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Stream ecosystem responses to an extreme rainfall event across multiple catchments in southeast Alaska

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SUMMARY

1. Floods are a key component of the flow regime of many rivers and a major structuring force of stream communities. Climate change is predicted to increase the frequency of extreme rainfall (i.e. return intervals > 100 years) leading to extensive flooding, but the ecological effects of such events are not well understood. Comparative studies of flood impacts are scarce, despite the clear need to understand the potentially contingent responses of multiple independent stream systems to extreme weather occurring at meso- and synoptic spatial scales.
2. We describe the effect of an extreme rainfall event affecting an area >100,000 km^2 that caused extensive flooding in SE Alaska. Responses of channel morphology and three key biological groups (meiofauna, macroinvertebrates and fish) were assessed in four separate and recently deglaciated stream catchments of contrasting age (38-180 years) by comparing samples taken before and after the event.
3. Ecological responses to the rainfall and subsequent flooding differed markedly across the four catchments in response to variations in rainfall intensity and to factors such as channel morphology, stream sediment composition and catchment vegetation type and cover, which were themselves related to stream age.
4. Our study demonstrates the value of considering multiple response variables when assessing the effects of extreme events, and highlights the potential for contrasting biological responses to extreme events across catchments. We advocate more comparative studies to understand how extreme rainfall and flooding affects ecosystem responses across multiple catchments.

Introduction

Floods are a significant feature of the flow regime of many rivers (Poff *et al.,* 1997), and a major force structuring stream communities (Lake, 2000; Jones, 2013). Extensive precipitation and/or snow melt can cause floods, but flow responses can vary markedly in space and time depending on antecedent conditions, catchment characteristics such as geology and relief, and human activities. Pluvial floods vary in magnitude and predictability as a result of the natural variability of precipitation, both within and between years, but a changing climate is expected to alter the frequency, intensity, spatial extent, duration and timing of extreme weather events (IPCC, 2013), and may result in unprecedented effects on river flow and associated riverine communities. Extreme or great floods can be defined as having discharges exceeding 100-year return intervals (Milly *et al.,* 2002). As such events are infrequent and unpredictable, knowledge of their ecological effects is incomplete, yet there is a growing need to improve understanding of their impact on river ecosystems as the climate changes.

The response of stream communities to flooding has been researched extensively over the past three decades (Niemi *et al.,* 1990; Yount & Niemi, 1990; Stanley *et al.,* 2010) yet there remain relatively few studies of extreme flooding. Floods can affect riverine ecosystems directly, as disturbance alters biodiversity, abundances and standing biomass, and indirectly, via changes to river channel and floodplain hydrology, geomorphology and biogeochemistry (Poff, 1997). Extreme floods may have particularly deleterious effects on stream benthic communities because they scour and redeposit sediments, and incise channels, potentially reducing habitat heterogeneity and the availability of flow refugia for biota (Death, 1997).

Responses to flooding may depend on channel morphology, sediment composition and habitat complexity (e.g. the presence of backwaters, pools and debris dams) which dictates the extent of in-stream refugia. These factors may vary between catchments, with those in earlier successional stages tending to have less complex, more unconsolidated glacial deposits than those that are older and/or less modified (Milner *et al.,* 2000, 2013). Thus stream communities in different catchments could vary in their responses to flooding. Flood responses may also be modulated by the precipitation history and nature of the catchment (e.g. vegetation type and cover) and the resultant hydrological history of the river because the flow regime is a major ecological filter (*sensu* Poff, 1997), influencing the composition of the local community and 'selecting' species with appropriate traits from the regional species pool.

In a typical flood, a large volume of fast-flowing water moves rapidly downstream, creating high channel shear stress. Organisms are dislodged, crushed by moving substrata or forced to migrate from the channel (Death, 2010). Invertebrate and fish communities often exhibit low resistance to floods and total abundance is usually reduced significantly (e.g. Vieira *et al.,* 2004; Kroon & Ludwig, 2010; McMullen & Lytle, 2012) but populations are frequently resilient and recover rapidly if pools of colonists remain within the system or in nearby areas (Milner *et al.,* 2013). Some individuals move actively or passively into high-flow refugia such as river margins, floodplains and possibly the hyporheic zone, returning to the main channel after flow recedes (e.g. Robertson *et al.,* 1995; Dole-Olivier, 2011; Sueyoshi *et al.,* 2014). Thus, habitat heterogeneity and connectivity are important for assemblage resilience (Matthews, 1998). The response of river biota to flooding may be taxon-specific, although few studies have considered a wide range of organismal groups (but see

Milner *et al.* 2013). Species responses can also be age-specific, for example, floods remove fine sediment thereby favouring gravel-nesting fish (e.g. Kroon & Ludwig, 2010; Matthews *et al.,* 2013), whereas , scouring and sediment deposition during floods can kill fish eggs. Additionally flood waters displace juvenile salmonids downstream unless they are able to find flow refuges (e.g. Harvey, 1987).

The impact of flooding on riverine communities is usually assessed within individual catchments (e.g. Olsen *et al.,* 2010; Stanley *et al.,* 2010; Mesa, 2010; Milner *et al.,* 2013) and there is a notable paucity of studies comparing the effects of floods on aquatic invertebrates across rivers and catchments (Death, 2007) with the exception of some patch-scale experimental manipulations (e.g. Gjerløv *et al.,* 2003; Melo *et al.,* 2003). However, adjacent catchments may be expected to differ in vegetation extent and type, and the rivers within them to differ in channel morphology, sediment composition and the degree of habitat complexity. In turn these differences may modulate ecosystem responses to extreme rainfall and subsequent flooding, highlighting the need to understand how independent systems respond during broad-scale extreme events and emphasising the importance of incorporating multiple catchments into studies of high flow impacts. By doing so we can begin to unpick the myriad of factors influencing community responses (Olden *et al.,* 2014).

This paper focuses on the effect of an extreme climatic event which led to extensive flooding of streams of differing habitat complexities in Glacier Bay, southeast Alaska. Over 400mm of rain fell over a 4-day period (21st – 24th November 2005) including > 130mm on a single day (Fig. 1). The intensity of the rainfall over 24 h indicated that this event had a return interval of > 100 years and its severity was compounded by the duration of the storm and extensive catchment snow cover (Milner *et al.,* 2013). Furthermore, rainfall intensity varied across the study area, being higher in the north

(170mm on 22nd November 2005) and lower in the south (110mm on 22nd November 2005) (Fig. 1). We assessed ecosystem response to this extreme rain and flooding event using three biological groups (meiofauna, macroinvertebrates and fish) from four streams at differing stages of development following glacial recession in Glacier Bay.

Our primary aim was to examine the impact of an extreme rainfall event leading to extensive flooding on stream ecosystems in multiple catchments across an 11,000 km^2 study area. We hypothesised that the flood event would have the following effects:

1. Stream geomorphology will be modified across the streams, with channel reconfiguration leading to reduced habitat heterogeneity.
2. Community total abundance will decline whereas taxon richness may increase or decrease depending on the habitat preferences of individual taxa. Stream communities will converge post-flood, as formerly contrasting communities 'reset' to an earlier stage of development.
3. Streams subjected to the highest rainfall intensity, and greatest flooding, should exhibit the biggest shifts in invertebrate community structure.
4. Responses to flooding will differ among the three organismal groups (meiofauna, macroinvertebrates and fish) depending on traits and/or timing of the flood with respect to life cycle stage.

Methods

Glacier Bay National Park and Preserve (GBNP) is located west of Juneau in southeast Alaska (58° 10′- 59° 15′N; 135° 15′- 138° 10′W). Glacial recession has created a deglaciated landscape, with a temporal scale of 220 years and a spatial scale of 11,000 km^2. The climate of Glacier Bay is temperate maritime, with mean annual temperature of 5 $^{\circ}$C (mean monthly range - 3 $^{\circ}$C to 13 $^{\circ}$C) and average annual precipitation of 1400 mm. A Neoglacial ice sheet once covered the majority of GBNP, reaching a maximum around AD 1700. A change in local climate c.250 years ago led to recession of the ice sheet (Chapin *et al.,* 1994). Detailed historical and geological information provides accurate information on the rate of glacial recession within GBNP, from which stream age can be estimated. Stream and catchment ages were defined as the time since ice recession from the stream mouth (Milner *et al.,* 2000).

Four streams (Table 1) were selected to represent c.180 years of catchment development following glacial recession (Milner *et al.,* 2000). The catchments of the older streams (140 - 180 years) had extensive forest cover, while those of the younger streams (38 - 65 years) possessed more intermittent and less complex vegetation.

To determine changes in stream channel cross-sections following the flood, tachometry channel cross-section data were collected in 1997 using a Sokkia dumpy level (Topcon, Tokyo, Japan) with tripod and staff. Measurements were taken at two separate locations within each study reach, at a maximum of 100 m apart, and located a maximum of 1 km from the stream mouth, hereafter termed ‘upper’ and ‘lower’ cross-sections. Annual observations demonstrated that these cross-sections did not change markedly prior to the extreme rain and flooding event in late 2005. GPS fixes at the floodplain terrace on both banks of the channel cross-sections facilitated re-surveying in 2006 to provide information on channel change. Floodplain area, bankfull width and detailed channel bed measurements were taken, allowing entrenchment ratios (width of flood-prone area/ width at bankfull) to be estimated. Only the upper cross-section could be re-surveyed in 2006 at Stonefly Creek. The percentage of pools in the habitat was determined before (Milner et al. 2000) and after the flood (Klaar et al. 2009).

For macroinvertebrates, samples collected in the same summer month before (2005) and after (2006) the flood were compared, excepting Berg Bay South stream where samples collected in July 2005 were compared with September 2006. For meiofauna, comparisons were made between samples collected in summer 2004 (before flood) and summer 2006 (after flood). For meiofauna four additional sets of samples (two in 2006 and two in 2007) were used to examine the recovery trajectory.

Meiofauna were collected in summer (June – August) from a representative sampling station located c. 0.5 - 1 km from the mouth of each stream using a Surber net (five replicates; 63µm mesh). Meiofauna are organisms which pass through a 1mm sieve but are retained by a 63µm sieve (Giere 1993) and usually incorporate the small instars of macroinvertebrates, as well as taxa such as copepods which remain in this size category throughout their life cycle. Macroinvertebrates were also collected from the same reaches using a Surber net (5 - 10 replicates; 330µm mesh). Both size fractions were preserved in 70% ethanol and later separated in the laboratory from detritus and inorganic matter before enumeration.

Macroinvertebrates were identified using Merritt *et al.* (2008). Meiofauna were identified using Thorp & Covich (2009) and Smith (2001). Macroinvertebrates < 1 mm were typically identified to order because their immaturity precluded assignment to genus and/or species.

Numbers of adult pink salmon (*Oncorhynchus gorbuscha*) spawners were estimated using the average of counts by two observers walking the length of the stream, and juvenile coho salmon (*Oncorhynchus kisutch*) densities (Catch Per Unit Effort - CPUE) with minnow traps baited with salmon eggs soaked previously in Betadyne iodine and fished for 2h (Milner *et al.,* 2000).

Data analysis

Pre- and post-flood data (based on mean densities from replicate Surber samples in each stream) were ordinated using non-metric multidimensional scaling (NMDS) using Bray-Curtis dissimilarity matrices.. One-way ANOSIM tested the null hypothesis that the taxonomic composition of meiofaunal and macroinvertebrate communities were unaffected by the flood. ANOSIM was conducted on individual replicates using Bray-Curtis dissimilarity scores with 10,000 permutations and Bonferroni-corrected significance values. A similarity of percentages (SIMPER) routine was used to identify five taxa contributing most to community dissimilarity before and after the flood in each stream. One-way ANOVA was then used to determine the significance of these taxonomic differences. All analyses were conducted on $\log_{10}(x+1)$ transformed data) and statistical tests were undertaken using SPSS v19. NMDS, ANOSIM and SIMPER were undertaken using PAST v3.0.

Results

The effect of the flooding on channel cross-sections varied markedly among the four study streams (Fig. 2; Table 2). At Stonefly Creek, infilling reduced channel width by 21% whereas at Wolf Point Creek the flood scoured the bed and banks, and increased channel entrenchment. However, the highest degree of channel change occurred at Ice Valley Stream, where depth (+17.2%) and width (+37.5%) increased and entrenchment decreased (Table 2). Channel migration was also evident in the lower transect profile (Fig. 2). The channel response at Berg Bay South Stream varied among transects, but generally, channel depth decreased as a result of infilling (47.5% and 3.4% decrease in channel depth post-flooding at the upper and lower transects respectively), and channel width increased. The occurrence of pool habitat - a measure of channel heterogeneity - was unaffected by the flood in Stonefly Creek and Ice Valley Stream, but declined in Wolf Point Creek, and increased in Berg Bay South Stream.

Flooding significantly reduced the taxon richness and total abundance of meiofauna in all streams except Ice Valley (Table 3). Declines in meiofaunal abundance ranged from 84 – 90% in Stonefly Creek, Wolf Point Creek and Berg Bay South. In Stonefly Creek, meiofaunal-sized Plecoptera and Ephemeroptera, Ostracoda and *Acanthocyclops vernalis* were absent from post-flood assemblages. In Wolf Point Creek absentees were Oligochaeta and *Cyclops scutifer*, and in Berg Bay South stream, these were meiofaunal-sized Plecoptera, Ephemeroptera and *Simulium* sp., Tardigrada, *Chaetogaster* spp., other Oligochaeta, Ostracoda, *Bryocamptus zschokkei* and *Cyclops scutifer.* Despite the immediate post-flood decline, meiofaunal taxon richness in Stonefly Creek, Wolf Point Creek and Ice Valley recovered later in 2006 and 2007 to fall within the range of pre-flood taxon richness (Fig. 3). In Berg Bay South meiofaunal taxon richness in 2006 and 2007 remained lower than that in pre-flood samples, however, all taxa collected before the flood were found in at least one post-flood sample suggesting that pre-flood taxa persisted within the stream albeit at low levels of abundance.

ANOSIM indicated that meiofaunal community composition was significantly affected by the flood in Stonefly Creek (ANOSIM r^2 = 0.76, P<0.01), Wolf Point Creek (ANOSIM r^2= 0.99, P<0.01) and Berg Bay South Stream (ANOSIM r^2 = 0.95, P<0.01) but not in Ice Valley. NMDS showed that Berg Bay South, Stonefly and Wolf Point Creek communities clustered together more closely post-flood, suggesting more similar meiofaunal communities in these disturbed streams (Fig. 5b).

SIMPER revealed that the identity of five taxa contributing most to pre- vs. post-flood community dissimilarity differed among streams, especially for meiofauna (Fig. 4b,Table 5). Abundances of these key taxa largely declined following the flood, although the cyclopoid copepod *Acanthocyclops vernalis* significantly increased in Wolf Point Creek (Fig. 4b).

The total abundance of macroinvertebrates declined following the flood in all streams except Ice Valley, but effects were statistically significant only in Stonefly Creek ($F_{1,8}$ = 33.25, P <0.001). Macroinvertebrate taxon richness was only significantly reduced by flooding at Wolf Point Creek ($F_{1,8}$ = 11.94, P <0.01). In this stream, macroinvertebrate taxa absent in post-flood samples were Coleoptera, *Ephemera*, Ephemerellidae, Hydracarina, *Suwallia forcipata,* and Trichoptera. For macroinvertebrates, SIMPER revealed that shifts in the abundance of Chironomidae and Simuliidae were observed in all streams pre- versus post-flood (Fig. 4a, Table 4), and that responses of some Plecoptera (*Suwallia forcipeta*) accounted for community change in Stonefly Creek, Wolf Point Creek and Berg Bay South Stream (Table 4). Abundances of these key taxa generally declined following the flood, but Chironomidae and *Ephemera* in Ice Valley Stream and Simuliidae and *Suwallia forcipata* in Berg Bay South Stream increased post-flood (Fig. 4a).

Macroinvertebrate community composition was significantly altered by the flood in the two younger streams Wolf Point Creek (ANOSIM $r^2 = 0.868$, $P < 0.01$) and Stonefly Creek (ANOSIM $r^2 = 0.868$, $P < 0.01$) but not in the older Ice Valley and Berg Bay South streams (Fig. 1). NMDS sample scores were more tightly clustered post-flood reflecting increased similarity among macroinvertebrate assemblages simplified by disturbance (Fig. 5a).

The highest abundance of spawning adult pink salmon and CPUE for juvenile coho were recorded in Wolf Point Creek, prior to the flood and densities in this stream also declined most strongly post-flood, with an eight-fold decline in returning spawning adult pink salmon and a fifteen-fold fall in coho juvenile CPUE (Table 2). In contrast, returns of adult pink salmon declined three-fold in Berg Bay South Stream after the flood and there was a slight increase in juvenile coho CPUE. In Ice Valley Stream, low numbers of returning pink salmon were recorded in both the pre- and post-flood years and juvenile coho CPUE declined three-fold following the flood (Table 2).

Discussion

Predicting how extreme rainfall and flooding will affect river ecosystems as the climate changes requires an understanding of how flood impacts vary across multiple catchments in response to factors such as rainfall severity, channel morphology and channel complexity, and, how different organismal groups respond to high flows. This study revealed that the effects of flooding caused by a single rainstorm varied markedly across our study streams in southeast Alaska. Several factors may account for the contrasting responses to this extreme climatic event observed among stream catchments, including stream geomorphology and catchment vegetation cover.

Geomorphic responses to the extreme rainfall and flooding event varied between the study streams [H1]. In the two younger streams, Stonefly Creek and Wolf Point Creek, where the highest rainfall occurred (>400mm in 4 days), there was a similar response of channel incision and increasing entrenchment due to channel bed and bank scouring. However, in the two older streams, Ice Valley and Berg Bay South, where rainfall was less intense (<300mm over 4 days), channel entrenchment decreased and the stream channels generally widened and decreased in depth. These variable responses may result in part from differences in channel bed sediment structure associated with stream age, which varied from 38 – 180 years (Stover & Montgomery, 2001; Sipos *et al.*, 2008). Younger streams (i.e. 38 - 65 years) are often dominated by unconsolidated glacial material which is more likely to be scoured from channel banks and bed during high flows (Carrivick *et al.*, 2013; Milner *et al.,* 2013), resulting in a more defined, incised channel. However, older streams (140 - 180 years) tend to have larger (Klaar *et al.,* 2011), and more stable bed substrates, as unconsolidated material has generally already been transported from the channel. In these older stable streams, flood water is more likely to spill out onto the floodplain, increasing channel width and decreasing channel depth as material transported from terrestrial and upstream locations is deposited further downstream.

The variable responses of the study streams to the extreme rainfall and flooding event may also result from differences in vegetation cover in the catchments. Older stream catchments are covered by more mature forest which may attenuate the effects of extreme rainfall, whereas younger catchments are more sparsely populated by less complex vegetation (e.g. Chapin *et al*., 1994; Fastie, 1995; Milner *et al*., 2007). Engstrom *et al*. (2000) suggested that catchment development over time can change soil structure, leading to greater surface runoff, which can in turn modify stream hydrology. Sediment structure, catchment vegetation (both of which vary with stream age) and rainfall intensity may interact to impact stream channel morphology following an extreme event, but more detailed geomorphological data collection would be required to untangle this further.

Changes in the meiofauna partially supported our second hypothesis, that community composition would change markedly in the months following the flood. Meiofaunal total abundance, taxon richness and community composition differed significantly in three of the four streams and became more similar post-flood, probably because the communities were reset to earlier stages of development (sensu Milner *et al.,* 2013) as a result of channel morphology change. Meiofauna are small and their resultant vulnerability to high flows is well documented (e.g. Robertson *et al*., 1995); however, they can be persistent in streams (Robertson, 2000) as demonstrated by our finding that post-flood taxon richness either fell within the envelope of pre-flood (2000-2004) taxon richness, or that pre-flood taxa were recorded in at least one post-flood sample. The abundance of most taxa declined following the flood, but in Wolf Point Creek, that of the predatory cyclopoid copepod *Acanthocyclops vernalis* increased markedly, possibly as a result of predatory/ competitive release (Gendron & Laville, 2000; Anderson & Ferrington, 2013) or the removal of fine sediments (Robertson & Milner, 2006).

Our results indicate that, for meiofauna, lower rainfall intensity did not necessarily cause a lesser community response because meiofaunal community composition differed significantly in Berg Bay South (experiencing lower rainfall intensity) as well as Stonefly and Wolf Point Creek (higher intensities) and the percent decline in abundance was similar in all three streams. Thus, for the meiofauna, our third hypothesis, thathigher rainfall will lead to larger community response, was unsupported. Meiofauna have a low threshold of entrainment into the water column (Palmer *et al.,* 1992) and thus washout may occur at relatively low flows.

Macroinvertebrate community composition changed significantly in some streams but not others and NMDS suggested that communities in three streams became more similar after the flood than before, providing further partial support for our second hypothesis. As has been found in many other studies, invertebrate total abundance and taxon richness generally declined following the floods (e.g. McCabe & Gotelli, 2000; Fritz & Dodds, 2004; Stanley *et al.,* 2010), although this was statistically significant only for some groups and some streams. Macroinvertebrate taxa absent from Wolf Point Creek and Stonefly Creek tended to be those favouring slow flowing/ depositional areas of streams thereby reflecting the reduction of these habitats post-flood (Milner *et al.* 2012). Significant changes in macroinvertebrate community composition following the floods were found only in the least stable, younger channels of Wolf Point and Stonefly Creeks where the most intense rainfall occurred. These streams were the only ones showing significant changes in total abundance (Stonefly Creek) and taxon richness (Wolf Point Creek), providing some support for our third hypothesis that streams experiencing the greatest rainfall would show the greatest changes in invertebrate communities. The response of juvenile coho salmon to flooding was also distinctive; CPUE declined post-flood in Wolf Point Creek but increased in Berg Bay South Stream, perhaps in response to the greater percentage of pools in the post-flood stream (Rosenfeld *et al.,* 2000; Roni, 2002). The number of adult pink salmon spawners decreased markedly in Wolf Point Creek and Berg Bay South Stream but recovered rapidly in the former in 2009 and 2011 (Milner *et al.,* 2013).

We found differences in the response of the three organismal groups to extreme flooding, for example, the meiofauna showed a greater response to the flood than macroinvertebrates, providing partial support for our fourth hypothesis. Our finding highlights the importance of considering the responses of multiple organismal groups to fully capture the effects of extreme events on stream communities.

Invertebrates in Ice Valley stream were apparently not affected by the flood, despite this stream experiencing the greatest degree of channel change. Here, abundance and taxon richness were both low prior to the flood, perhaps reflecting low channel stability and the higher proportion of bedrock in the channel (Barnes *et al.,* 2013), and the invertebrate community was dominated by Chironomidae, a group thought to be resilient to flooding events (Death, 2007; Collier & Quinn, 2003).

We examined stream community response to a synoptic-scale extreme rainfall event across several independent catchments. Multiple interacting factors determined community response to these events. Rainfall intensity varied across catchments and stream community response also differed among streams, perhaps in response to this variation. The stream catchments also differed in developmental stage leading to variation in channel morphologies, sediment composition and catchment vegetation cover and type. These differences undoubtedly modulated the effect of the rainfall on the stream communities. Our findings are consistent with those of Collier & Quinn (2003), who found that streams draining catchments with less complex vegetation (pasture) were more affected by flooding than those draining forested catchments, and Death & Zimmermann (2005) reported that the effects of flood on invertebrate diversity were less in forested reaches than in downstream pasture reaches because communities in forests were not reliant on recovery of the periphyton food base. There were also significant hydrological contrasts among catchments under different vegetation cover (e.g. Schoonover *et al.*, 2006; Germer *et al.*, 2010; Brown *et al.*, 2010) which can undoubtedly affect the composition and dynamics of constituent biological groups of streams in these environments. Predicting the ecological effects of extreme events across different catchments will undoubtedly require a more detailed understanding of how these systems function hydrologically.

Our study highlights the difficulties that arise when examining cross-catchment responses to disturbance. Potentially, ecosystem responses to extreme rainfall and subsequent flooding were 'confounded' by differences in rainfall and age across the catchments. Disentangling these interactions requires investment in spatially distributed, long-term monitoring networks to capture multiple events across a variety of river systems, and/or to continue with opportunistic sampling of extreme events so that future meta-analyses can extract information on common responses (Olden *et al.,* 2014). Regrettably, both of these options are limited by both time and resources. There is an emerging consensus that extreme events will increase in frequency and magnitude over coming decades as the climate changes and thus identifying and implementing strategies to manage this change is of primary importance, tasks that are currently hampered by our lack of knowledge and understanding regarding ecosystem responses to extreme flooding across multiple catchments.

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FIGURES.

Fig. 1 Map of Glacier Bay showing location of the four streams (1. Stonefly Creek, 2. Wolf Point Creek, 3. Ice Valley Stream, 4. Berg Bay South Stream). Inset bar charts show daily rainfall (cm) recorded over 5 days in November 2005 near Wachusett Inlet and Berg Bay.

Fig. 2 Channel cross-sections for the four streams, showing channel morphology before and after the 2005 flood. SFC Stonefly Creek, WPC Wolf Point Creek, IVS Ice Valley Stream, BBS Berg Bay South Stream. Note both axes are scaled to data.

Fig. 3 Taxon richness of the post-flood meiofaunal community ($\bar{x}$ +1SE) in (a) Stonefly Creek, (b) Wolf Point Creek, (c) Ice Valley Stream and (d) Berg Bay South Stream. The hatched rectangle shows the range of taxon richness in pre-flood samples (2000-2004). The y-axis is scaled to data.

Fig. 4 Abundance m^{-2} ($\bar{x} + 1\mathrm{SE}$) of the five taxa contributing most to dissimilarity of (a) macroinvertebrate and (b) meiofaunal communities before and after the flood in (i) Stonefly Creek, (ii) Wolf Point Creek, (iii) Ice Valley Stream and (iv) Berg Bay South Stream. The y-axis is scaled to data.

Fig. 5 NMDS plots of (a) macroinvertebrates in summer 2005 and 2006 and (b) meiofaunal communities in summer 2004 and 2006. SF Stonefly Creek, WPC Wolf Point Creek, IV Ice Valley Stream, BBS Berg Bay South Stream.

Table 1. Characteristics of Stonefly Creek (SFC), Wolf Point Creek (WPC), Ice Valley Stream (IVS) and Berg Bay South Stream (BBS), Glacier Bay.

	Age	Reach gradient (%)	Stream length (km)	Drainage area (km^2)	Stream order	Average discharge ($m^3\ s^{-1}$)	Dominant substrate	Dominant riparian vegetation
SFC	38	1.75	3.5	10.0	2	1.28	Cobble	Alder
WPC	65	1.14	5.6	29.8	2	2.29	Cobble	Alder
IVS	140	0.98	8.3	19.4	2	3.02	Cobble	Alder/ cottonwood
BBS	180	0.80	7.2	33.1	3	4.95	Large gravel/small cobble	Alder/ cottonwood/ Sitka spruce

Table 2. Channel entrenchment ratios, percentage of pools in the study reaches and coho (*Oncorhynchus kisutch*) juvenile fish CPUE in Stonefly Creek (SFC), Wolf Point Creek (WPC), Ice Valley Stream (IVS) and Berg Bay South Stream (BBS), Glacier Bay before (summer 2005) and after (summer 2006) extreme flooding in the winter of 2005. Pre-flood adult pink salmon (*Oncorhynchus gorbuscha*) counts are for summer 2005 and post flood are summer 2007. Fish data not available (-) for Stonefly Creek.

	Entrenchment ratio		% pool		Coho CPUE		Adult Pink Salmon	
	Pre-flood	Post-flood	Pre-flood	Post-flood	Pre-flood	Post-flood	Pre-flood	Post-flood
SFC	1.3	1.4	0	0	-	-	-	-
WPC	3.4	2.4	0.2	0	9.3	0.6	13000	1500
IVS	1.9	2.2	3.8	3.7	5.3	1.6	<100	<100
BBS	1.1	3.0	2.2	5.6	5.5	8.3	7000	1500-2500

Table 3: One-Way ANOVA testing the effect of the flood on the meiofaunal community in four study streams. N.S., non significant (P>0.05).

	Total abundance		Taxon richness	
	F value	*P*	*F* value	*P*
Stonefly Creek	$F_{(1,8)}$ = 33.01	0.001	$F_{(1,8)}$ =18.75	0.003
Wolf Point Creek	$F_{(1,8)}$ = 31.22	0.001	$F_{(1,8)}$ = 14.5	0.005
Ice Valley Stream	$F_{(1,8)}$ = 0.77	N.S.	$F_{(1,8)}$ = 1.44	N.S.
Berg Bay South Stream	$F_{(1,8)}$ =22.78	0.001	$F_{(1,8)}$ = 43.63	<0.001

Table 4. SIMPER results for five taxa contributing most to pre- vs. post-flood macroinvertebrate assemblage dissimilarity in four streams in Glacier Bay, Alaska. Mean community dissimilarity before and after flooding: Stonefly 86.7%, Wolf Point 23.2%, Ice Valley 79%, Berg Bay South 46.2%.

(a)

Macroinvertebrates	Stonefly Creek	Wolf Point Creek	Ice Valley Stream	Berg Bay South Stream
Chironomidae	15.7%	5.7%	42.9%	13%
Simuliidae	53.6%	23%	9.9%	17.7%
Ceratopogonidae	-	10.1%	-	-
Tipulidae	6.8%	-	-	-
Plecoptera	5.6%	24.2%	-	12.7%
Suwallia forcipeta	5.6%	23.7%	-	11.8%
Ephemera	-	-	4.2%	-
Malenka californica	-	-	-	13%
Neoephemeridae	-	-	4.2%	-
Arthropleona	-	-	12.9%	-

Table 5. SIMPER results for five taxa contributing most to pre- vs. post-flood meiofaunal assemblage dissimilarity in four streams in Glacier Bay, Alaska. Mean community dissimilarity before and after flooding: Stonefly 52.2%, Wolf Point 63%, Ice Valley 62.4%, Berg Bay South 62.8%.

Meiofauna	Stonefly Creek	Wolf Point Creek	Ice Valley Stream	Berg Bay South Stream
Chironomidae	-	-	61.5%	13.2%
Simuliidae	-	14.8%	-	7.9%
Plecoptera	-	-	20.1%	9.3%
Ephemeroptera	8.4%	-	-	27.3%
Oligochaeta	-	17.3%	-	-
Chaetogaster	17.1%	-	-	-
Nematoda	11%	-	-	-
Tardigrada	15.1%	-	8.6%	-
Acanthocyclops vernalis	12.6%	17.4%	-	-
Cyclops scutifer	-	15.8%	-	-
Bryocamptus zschokkei	-	-	-	7%
Hydracarina	-	15.4%	-	-

Fig. 1

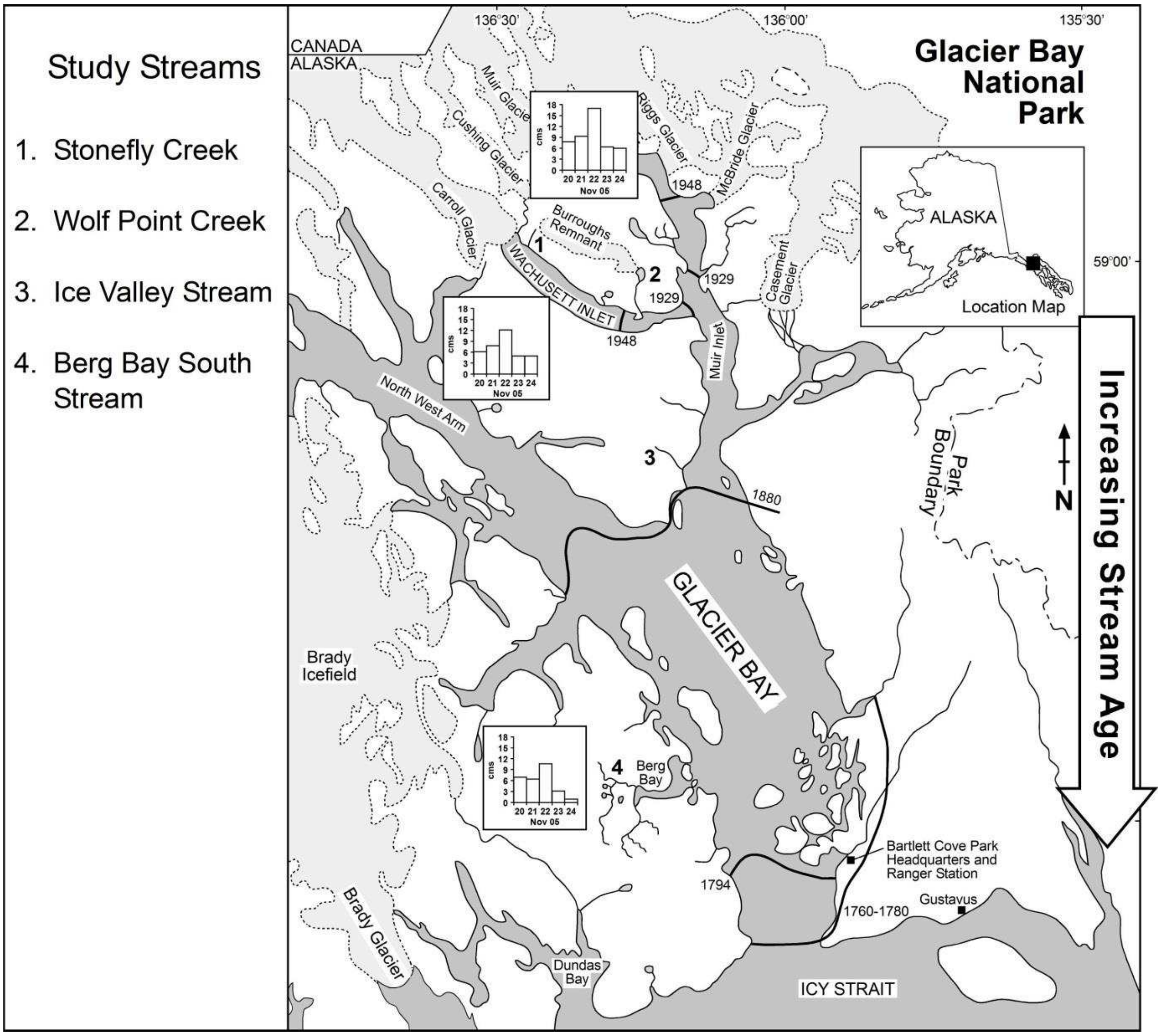

Study Streams
1. Stonefly Creek
2. Wolf Point Creek
3. Ice Valley Stream
4. Berg Bay South Stream
Glacier Bay National Park
CANADA
ALASKA
136°30'
136°00'
135°30'
59°00'
ALASKA
Location Map
Increasing Stream Age
N
Muir Glacier
Cushing Glacier
Carroll Glacier
Riggs Glacier
McBride Glacier
Casement Glacier
Burroughs Remnant
WACHUSETT INLET
Muir Inlet
North West Arm
GLACIER BAY
Brady Icefield
Brady Glacier
Berg Bay
Dundas Bay
ICY STRAIT
Park Boundary
Bartlett Cove Park Headquarters and Ranger Station
Gustavus
1948
1929
1880
1794
1760-1780
cms
Nov 05

Fig. 2

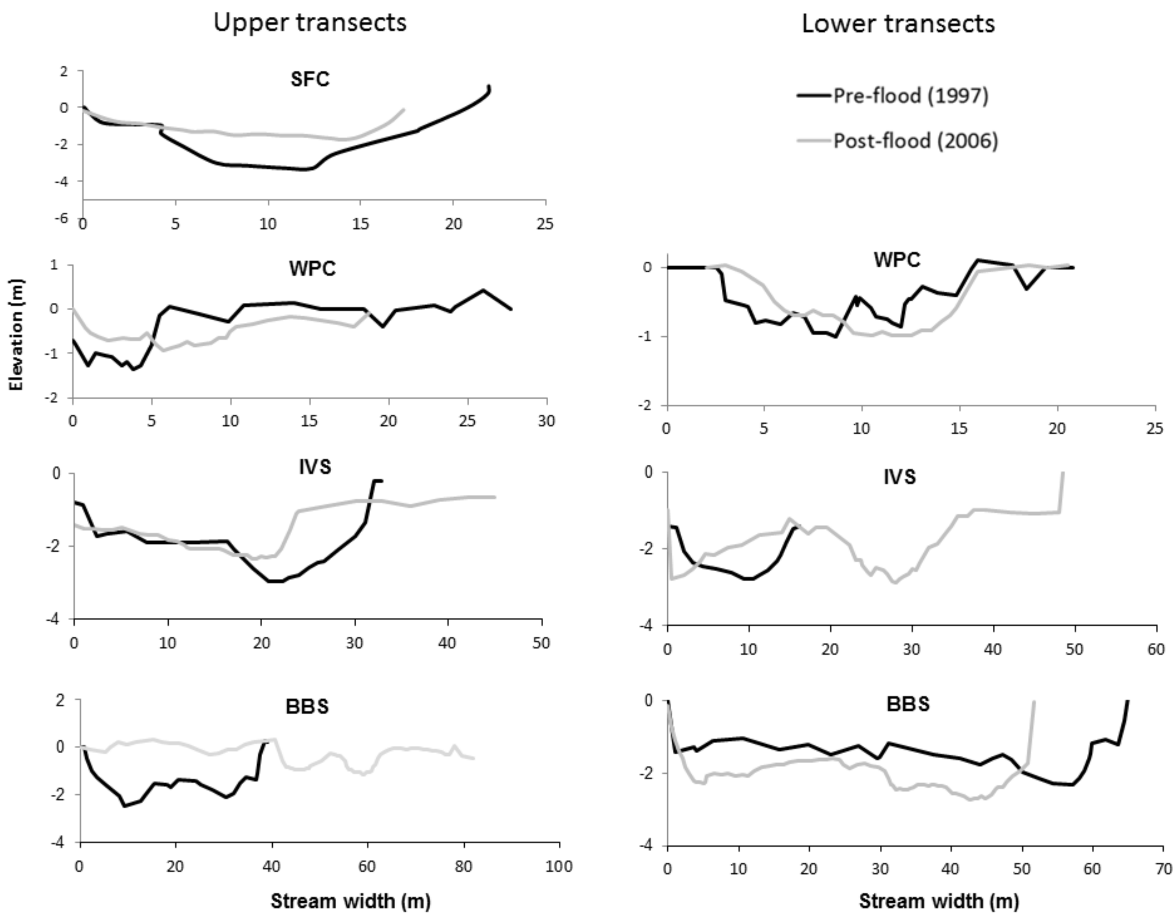

Upper transects
Lower transects
SFC
Pre-flood (1997)
Post-flood (2006)
WPC
WPC
Elevation (m)
IVS
IVS
BBS
BBS
Stream width (m)
Stream width (m)

Fig. 3

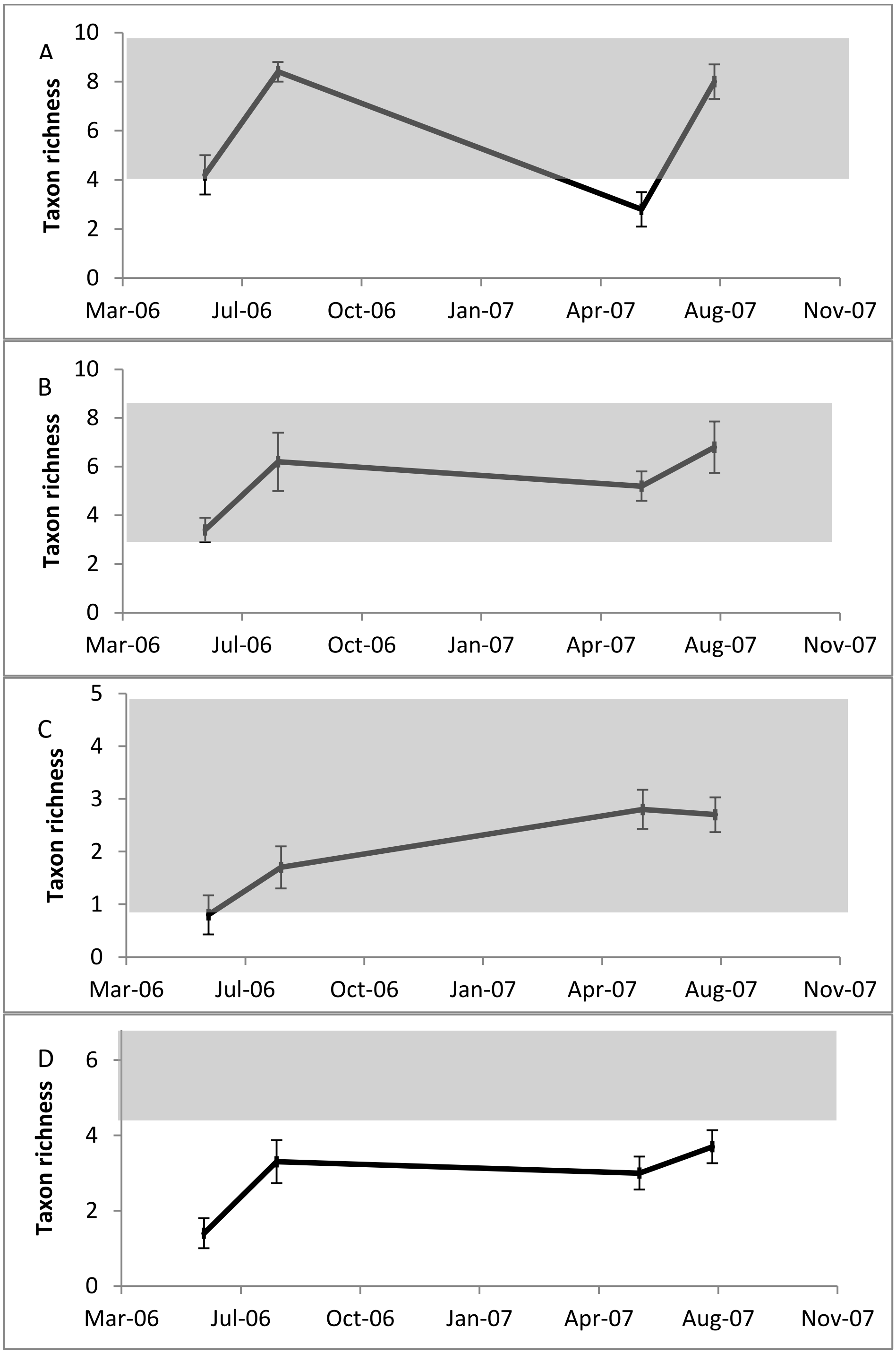

A
B
C
D
Taxon richness
0
2
4
6
8
10
1
3
5
Mar-06
Jul-06
Oct-06
Jan-07
Apr-07
Aug-07
Nov-07

Fig. 4.. A Macroinvertebrates B Meiofauna

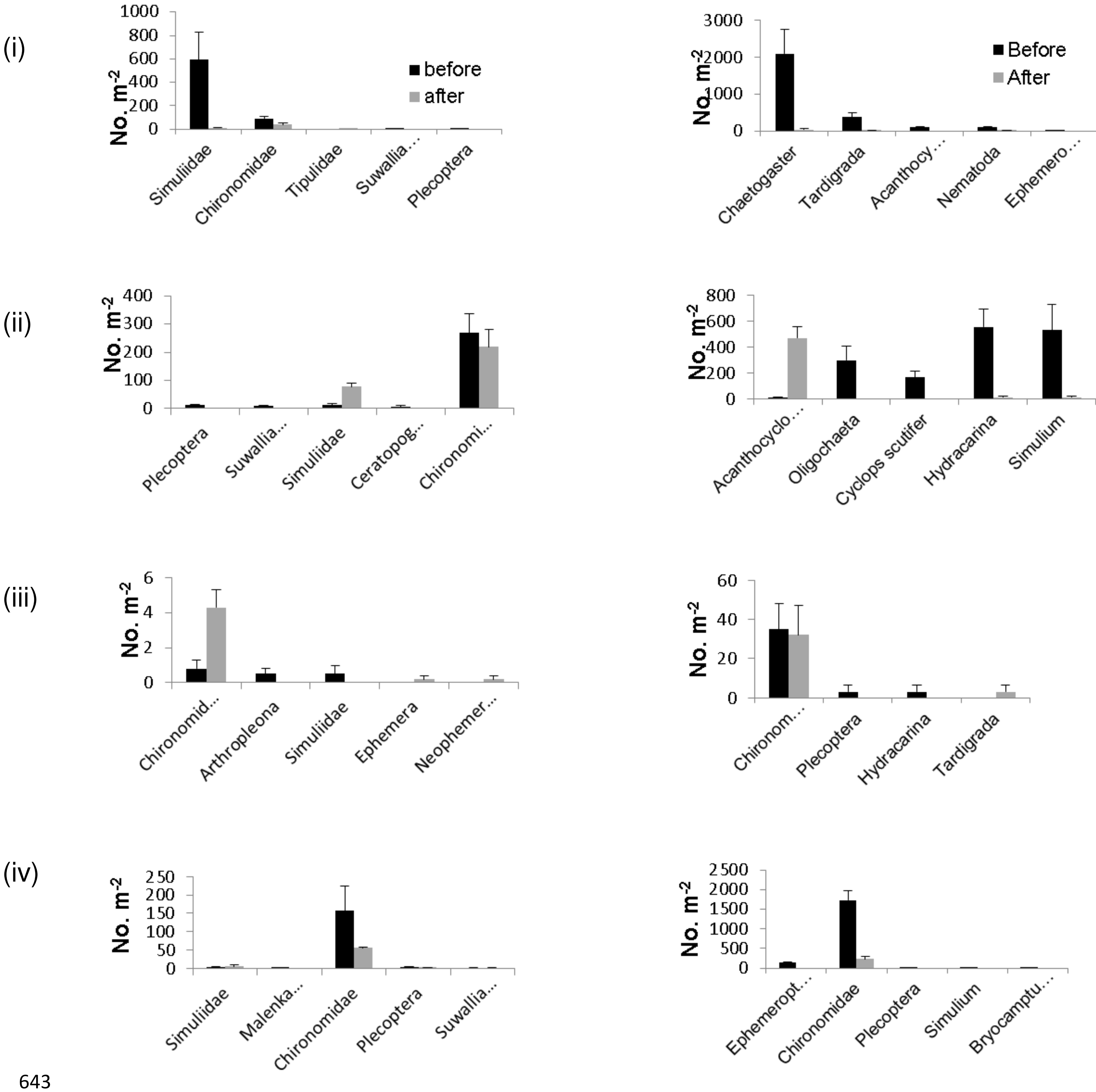
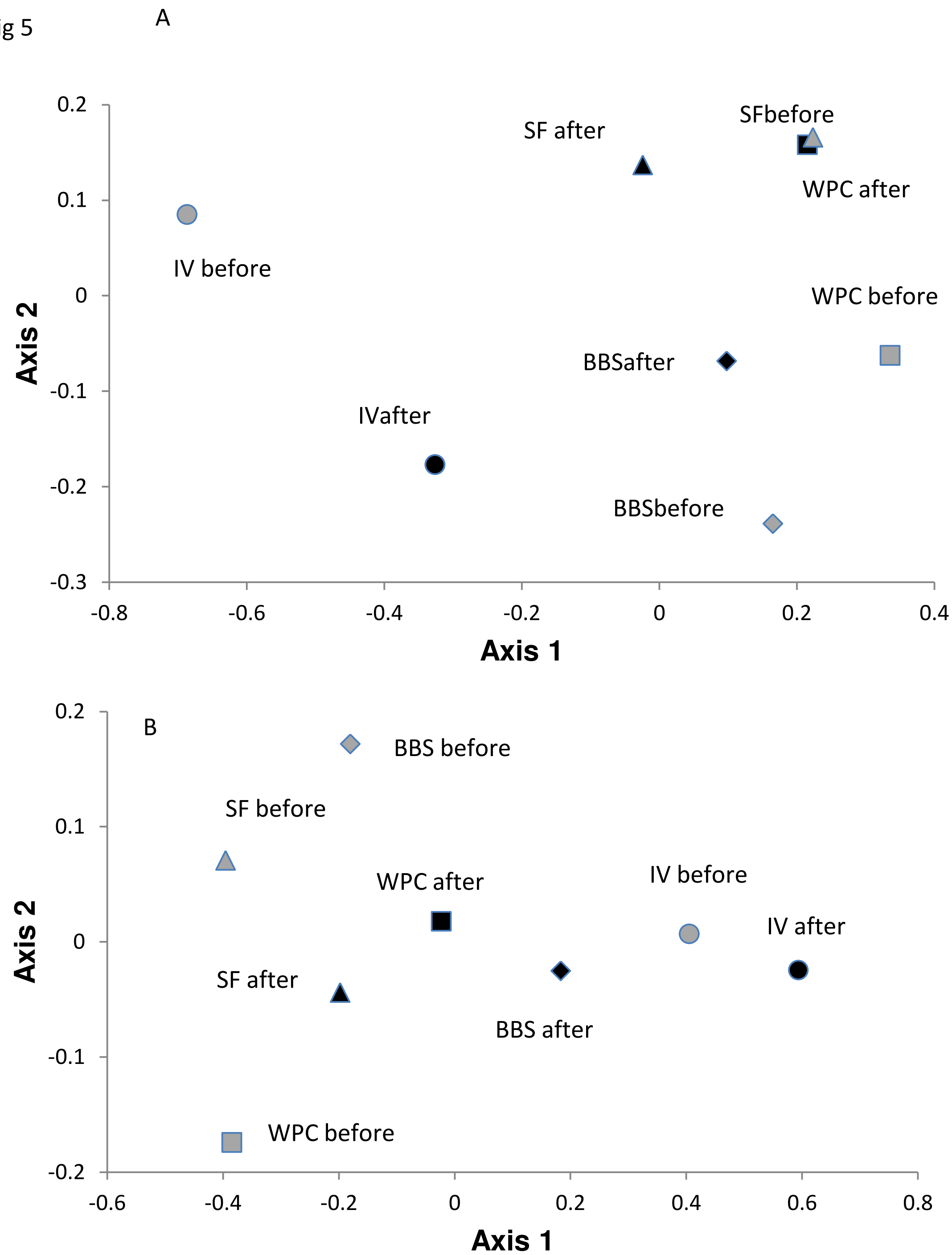


Fig 5


A
SF after
SFbefore
WPC after
IV before
WPC before
BBSafter
IVafter
BBSbefore
Axis 2
Axis 1
0.2
0.1
0
-0.1
-0.2
-0.3
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
B
BBS before
SF before
WPC after
IV before
IV after
SF after
BBS after
WPC before
Axis 2
Axis 1
0.2
0.1
0
-0.1
-0.2
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8