found at higher bank elevations in the riparian zone (Nilsson 1983), which can explain why small seedlings’ performance at the top elevation was good regardless of reach and worse along the lowest elevation. Low frequency and short duration of inundation events characterize the top level for all reaches, and many and long inundation events occur along the lowest level. Small seedlings from *BP* were clearly negatively affected by increasing hydropeaking intensity mirrored in different reaches and bank elevations,
and were, thus, good indicators of hydropoeaking impact. The best variables to measure hydropoeaking impact through birch were those related to the stem (length and biomass), which clearly responded negatively to hydropoeaking. Root-related variables also responded negatively, but in addition they seemed to be affected by the topography of the banks due to underground water table. Leaf-related variables (numbers and biomass) were not as good indicators of hydropoeaking impact. In contrast to small seedlings, high seedlings from _Bp_ did not respond as clearly to the hydropoeaking gradients. Except for at the lowest level (i.e. highest inundation frequency), they were not significantly negatively impacted but also not growing, which might be due to the stressful conditions. Consequently, _Bph_ seedlings are not a good indicator of hydropoeaking impact; however, they could be considered for restoration of levels 2 to 4 at sterile shorelines of rivers and reservoirs affected by hydropoeaking. The high mortality and no significant differences in the performance of _Bps_ seedlings among bank levels in B. Övre are most likely due to erosion processes resulting from woody debris deposited by the current on the planting areas in this reach, which is masking the direct effects of hydropoeaking. Hence, no clear relationships between hydropoeaking and performance of _Bp_ along the most often inundated level (lowest level) in this reach is likely due to small sample size as a consequence of surviving seedlings. In contrast, high survival of _Ca_ seedlings along all reaches and bank levels is related to the higher tolerances to flooding of this species, and low levels of removal might be due to its long tap root which strongly fixes it to the ground (Fuxi et al. 2015).

The results from this study clearly indicate a strong negative correlation between germination success of _Bp_ and hydropoeaking. The rate of water rise and fall is critical for recruitment of seeds and their germination capacity. Under rapid water rise and fall rates, seeds may be removed by water current, and those which are able to stay in the soil suffer from sudden desiccation or inundation and are unable to germinate (Mahoney and Rood, 1998). Therefore, it was expected that the rapid rise and fall of the water table in the reaches affected by hydropoeaking, and also along the lowest, most inundated levels, greatly reduced the germination success for _Bp_. In this study, the erosion factor was removed since the seeds were fastened under a fabric for practical reasons, and even without erosion the frequency, duration, and rate of change of the water table in the hydropoeaking reaches were still enough to halt the germination of _Bp_ almost completely. The decrease in germination success at the highest elevation from Granåker was probably because of drought, since the water table never reached this level. As the high _Bp_ survived in all reaches, it seems as if recruitment in this species is the bottleneck constricting its spread along the highly regulated Umeå River. For _Ca_, Germination success was higher than for _Bp_, and more germination occurred at the hydropoeaking reaches. This is not unexpected, since _Ca_ is more water tolerant than _Bp_, and explains the naturally low position of _Ca_ along the river banks. With regards to this, there was also a trend when looking at among-species differences between sampling events. Almost no seeds of _Ca_ had germinated in mid-season but instead later in the season. The fabric covering the seeds were not removed at mid-season to check germination success for practical reasons, so a few germination events could have gone unnoticed in some cases, but the results still suggest a delay in germination in _Ca_. As no significant trends were seen in survival, erosion, or germination of _Ha_, this species does not seem to be impacted by hydropoeaking, and recruitment does not seem to be a problem as the germination rates are very high.

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Spxm is native to the area and measurements were taken on cuttings from local specimen. These species are naturally found at mid-elevation in the riparian zone (Nilsson 1983). In general, I found that Spxm survived and was able to grow successfully along impacted reaches regardless the degree of hydropoeaking. Consequently, it can be used for restoration of impacted sites at the upper levels where it appeared to have the best performance, while it is not a good indicator of hydropoeaking impact. Behavior of this species is related to its water requirements and flooding tolerance. Salix spp. is an ecological pioneer that colonise barren riparian river banks and is, above the riparian zone in northern Europe, followed in succession by conifers (Rood et al 2003). Salix spp. is very sensitive to drought (Rood et al. 2003) and needs to be in contact with the capillary fringe to grow and survive (Mahoney and Rood 1998). Morphological features such as flexible stems and re-sprouting abilities make willows very flood resistant (Kuzovkina et al. 2005). Hence, suitable conditions are met at the upper levels of the reaches affected by hydropoeaking and at intermediate levels along the free-flowing reaches, which is consistent with our results. The lowest survival and performance values of Spxm were found at the lowest level in all reaches regardless of their hydropoeaking intensity, and also at the highest level of the free-flowing one. Increase in number of leaves was significantly different both along the lowest banks affected by the highest hydropoeaking intensity, i.e., Harrsele, and at the free-flowing reach, i.e., Granåker; the highest increase in leaves shifted towards higher levels with higher hydropoeaking intensity. Stem length, however, was not responsive to hydropoeaking intensities, probably because the cuttings used their resources to produce new leaves and roots (as seen in field), so this variable is not effective as an indicator of growth or hydropoeaking response.

4.2 Mitigation
I used four species to test hydropoeaking impacts in order to find the best phytometer for evaluating hydropoeaking impacts and for monitoring mitigation efforts. A phytometer is a plant whose performance will directly reflect the environmental differences that it is exposed to (Dietrich et al. 2013, 2015). Phytometers are used to evaluate a wide range of different environmental impacts and habitat conditions, but to my knowledge, no phytometers have been used to test for hydropoeaking effects. Ha is a common phytometer suggested by Dietrich et al. (2013), and, despite being non-native, it was included in our experiments together with other native riparian species, because it does not reach its flowering stage in northern Sweden and therefore its spread is not a risk. While Bp was the best phytometer for testing effects of hydropoeaking, followed by Ca, i.e. they showed the clearest relationships to this particular environmental alteration; performance and survival of Ha were unresponsive to hydropoeaking intensities. Ha is therefore not recommended as a phytometer for hydropoeaking tests. This is somewhat surprising since it is an annual species, which means rapid growth and development, and, hence, it is suitable for short-term studies when there is no time to test the same patterns in slower growing species. Further, it has big seeds that are easy to handle and with a large endosperm that will let it reflect the physical conditions rather than resource availability (Deitrich et al. 2015).

As Dietrich et al. (2013) suggests, phytometers could also be used for restoration purposes. According to our results, only Cas seedlings would be adequate for restoring the bare riparian areas along impacted reaches and at the same time serve as an indicator of the hydropoeaking impacts, and thereby acts as a monitoring tool to assess restoration success. The other species,
independent on size, would not be adequate for both purposes simultaneously. For the species that did respond to hydropeaking, their growth and survival were adversely impacted by extreme hydropeaking intensities. Consequently, from this study, I conclude that Bps and Cas seedlings are appropriate indicators of hydropeaking, whereas Cah seedlings and cuttings from Spxm could be used solely for restoration in the Umeå and Vindel rivers. When restoring river banks with woody species such as Spxm, the benefits to the riparian zone include control of bank erosion due to root stabilization, improving water quality in the stream, nutrient cycling, and stream shading. Often Salix spp. is used in restoration projects to “jump start” the re-vegetation process (Deitrich et al. 2015), and the results from this study confirm this is a viable restoration method. But achieving success in riparian ecosystem projects often results from a combination of direct actions, such as planting, and indirect actions, such as restoring the natural hydrological regime, to some degree in both temporal and spatial scales. Efforts to naturalize the flow regime as far as it is economically feasible (i.e., environmental flows) are key to achieve a good ecological status of impacted reaches. This would imply reducing the frequency and duration of the inundation events, which occur on an hourly scale, but any restoration towards a more natural flow regime competes with hydropower production of electricity (Stromberg 2001). Additionally, riparian areas of river reaches affected by hydropeaking do not suffer from any flooding disturbance, but seasonal fluctuations are needed to re-establish recruitment and morphological processes such as meandering channel widening/re-narrowing and for creating side channels (Stromberg 2001). Occasional simulated spring floods have been seen to benefit the establishment of Populus and Salix (Stella et al. 2010; Rood et al. 2003; Stromberg 2001; Mahoney and Rood 1998). Naturally, these regeneration floods occur every 5 to 10 years (Stromberg 2001). Success rates towards desired ecosystem changes in restoration vary greatly. Failures often occur when mitigation measures address symptoms instead of underlying causes for ecosystem decline. Research and adaptive management should be integrated to increase success rate for specific restoration projects but also to increase the knowledge for coming projects (Stromberg 2001; Dietrich et al. 2013). As an example, results from this study can be used as objective information about which hydropeaking intensities might cause severe changes in the performance and survival of the three analysed species, and then justify the ecological importance of every drop of water that does not benefit hydropower production. The results will in that way aid in the debate on which mitigation actions has the greatest ecological effects.

In this study, most of the measured biological variables for Bp were negatively impacted with increasing hydropeaking intensity, as shown by a progressive pattern when hydropeaking increases from Granåker to Harrsele. A clear threshold for irreversible effects of hydropeaking is hard to pin point. When instead looking at effects of bank levels (i.e. inundation frequency), level 1 stands out as the elevation on the river bank where Bps seedlings were irreversibly affected. Hence, this threshold could be taken into account if this species were to be used in restoration projects, or for defining environmental flows. A hydrological characterization of this low level should be the next step to develop a threshold value, and it should be easily done based on the pressure loggers that were installed. Once this threshold is defined, specific flow regime mitigation suggestions could be given. The impact of inundation frequency at level 1 is also noticeable in survival; species survived here only in the free-flowing reach. Germination of Bp does show a clear difference among reaches and a threshold can be found at the free-flowing river. Clearly, some processes of the natural flow regime in the Vindel River compared to the
Ume River have positive effect on the germination of this species. Again, deep analysis of the flow records would help to find a flow-related mitigation action to re-establish key processes in the regulated river. Ca is responding positively in both the regulated and free flowing rivers and an impact threshold is not obvious, which means that there is no need for mitigation actions for seedlings of this species (small or high). However, there is a large difference when looking at germination. Flow regimes like those in Granåker and Bålfforsen have germination rates for Ca above 50% at 3 out of 4 levels, while, at the other reaches, only 1 or 2 levels show germination rates above 50%, which seems to be a distinct threshold at which the germination of Ca is irreversibly impacted. As such, hydrological information about underlying bank elevations could guide flow-related mitigation actions that would increase germination of Ca. This would be the most effective effort to increase the viability of this riparian species. Spxm survival rate was very high in both impacted and free-flowing reaches so no impact threshold was found. However, despite the high survivability of this species even under high hydropoeaking intensities, the fact that no willows are found along the shores of the Umea River reveals that recruitment may be the bottleneck of this species, and other authors have highlight the importance of natural floods for both seed and vegetative germination of Salix (Mahoney and Rood 1998; Stromberg 2001; Rood et al. 2003; Stella et al. 2010). Such floods that, according to our results, would trigger regeneration of willows are absent along rivers affected by hydropoeaking.

4.3 Methodology

The negative values obtained after calculating the differences between the final and initial measurements for stem length and leaf biomass might be the result of the methodological approach. The initial measurement was taken when the plant was still in the pot in the greenhouse, whereas the final measurement was taken in the field where seedlings were probably dug down deeper than they were in the original pot’s soil. On the other hand, the negative values for leaf biomass could be due to the use of estimations of the initial measurements, which might have overestimated the initial biomass. Negative values for stem length and leaf biomass were therefore interpreted as no growth in stem length or biomass (negative values were used as zero). Finally, potential losses of roots when harvesting and cleaning might have led to underestimations of the final root length and biomass. But in the end, these unreal values do not affect the trends shown by the data, since all seedlings have been measured in a consistent manner.

4.4 Conclusions

There is no consensus among studies suggesting in what direction the riparian vegetation will move towards under the effects of hydropoeaking. My study suggests that hydropoeaking promotes herbaceous species, such as Ca, that are adapted to higher frequency and duration of inundation events, and disfavours woody species, such as Bp, whose water requirements are not as high. However, tests during a single growing season should be further complemented with longer experiments, to be able to derive results about the likelihood of survival in these species during winter conditions. Differences between the free-flowing reach and the remaining regulated reaches were significant for most measured biological variables and species. Thresholds, at which irreversible consequences can be seen, in the response of species to hydropoeaking are possible to identify for certain species and seedling sizes according to my study. In general, the seedlings’ stems grew (i.e., increased in length and biomass), while their roots did not show
significant changes (i.e., maintenance of root length and biomass), and they tended to loose leaves (i.e., decrease in the number and biomass of leaves), but specific changes to hydropoeaking were species specific. Overall, Bp small was the best seedlings to indicate a hydropoeaking impact, and the higher seedlings of this species can be used in restoration, because it is native and they survived well at high bank elevations. Ca is also a good candidate for both restoration and as an indicator species; the small seedlings for both purposes and the high only for restoration. Contrary to other studies, Ha was not suitable for any of the two purposes. Local cuttings of Spxm can be used in restoration, but responses to hydropoeaking were too week for this species to be used as an indicator over the short term.

To maintain or regain the natural riparian zone, it is essential to know which durations and frequencies of flows are required to maintain the most important processes (Jansson et al. 2000). Using native plants as phytometers, as I did in this study, could be a useful evaluation tool. Mitigation actions to restore future generations of native riparian plant species in northern Sweden should be focused on restoring a flow regime that will re-establish the natural germination processes. A deep analysis of the flow records is required to define specific flow characteristics that ensure germination of each species. Cultural and communication problems between theoretical ecologists and practical engineers must be overcome to be able to implement a sustainable hydropower production (Jager and Smith 2008). One way of doing this would be to present thresholds, based on results from empirical research such as I show in this study, to back up necessary mitigation actions.
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References


Bieri M. 2012. Operation of complex hydropower schemes and its impact on the flow regime in the downstream river system under changing scenarios. Laboratoire de Constructions Hydrauliques (LCH), communication 52. ISSN 1661-1179.

Brisbane Declaration Conference, held in Brisbane, Australia, on 3-6 September 2007. Environmental Flows1 are Essential for Freshwater Ecosystem Health and Human Well-Being.


