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8 **Understanding processes of island development on an island braided river over**
9 **timescales from days to decades**

10 **Short title: Understanding processes of island development**

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27 **ABSTRACT**

28 Bar colonization by vegetation and subsequent island formation is a key bio-
29 geomorphological process in fluvial landscape evolution. Here we investigate morphological
30 and ecological evolution of river islands over timescales from single floods to decades,
31 focussing on islands initiated by deposited trees that sprout to form vegetated patches.

32 On a braided reach of the high-energy Tagliamento River, Italy, we monitored 30 pioneer
33 islands of 1-17 years age in comparison with unvegetated bar surfaces, open areas between
34 islands, and established islands surfaces. We integrated morphological, surface sediment
35 and vegetation properties of islands initiated by different flood events, combining evidence
36 from remotely-sensed and ground observations, flow and climate time series.

37 At a decadal time scale, pioneer islands aggrade rapidly to the elevation of the mean annual
38 flood, showing a steady increase in vegetation canopy height, fining of surface sediments
39 from predominantly gravel to silty-sand with a notable clay and organic fraction. The
40 standing vegetation included over 130 species, with the largest number on island surfaces of
41 intermediate elevation and flood disturbance. As islands age, standing vegetation becomes
42 comprised mainly of competitor species with transient seed banks and typical of woodland,
43 scrub, pasture and wetland habitats, whereas the winter seedbank is dominated on all
44 surfaces by ruderal species with persistent seedbanks, mainly associated with aquatic,
45 wetland, pasture, arable and wasteland habitats. At shorter timescales, the bio-
46 geomorphological trajectory of pioneer islands is initiated by large flood events that control
47 the elevation of deposited trees, and subsequent flows that control tree survival and
48 establishment. Island morphological evolution depends on the frequency-magnitude of
49 sediment and seed delivery and redistribution by flood and possibly wind events, whereas
50 island ability to retain sediments reflects the degree of vegetation establishment, which in the

51 short-term may vary with seasonal to annual moisture supply, substrate characteristics and
52 climatic growth conditions.

53

54 **KEY WORDS**

55 **river islands, biogeomorphology, fluvial processes, riparian vegetation, wind**

56

57 **INTRODUCTION**

58 Islands provide morphological and biological complexity to river environments (Ward et al.,
59 2002b, Gurnell et al., 2005) and are an important element of river morphodynamics (Hupp
60 and Osterkamp, 1996; Schnauder and Moggridge, 2009). Although the susceptibility of a
61 river reach to island development depends primarily on physical setting and fluvial processes
62 (e.g. Osterkamp, 1998, Osterkamp et al., 2001, Moretto et al., 2014, Perona et al., 2014,
63 Baubiniené et al., 2015, Belletti et al., 2015), river islands develop within susceptible river
64 reaches through interactions between vegetation and fluvial processes (Gurnell et al., 2001,
65 2012). Such interactions have been observed in the field (e.g. Corenblit et al., 2009,
66 Wintenberger et al., 2015, Bywater-Reyes et al., 2017), through analysis of time sequences
67 of aerial images (e.g. Bollati et al., 2015, Mardhiah et al., 2015, Corenblit et al., 2016) and in
68 flume experiments (e.g. Bertoldi et al., 2015, Gran et al., 2015, Diehl et al., 2017).

69 Many different styles of island have been recognised and attributed to a variety of physical
70 processes (e.g. Wyrick and Klingeman, 2011) but island development additionally reflects
71 two broad types of interactions between vegetation and fluvial processes, either singly or in
72 combination (Gurnell et al., 2001, 2012). 'Building' islands evolve as a result of the
73 colonisation of mid-channel bars by vegetation and the further retention and stabilisation of
74 sediment on the bars by vegetation. 'Dissection' islands are created by flows of water across
75 pre-existing vegetated surfaces (e.g. floodplains, large islands), where the flow paths and
76 the success of flows in dissecting the land surface depend to some degree on the
77 distribution and type of vegetation that is present, and the degree to which root systems
78 prevent or redirect the dissection and downcutting process. 'Complex islands' develop from
79 some combination of these two processes.

80 In this paper we focus on 'building' islands, where vegetation colonisation and growth plays
81 a pivotal role in the retention and stabilisation of materials that underpin the island's
82 aggrading morphology. Even in the lowest energy freshwater environments, retention and
83 stabilisation of organic material, created by local vegetation under the influence of plant-
84 groundwater-surface water interactions and related nutrient dynamics, underpins soil
85 formation and the topographic development of 'tree islands' (Wetzel, 2002). As flow energy
86 increases, interactions between plants and physical processes of mineral sediment transfer
87 and retention increasingly drive island development (Bertoldi et al., 2009). In addition, the
88 range of plant species that are able to grow sufficiently rapidly to remain anchored and avoid
89 uprooting or stripping by fluvial processes and to intercept, retain and stabilise organic and
90 mineral sediments, reduces as flow energy increases. Thus, in relatively low energy river
91 environments a range of both woody and non-woody plants can initiate island development
92 by retaining and stabilising mainly finer sediments. However, as flow energy increases,
93 plants that are able to engineer island development are predominantly woody. Furthermore,
94 whereas seedlings of woody plants grow sufficiently rapidly to initiate island development on
95 many rivers, in very high energy systems woody species that are able to propagate
96 vegetatively become the main island engineers because of their ability to rapidly sprout and
97 grow robust above- and below-ground biomass that can withstand strong shear stresses and
98 deep burial during flood events (Gurnell, 2014).

99 Here we build on a conceptual model of island development proposed by Gurnell et al.
100 (2001) that is applicable to high energy rivers of the northern temperate zone, where
101 Salicaceae species dominate the riparian woodland. The model envisages three phases of
102 building island development, from the deposition of entire uprooted trees and other living
103 large wood (i.e. capable of resprouting) on bar surfaces during the falling limb of flood
104 events, through an initial pioneer island phase of sprouting and sediment retention, to an
105 established island phase as a result of the aggradation, enlargement and coalescence of
106 pioneer islands. Since 2001, a number of refinements to the conceptual model have been
107 introduced (Gurnell and Petts, 2002; Gurnell et al., 2012, 2016), and empirical evidence has
108 been presented to support specific aspects of the model, including for example, island
109 morphological (Bertoldi et al., 2011), sedimentological (Gurnell et al., 2008), soil (Mardhiah
110 et al., 2014, Bätz et al., 2015), and vegetation development (Francis et al., 2008, Perona et
111 al., 2014); living wood recruitment and dynamics (Bertoldi et al., 2013); early growth rates of
112 tree seedlings, cuttings and deposited trees (Francis et al., 2005, 2006, Francis and Gurnell,
113 2006, Francis, 2007; Moggridge and Gurnell, 2009) and interactions among developing
114 subsurface tree root and shoot biomass and sediment retention (Holloway et al., 2017 a, b,
115 c). In this paper we integrate empirical evidence of the processes and forms that accompany
116 island evolution over decadal to event timescales, focusing on a single island-braided river
117 reach of the Tagliamento River, Italy. Specifically, we consider:

- 118 (i) Trajectories of island topographic and vegetation canopy development based on
119 the analysis of multi-temporal airborne Lidar data
- 120 (ii) Trajectories of vegetation succession and surface sediment development based
121 on field sampling and measurements conducted on island and inter-island
122 surfaces of different age
- 123 (iii) Short-term (seasonal, event) adjustments reflecting flow and surface sediment
124 dynamics that may influence the longer-term trajectories identified in (i) and (ii)

125

126 **METHODS**

127 The research was conducted on a reach of the braided, gravel-bed Tagliamento River, Italy
128 (Figure 1). The Tagliamento is one of the few European rivers that maintains largely intact
129 morphological and ecological dynamism and complexity along much of its length, and is
130 therefore considered a reference river system for the Alps and a model system for large
131 rivers (Tockner et al., 2003). The river runs 172 km from source to mouth and its climate
132 varies from alpine to mediterranean. Most importantly for this research, it maintains river
133 islands along several reaches, which have been the focus of a range of
134 hydrogeomorphological and ecological investigations over the last two decades (see Gurnell,
135 2016). The island-braided reach focused on here (46°12' N, 12°59' E) is in the prealpine
136 section (140 m a.s.l.) and has a wet mediterranean climate with a mean annual precipitation
137 of approximately 2000 mm. Peak river flows are in spring (snowmelt) and autumn (rainfall).
138 The water table at the study site showed subdued variation through the year as a result of
139 groundwater upwelling induced by local narrowing of the river valley towards a gorge section
140 approximately 2 km downstream.

141 Information was assembled from airborne Lidar surveys, river stage records, field campaigns
142 and the laboratory analysis of field samples to investigate the morphological, surface
143 sediment and vegetation evolutionary characteristics of islands within the study area. The
144 timing of the Lidar surveys, tree deposition events that initiated the studied pioneer islands,
145 and field measurement campaigns are plotted in relation to the January 2000 to February
146 2017 time series of daily river stage (corrected to detrended elevations within the study
147 reach, see below for correction method) in Figure 2.

148

149 **Lidar data, river stage and climate station records**

150 Three airborne Lidar surveys were available for analysis, captured in May 2005, August
151 2010 and October 2013. The Lidar surveys covered the study reach and had a spatial
152 resolution ranging from 1 (2005 survey) to approximately 10 points/m² (2013 survey). These
153 were analysed to obtain tree canopy height and detrended surface elevations for all field
154 sampling locations on surfaces of different age and type (see the following subsection on
155 'Field sampling and measurements').

156 The free software FUSION, developed by the U.S. Department of Agriculture, Forest
157 Service, Remote Sensing Applications Center (available at <http://www.fs.fed.us/eng/rsac/>)
158 was employed to filter the Lidar point cloud differentiating between ground points and
159 vegetation points. From this information we obtained a Digital Elevation Model (DEM) and a
160 Canopy Surface Model (CSM), with a spatial resolution of 2 m for 2005 and 1 m for 2010
161 and 2013 (see Bertoldi et al., 2011 for further details). River bed and vegetation canopy
162 elevations were extracted from these two raster data sets within circular areas of 5 m radius
163 centred on the 2016/2017 field sampling locations. Since there was considerable flood
164 disturbance of lower areas of the river bed between October 2013, when the most recent
165 Lidar data were captured, and 2014, when the trees initiating the youngest studied pioneer
166 islands were deposited, analysis of the Lidar data was confined to sampling points on
167 established islands (probably initiated in the mid to late 1970s, hereafter conservatively
168 labelled 1980), pioneer islands initiated in 2000 and 2004, and surfaces between the 2000
169 and 2004 islands.

170 The extracted elevation data was detrended to remove the impact of the down-valley slope
171 and thus highlight the relative cross-sectional river bed elevation of the sampling locations
172 and sites. Detrending was achieved by computing a moving average of the 2005 DEM,
173 based on an 800 m square window (800 m approximates the typical width of the active river
174 corridor). Within each 800 m square window, areas outside of the active corridor were
175 excluded when calculating the average bed elevation, which was then subtracted from all
176 three DEMs to allow for a direct comparison of the temporal evolution of the different
177 surfaces.

178 In order to explore the degree to which detrended surface elevation and vegetation canopy
179 height varied across the different sampled surfaces, through time, and in relation to
180 interactions between surfaces and time, generalised linear models were estimated to explore
181 the dependence of vegetation canopy height and surface elevation on sampled surfaces,
182 year of Lidar observation, and interactions between surface and year. The statistical
183 significance of differences between particular surfaces, years and surface-year interactions
184 were explored using the Bonferroni method ($P < 0.05$).

185 River stage records from the Villuzza gauging station, located approximately 2 km
186 downstream from the study reach, provided information on flow events and sequences to aid
187 interpretation of the morphological, sedimentary and vegetation data sets that were
188 collected. River stage at Villuzza was linked to the detrended bed surface elevation of the
189 study reach using oblique photographs captured with a temporal resolution of one hour by
190 applying the method described by Bertoldi et al. (2009) and further developed by Welber et
191 al. (2012). Inundation maps at different flow stage were compared to the 2010 and 2013
192 DEMs to obtain a relationship that transformed the river stage measured at Villuzza into the
193 detrended DEM elevation coordinates. This allowed the frequency of inundation of the
194 sampled locations and sites, based on 2000-2017 daily maximum stage records, to be
195 estimated as well as their potential inundation between the two sampling campaigns in 2016
196 and 2017.

197 Air temperature, solar radiant energy exposure, precipitation and wind speed data from a
198 climatological station at Osoppo, about 7 km upstream (North-East) of the study reach, was
199 used to explore conditions relevant to the interpretation of field data. In particular, air

200 temperature data were used to estimate accumulated Growing Degree Days (GDD) that
201 could indicate likely vegetation development at the time of field surveys. GDD was estimated
202 as follows:

$$203 \text{ accumulated GDD} = \sum_1^n \left(\frac{T_{max} + T_{min}}{2} - T_{base} \right)$$

204 Where T_{max} and T_{min} are the maximum and minimum temperature on each day, T_{base} is
205 10°C , 1 is 1st January and n is the Julian day for which the estimate is required. This was
206 complemented by analysis of accumulated solar radiant energy exposure.

207 Wind speed and precipitation data were combined with river stage information from the
208 Viluzza gauge to explore climate conditions between field surveys.

209

210 **Field sampling and measurements**

211 Several types of sampling and measurement were undertaken in the field.

212 Surface sediments were sampled from 14th to 17th June 2016 and 22nd to 23rd February 2017
213 to investigate their calibre, organic content and viable seed content. Following previous
214 detailed analysis of historical air photographs to confirm timing of tree deposition / island
215 initiation and estimation of contemporary tree ages using dendrochronology (Mardhiah et al.,
216 2015), samples were taken from surfaces of known age representing established islands (EI)
217 initiated in the mid to late 1970s (1980EI); pioneer islands (PI) initiated during floods in late
218 2000, 2004 and 2014 (2000PI, 2004PI, 2014PI); areas between (btwn) 2000 and 2004
219 pioneer islands (2000btwn, 2004btwn) and across the unvegetated surface of gravel bars
220 (unveg). Sampling on 2000, 2004 and 2014 pioneer islands centred on the largest central
221 tree (2000PI, 2004PI) or a central point along the deposited tree (2014PI); the largest
222 (oldest) trees on established islands (1980EI); locations close to the sampled pioneer islands
223 but not on island surfaces (2000btwn, 2004btwn) and randomly located locations on
224 unvegetated bar surfaces (unveg). In each case a cylindrical, 6 cm diameter sediment sub-
225 sample was taken to a depth of 5 cm at the central location and at approximately 5m
226 upstream, downstream and to either side of this central location. Where sampled pioneer
227 islands were less than 10 m in either length or width, sub-samples were taken as far as
228 possible from the centre up to a distance of 5 m but within the morphological limits of the
229 island. A single aggregate sample was generated for each sampling location by combining
230 these five subsamples. Aggregate samples were obtained from ten different sampling
231 locations (Figure 1) for each of the surfaces of different age (1980EI, 2000PI, 2004PI,
232 2014PI, 2000btwn, 2004btwn, unveg). This yielded a total of 70 aggregate samples for June
233 2016 and 69 for February 2017 (one 2014 pioneer island was removed by an intervening
234 flood and so could not be sampled). Although islands exhibit high vertical heterogeneity and
235 distinct layering of sediments as a legacy of past disturbance events, previous investigations
236 of sediment profiles to depths of over 1.5 m below the surface of established islands have
237 revealed a weak upward fining of sediments, typically with a distinct sand and finer layer at
238 the surface (for example, see profiles illustrated in Holloway et al., 2017b). In the present
239 analysis, we focused on the top 5cm of sediment as this is not only indicative of the most
240 recent sediment deposition but, as a consequence, it is most likely to contain viable
241 propagules, recently deposited through local seed fall, anemochory or hydrochory. It is also
242 the most relevant to plant germination. Furthermore, seed bank studies are typically
243 conducted on samples taken to a depth of 5 cm (Thompson et al., 1997).

244 In addition to sampling surface sediments, in June 2016 the height of the 2000PI and 2004PI
245 central trees was also measured using a clinometer, and a vegetation survey was conducted
246 at 5 of the sampling locations (area approximately 10m x 10m) on each of the island
247 surfaces of different age (1980EI, 2000PI, 2004PI, 2014PI). Information was also available
248 from a vegetation survey conducted in July 2011 using the same methodology. This survey

249 focussed on five 2000, five 2004 and five 2010 pioneer islands. The last were almost 1 year
250 old at the time of the 2011 survey and so provide a comparison with the 2014 pioneer
251 islands that were approximately 1.5 years old when surveyed in 2016.

252

253 **Surface sediment analysis**

254 Following field sampling, all the aggregate surface sediment samples were air dried and
255 passed through a 4 mm sieve at the field station to ensure retention of all viable seeds. The
256 weight of sediment and coarse organic material in the >4 mm fraction were separately
257 weighed at the field station and an approximate 300 g subsample of the <4 mm fraction was
258 transferred to a UK laboratory for organic matter and particle size analysis (described in this
259 section) and investigation of the soil seed bank (described in the following section).

260 In the laboratory, organic content of the <4 mm fraction of all 139 samples was determined
261 by loss on ignition, and the mineral particle size distribution was determined at a resolution
262 of 1 ϕ from -2 ϕ (4 mm) to -12 ϕ by sieving through 2 mm (-1 ϕ) and 1 mm (0 ϕ) sieves and
263 then passing a subsample of the <1 mm fraction through a laser sizer to identify the particle
264 size distribution below 1 mm (0 ϕ).

265 Multivariate analyses were used to investigate broad patterns in the values of six summary
266 properties of the surface sediments: %organic (of the total sample), D50 (ϕ), %gravel,
267 %sand, %silt, %clay (of the total mineral fraction). The six variable data set was analysed
268 using Agglomerative Hierarchical Cluster Analysis (AHC) with Euclidean distance as the
269 distance measure and Ward's clustering algorithm. The number of clusters that most
270 effectively summarised variations in the samples was selected using the AHC agglomeration
271 schedule plot coupled with an analysis of the statistical significance of differences among the
272 six surface sediment properties between the clusters. The statistical significance of
273 differences between clusters was assessed using Kruskal Wallis tests followed by multiple
274 pairwise comparisons using Dunn's procedure with Bonferroni correction of the significance
275 level. This non-parametric test was selected because most of the variables were measured
276 on a percentage scale, and thus values were confined to the range 0 to 100.

277 Principal Components Analysis (PCA) was also applied to the six surface sediment property
278 data set to assess whether any broad gradients were present in the data that could support
279 interpretation of contrasts between the sampled surfaces of different age and type. Because
280 most of the surface sediment properties were expressed as percentages, the PCA was
281 performed on a (non-parametric) rank correlation matrix. In order to illustrate contrasts
282 between the surface sediment classes identified by AHC, samples were coded by sediment
283 cluster or class on a scatter plot of each sample's score on the first two PCs.

284 An average distribution for each surface age and sampling date (i.e. averages of ten particle
285 size distributions) was calculated for particle size distributions for the <1mm (0 ϕ) mineral
286 fraction (i.e. coarse sand and finer), which was entirely analysed by laser sizer. Overlays of
287 the average distributions were used to explore changes in the composition of the mineral
288 sediment in this coarse sand and finer fraction between sampling dates on the surfaces of
289 different age. The differences between groups of particle size distributions drawn from
290 different surfaces on two sampling dates (June 2016, February 2017) were investigated by
291 estimating generalised linear models for each of the ten, fifty and ninety percentiles (D10,
292 D50, D90) of the particle size distributions, using sampling year (2016, 2017), surface
293 (1980EI, 2000PI, 2000btwn, 2004PI, 2004btwn, 2014PI, unveg) and interactions between
294 year and surface as the explanatory variables. The percentile values were estimated using
295 Gradistat software (Blott and Pye, 2001) and are expressed in ϕ units. The statistical
296 significance of differences between groups was established using the Bonferroni method
297 ($P < 0.05$).

298

299 **Standing vegetation and soil seed bank analysis**

300 The viable seed bank contained in the February 2017 surface sediment samples was
301 quantified using germination trials. By gathering surface sediments in February, only the
302 more persistent seed bank was sampled, since few species produce seeds during winter.
303 Subsamples of 60 gms weight were extracted from the <4 mm fraction of the aggregated
304 surface sediment samples from each sampling location and were refrigerated (*circa* 4°C) on
305 arrival at the laboratory. These were stored until June 2017, when a 10 week germination
306 trial was conducted in outdoor poly-tunnels. No artificial lighting or heating was used in the
307 tunnels. The sediment subsamples were sprinkled onto 3 cm deep sterile soil (John Innes
308 #2) in 10 cm x 20 cm seed trays. The seed trays were watered regularly to maintain the soil
309 at field capacity, and the trays were rearranged in the poly-tunnels at the end of each week
310 to randomise germination conditions. As seeds germinated, the seedlings were identified to
311 species and then removed from the trays. In some cases the seedlings were transferred to
312 individual pots and grown on to support species identification. From these data, the number
313 of viable seeds per m² and seed species composition were estimated for each sample. In
314 order to compare with other living components of organic material in the sampled sediments,
315 information on seed abundance (seeds per m²) in the February 2017 seedbank was
316 compared with information on root and hyphal length collected across islands of different
317 age (1980, 2000, 2004, 2010) and unvegetated bar surfaces (unveg) during May 2012 (for
318 analytical methods see Mardhiah et al., 2014).

319 The standing vegetation was also surveyed on two occasions. Between 18 and 20 June
320 2016, the standing vegetation was recorded on five pioneer island and established island
321 surfaces of different age (2014PI, 2004PI, 2000PI, 1980EI). A walk over survey was
322 conducted within the approximate 10m by 10m area from which surface sediment samples
323 were taken and the presence of plant species was recorded within a search period of up to 1
324 hour. A survey of the standing vegetation was also conducted between 22 and 25 July 2011
325 using exactly the same methods as in June 2016, although only pioneer islands were
326 surveyed. Five randomly selected pioneer islands dating from each of 2000, 2004 and 2010
327 (close to 1 year old at the time of survey) were surveyed.

328 Using information from Hodgson et al. (1995), the seed bank type (i.e. transient, short-term
329 persistent, long-term persistent), most common terminal habitat, and functional type (Grime
330 et al., 2007) were identified for as many of the species recorded in the standing vegetation
331 and seed bank as was possible. For functional type, a score between 0 and 1 was assigned
332 to C (competitor), S (stress-tolerator) and R (ruderal) components of the CSR functional type
333 for each species (Hunt et al., 2004) to allow quantitative comparisons between sampling
334 locations and between the species found in the two standing vegetation surveys and the
335 seedbank germination trial. These properties of the standing vegetation and seedbank were
336 then displayed using bar graphs to explore any apparent changes in the proportions of
337 functional types present according to surface age. Similarities in the species composition of
338 the standing vegetation and viable seed bank were assessed using Agglomerative
339 Hierarchical Cluster analysis with the Jaccard coefficient as the similarity measure and
340 clustering determined using the unweighted pair group average.

341 All statistical analyses presented in this paper were conducted using Minitab 18 or XLSTAT
342 2017.

343

344 **RESULTS**

345 **Surface elevations and inundation frequency.**

346 A generalised linear model revealed statistically significant variations in detrended river bed
347 elevation across different surfaces and through the time sequence of Lidar surveys, but
348 there were no significant interactions between surfaces and time (Table 1). Bed elevations
349 were significantly higher in 2013 and 2010 in comparison with 2005, and the sampling sites
350 on the 1980 established island surfaces were significantly higher than the pioneer island and
351 between-island sampling sites initiated in 2000, which were in turn significantly higher than
352 surfaces initiated in 2004. However, there was high variance in the elevation of the pioneer
353 island and between island surfaces initiated in 2000 and 2004, and thus there was no
354 statistically significant difference in the elevation of the pioneer island and between island
355 surfaces initiated in either 2000 or in 2004.

356 The inter-quartile ranges in the detrended elevation of sampling locations on the 1980, 2000
357 and 2004 surfaces are illustrated in Figure 3 in relation to the water level duration curve
358 (estimated from 2000-2017 daily maximum stage records at Viluzza). The interquartile
359 ranges indicate that at the time of the 2005 Lidar survey, the recently deposited 2004PI were
360 inundated between approximately 9 and 40 days each year, whereas the 2000PI were
361 inundated between 0.8 and 3 days per year and the 1980EI were sufficiently elevated that
362 they were not inundated by the 2 year return period flood. These large differences in
363 inundation frequency explain why the interquartile ranges indicate a clear increase in
364 detrended surface elevation of the 2004PI and 2004btwn sampling locations through time.
365 The upper quartile of these elevations reaches the lower quartile of the 2000PI and
366 2000btwn sampling locations by 2013. The maximum water stage reached between
367 sediment sampling campaigns in June 2016 and February 2017 is also indicated on Figure
368 3, showing that most of the 2004 sampling locations were inundated during this period,
369 whereas all of the 1980EI and most of the 2000PI and 2000btwn sampling locations were
370 not inundated.

371

372 **Surface sediment composition**

373 AHC applied to six surface sediment properties (D50(ϕ), %organic, %gravel, %sand, %silt,
374 %clay) yielded six significantly different clusters, which characterised distinct sediment
375 classes within the 139 aggregate samples that were analysed. The number of samples
376 assigned to each class and the centroid values of each surface sediment property within the
377 six classes are presented in Table 2 and the degree to which each of the six properties
378 displayed by sediment samples assigned to each class displayed significant differences are
379 also summarised in Table 2.

380 PCA identified two major gradients or PCs that together explained 93% of the variance in the
381 six variable data set. Focussing on high (>0.7 and <-0.7) PC loadings (Table 3), PC1
382 describes a gradient of decreasing %gravel (high negative loading) and increasing %silt,
383 %clay, %organic and median particle size (D50 in ϕ units indicating sediment fining) (high
384 positive loadings), whereas PC2 describes an independent gradient of increasing %sand.

385 The AHC and PCA results are combined in Figure 4, where they can be compared with the
386 surface type, age and survey year relevant to each sample, displayed on a scatter plot of the
387 sample scores on the first and second PCs identified in the PCA. These scatter plots
388 indicate that samples drawn from unvegetated bar surfaces (unveg), between pioneer
389 islands (2000btwn, 2004btwn) and from the youngest pioneer islands (2014PI) (Figure 4 (i))
390 are predominantly associated with gravel, gravel-sand and sand-gravel sediments (classes
391 A, B, C, Figure 4 (iv)). The older pioneer (2004PI, 2000PI) and established (1980EI) islands
392 show a range of surface sediment sizes from predominantly sand, through sand with some
393 silt, to sand-silt sediments, with a progressive increase in the D50 (in ϕ units, indicating
394 sediment fining) and organic content (classes D,E,F, Figure 4 (iii)) with increasing surface
395 age (Figure 4 (v)). There is also some evidence of a change in surface sediment
396 characteristics between summer 2016 and late winter 2017 (Figure 4 (ii)), particularly a shift

397 from sand towards silt and clay (Figure 4 (iii)) in the area on the right of the plot, where
398 scores on PC1 exceed 0 (Figure 4 (ii)).

399 Focussing on the <1mm (>0 ϕ , coarse sand and finer) sediment fraction (Figure 5), which is
400 the size fraction analysed entirely by laser sizer, the average particle size distribution for all
401 surfaces appears to fine between June 2016 samples and February 2017 apart from those
402 extracted from established island (1980EI) and unvegetated surfaces (Figure 5, compare A
403 and C with B and D). The most pronounced changes are observed for the 2004PI, 2014PI
404 and 2004btwn locations. The change for 2014PI is particularly noticeable, moving from a
405 distribution that is very similar to the unvegetated (unveg) surfaces in 2016 to a distribution
406 that is approaching that of the vegetated surfaces (2004PI, 2000PI, 1980EI) in 2017,
407 indicating a fast evolution of these finer sediments on pioneer islands in their first 1 to 2
408 years.

409 This apparent fining trend in the < 1mm fraction is supported by box plots and generalised
410 linear models for the D10, D50 and D90 percentiles (in ϕ units) of the 10 individual particle
411 size distributions within each of the surface and sampling time groups (Figure 5E, F and G).
412 The generalised linear model for the coarsest percentile (D10, Table 4), explains 66% of the
413 variance, with a statistically significant overall fining of sediment between years, a significant
414 decrease in the D10 particle size between the older island surfaces (1980EI, 2000PI,
415 2004PI), the youngest PI and oldest between island surfaces (2014PI, 2000btwn), and the
416 youngest between island and unvegetated bar surfaces (2004btwn, gravel). There were no
417 statistically significant interactions between surfaces and year. This is supported by the box
418 plots (Figure 5E), which show little change between years apart from a slight hint of fining on
419 the youngest island (2014PI) surfaces. The results from this analysis should be treated with
420 a little caution because some estimated D10 values for the coarsest samples (mainly from
421 2004btwn and unveg surfaces) fall between 0 and -1 ϕ (i.e. slightly larger than the less than
422 1 mm (0 ϕ) range of the analysed data). This is an artefact of the very large percentage of
423 particles in the 0 to 1 ϕ fraction in these relatively coarse samples, which have highly skewed
424 frequency distributions. The model for D50 particle size is similar to that for D10 (Table 4,
425 Figure 5F), explaining 62% of the variance, and revealing the same statistically significant
426 patterns in fining between years and surfaces with no statistically significant interactions
427 between years and surfaces. However, the finest percentile (D90) reveals a more complex
428 fining pattern (Figure 5G, Table 4). The generalised linear model explains 57% in the
429 variance of D90. Once again there is a statistically significant overall fining of surface
430 sediment between years. The older island surfaces (1980EI, 2000PI, 2004PI) are finer than
431 the between island surfaces (2000btwn, 2004btwn), which are finer than the open,
432 unvegetated surfaces (unveg). In addition, the youngest island surfaces (2014PI) are finer
433 than the unvegetated bar surfaces (unveg). There are also some significant year-surface
434 interactions within the D90 data. The older island surfaces in both years (1980EI, 2000PI,
435 2004PI) and the youngest island and between island surfaces (2014PI, 2000btwn,
436 2004btwn) in 2017 are finer than the between island surfaces (2000btwn, 2004btwn) in
437 2016 and the unvegetated surfaces (unveg) in both years. These results illustrate a stronger
438 fining of between island and younger island (2014PI, 2000btwn, 2004btwn) surfaces than
439 other surfaces between the two survey years.

440 A final investigated property of the surface sediments was the living organic material that
441 they contain. Some living components are illustrated in Figure 6, including viable seeds per
442 m² estimated from the February 2017 surface sediment samples (Figure 6B), and the fungal
443 hyphae (Figure 6C) and root content (Figure 6D) estimated from samples extracted from
444 different surfaces during May 2012 by Mardhiah et al. (2014). Each of the three graphs in
445 Figures 6 B, C and D represents a snap shot of properties that vary greatly through time.
446 However, it is interesting to note that while roots and hyphae, which are largely developed *in*
447 *situ*, show a steady increase with surface age, seeds, which may be deposited locally but
448 are also subject to transport and deposition by various agents (e.g. water, wind), show a

449 more variable pattern with greatest abundance on the 2004PI surfaces at the time of
450 sampling, whereas unvegetated surfaces show the lowest abundance.

451

452 **Vegetation**

453 Vegetation canopy height estimates from the three Lidar surveys (2005, 2010, 2013) and
454 field clinometer measurements (2016) are shown in Figure 6A. Clinometer measurements
455 were only made at the 2004PI and 2000PI sampling locations, where both the top of the
456 canopy and the underlying ground surface could be seen clearly from a single measurement
457 point and thus accurately measured. The two box plots for these 2016 field measurements
458 indicate a realistic increase from the earlier Lidar estimates for the same surfaces and
459 sampling locations, suggesting that the Lidar estimates of canopy height for the other three
460 dates are quite accurate. Overall the island surface data (1980EI, 2000PI, 2004PI)
461 presented in Figure 6A define a growth curve for the *P. nigra* dominated woodland within the
462 reach. This indicates rapid vertical growth of approximately 1m each year for at least the first
463 15 years, after which vertical growth reduces as this species approaches maturity. The data
464 also illustrate the development of some vegetation cover between pioneer islands.

465 A generalised linear model for vegetation canopy height reveals statistically significant
466 ($P < 0.05$) differences among the surfaces, through the time sequence of surveys, and also
467 significant interactions between surfaces and time (Table 1). Canopy height increased
468 significantly from 2005 to 2010 and then to 2013. Furthermore, the canopy was higher at
469 1980EI locations than at 2000PI locations, which was in turn higher than at 2004PI locations,
470 and again higher than at 2000btwn and 2004btwn locations. Significant interactions illustrate
471 how in 2005 all 2000PI and 2004PI surfaces had a low vegetation canopy that was not
472 significantly different from the 2000btwn and 2004btwn locations. However, in later surveys,
473 the canopy progressively increased in height across the 2000PI and 2004PI surfaces, so
474 that the canopy on 2000PI surfaces in 2013 was significantly higher than that on 2000PI
475 surfaces in 2010 and the canopy on 2004PI surfaces in 2013, and these in turn were higher
476 than the canopy on 2004PI surfaces in 2010. The 1980EI surfaces supported the highest
477 vegetation canopy at all dates.

478 The composition of the vegetation was explored in July 2011 and June 2016 through walk-
479 over surveys of 5 pioneer islands of three different ages. Pioneer islands initiated in 2000
480 and 2004 were explored on both dates as well as newly formed pioneer islands (2010PI in
481 the 2011 survey and 2014PI in the 2016 survey). In addition surveys at five of the 1980EI
482 sampling locations were explored in 2016. Viable seed species were also identified for all
483 2017 sampled surfaces (1980EI, 2000PI, 2004PI, 2014PI, 2000btwn, 2004btwn, unveg).

484 In total, 138 plant species were identified across the three surveys. In addition to the earlier
485 survey date, there was a colder spring in 2016 than in 2011. The accumulated growing
486 degree days (GDD) to 18 June 2016, when the vegetation survey commenced, was 470 in
487 comparison with 632 to the same date in 2011, and the accumulated GDD to 22 July 2011,
488 when the vegetation survey commenced in 2011, was 1040. The accumulated solar radiant
489 energy exposure from 1st January to 18th June 2016 was 1752 MJ/m² and from 1st January to
490 18th June 2011 was 2339 MJ/m² (about 33% more than in 2016 for the same time period).
491 The accumulated solar radiant energy from 1st January to 22nd July 2011 was 3104 MJ/m².
492 These contrasts in accumulated GDD and solar energy receipt probably explain differences
493 in the standing vegetation. Few species were in flower and many species had probably not
494 emerged sufficiently to be recorded during the June 2016 vegetation survey, whereas
495 vegetation development was much more advanced during the 2011 survey. While 105
496 species were recorded in the standing vegetation in July 2011, only 76 were recorded in
497 June 2016, and only 30 were recorded in the February 2017 seed bank. Of the 138 recorded
498 species, seven (less than 5%) were alien (*Amorpha fruticosa*, *Aster novi-belgii*, *Buddleja*
499 *daurica*, *Conyza Canadensis*, *Datura stramonium*, *Juncus tenuis*, *Robinia pseudoacacia*). Of

500 the 30 species identified in the seedbank only two (7%) were alien: *Buddleja davidii* and
501 *Juncus tenuis*. The number of viable seeds in the winter seedbank should also be
502 considered in the light of the stark contrasts in the longevity of the seedbanks associated
503 with the standing vegetation observed across the different types and ages of sampled
504 surfaces described below.

505 Agglomerative Hierarchical Cluster Analysis was used to explore the similarity in species
506 composition of the standing vegetation (2011, 2016) and the seed bank (2017) (Figure 7).
507 The seed bank composition showed very little similarity to the standing vegetation. There
508 was also a contrast in species composition displayed by the two standing vegetation
509 surveys. The species composition of pioneer islands surveyed in 2011 showed reasonable
510 similarity and clustered in turn with the 2000 and 2014 pioneer islands surveyed in June
511 2016. However, the vegetation species composition of 2004 pioneer islands surveyed in
512 2016 was most similar to the 1980 established islands, whereas that of the 2000 pioneer
513 islands surveyed in 2016 was most similar to the 2014 pioneer islands. Furthermore,
514 vegetation composition of the latter was more similar to pioneer islands surveyed in 2011
515 than to the 2016 vegetation of the 2004PI and 1980EI surfaces. This illustrates some notable
516 differences in the rate of development of vegetation on pioneer islands of different date.

517 Broad characteristics of the identified species are summarised in Figure 8. Far fewer species
518 were found in the seed bank than in the standing vegetation (Figure 8A). Information on 67%
519 (92) of these species was extracted from Hodgson et al. (1995) and Grime et al. (2007). In a
520 few these cases, where the specific species was not included, it was possible to extract plant
521 strategies and characteristics based on closely related species in the same genus. The
522 number of species according to data source (seed bank, standing vegetation), sampling date
523 and surface type for which characteristics were extracted from Hodgson et al. (1995) is
524 illustrated in Figure 8A (labelled 'species analysed'). Three characteristics of the analysed
525 species - functional type, seed bank type, typical terminal habitat type - are summarised in
526 Figures 8B, C and D, respectively, across the seed bank and standing vegetation data sets
527 for surfaces of different age.

528 The February 2017 seed bank was dominated by species whose primary strategy was
529 ruderal, whereas predominantly competitor species were present in the standing vegetation
530 (Figure 8B). Furthermore, the competitor strategy was stronger in species observed on the
531 2004 and 2000 pioneer islands and 1980 established islands than on the early stage pioneer
532 islands (2010 and 2014). Seed bank persistence also varied across the species identified in
533 the seed bank and standing vegetation (Figure 8C), with the seed bank, particularly on
534 unvegetated bar and between-pioneer island surfaces, being dominated by species
535 associated with a long-term persistent seed bank (i.e. seeds remaining viable for at least five
536 years), whereas the standing vegetation on pioneer and established island surfaces shows
537 an increasing proportion of species associated with a transient seed bank (i.e. seeds that
538 rarely remain viable for more than a year) as the age of the surface increases. The 1980EI
539 surfaces are dominated by species with a transient seed bank (62% species) and a very
540 small proportion (15%) are associated with a long term persistent seed bank.

541 There are also strong contrasts in the commonest terminal habitat with which the species
542 are associated (Figure 8D). In Figure 8D, the terminal habitats listed in Hodgson et al. (1995)
543 have been aggregated into broad groups related to moisture, vegetation cover and type and
544 degree of natural or human disturbance. The February 2017 seed bank contained a number
545 of species associated with water habitats that were not observed in the standing vegetation,
546 almost no species associated with woodland, none associated with scrub, but species
547 associated with pasture and meadow habitats were present. In contrast, the standing
548 vegetation displayed species whose terminal habitats included pasture and meadow, scrub
549 and woodland, and the proportion of species associated with these terminal habitats
550 increased with surface age. At the same time, although no species associated with water
551 habitats were observed in the standing vegetation, wetland species were present in a

552 declining proportion with surface age and three river bank species were found only in the
553 standing vegetation of pioneer islands. Species associated with bed rock and scree habitats
554 were present in the standing vegetation and seed bank of all investigated surfaces apart
555 from the seedbank samples drawn from unvegetated and between pioneer island surfaces.
556 However, species associated with wasteland habitats were mainly confined to the standing
557 vegetation.

558

559 **DISCUSSION**

560 The results presented in this paper support discussion of the evolution of islands over years
561 to decades and also the influential processes that occur over days to months. These themes
562 are discussed below in two subsections, and are followed by a final subsection which
563 includes some concluding remarks and reference to management applications.

564

565 **Evolution of islands over years to decades**

566 Analysis of aerial images (Mardhiah et al., 2015) and field observations confirm that
567 established and pioneer islands that persisted and developed up until the last field campaign
568 in 2017 were initiated by deposition of uprooted trees during flood events that occurred in the
569 mid to late 1970s and during 2000 and 2004 (the last two characterised by a recurrence
570 interval of >10 years and 3 years, respectively). Therefore, pioneer island establishment is
571 not a frequent process. Specific conditions are needed that occur occasionally when
572 compared with the starting processes of vegetation erosion and large wood deposition,
573 which have been observed to occur during low magnitude floods with a recurrence interval in
574 the range 1 to 2.5 years (Bertoldi et al., 2013; Surian et al., 2015). Flood history appears to
575 be more relevant than peak magnitude in island development, as also highlighted by Belletti
576 et al. (2014) in their regional scale study of 12 braided rivers. A combination of
577 morphological reworking, the creation of appropriate surfaces, vegetated bank erosion and
578 deposition of the uprooted trees, followed by a few years of lower flow are all necessary. For
579 example, evidence from airborne Lidar surveys shows a gradual but clear aggradation of the
580 2004PI surfaces over an 8 year period. Their median detrended elevation increased from -
581 0.285 m in 2005 to +0.168 m in 2010 to +0.176 m in 2013 (average aggradation of
582 approximately 0.057 m per year). These 2004 pioneer islands were initiated at a very low
583 elevation, compared to that of other uprooted and deposited trees observed in the same
584 reach. Bertoldi et al. (2013) reported trees deposited in the range 0 to 0.5 m during a flood in
585 2009, and those did not survive subsequent floods. Furthermore, although the 2014
586 deposited trees could not be located on the 2013 Lidar, it is very likely that they were
587 deposited at an elevation of approximately 0.1-0.3 m, comparable to that of the 2004 pioneer
588 islands almost 10 years after deposition. A similar wide range of deposited tree elevation
589 was reported also by Raple et al., 2017 (when transformed from elevation above low flow to
590 elevation above the mean). This reinforces the crucial role played by flood history. The
591 survival of the 2004 pioneer islands was possible only because of the occurrence of 3
592 particularly dry years following their deposition, enabling deposited trees to anchor
593 themselves and grow before being affected by significant flood disturbance.

594 The evidence for aggradation of the older and higher 2000PI and 1980EI surfaces over this
595 period is equivocal, suggesting a rapid slowing in aggradation once island surfaces have
596 developed above the level of relatively frequent inundation (e.g. elevations that are reached
597 for less than one day per year, Figure 3).

598 The islands developed around deposited uprooted trees and aggraded as new trees
599 sprouted from them (e.g. Figure 1, 2002 image shows sprouting trees deposited in 2000). In
600 nearly all cases, the deposited trees that initiate pioneer islands in the study reach are black
601 poplar (*Populus nigra*), a facultative phreatophyte capable of rapid root growth in response

602 to different water and sediment conditions (Holloway et al., 2017a, b, c), and the Lidar data
603 and field measurements show that deposited trees of this species can regenerate to produce
604 a canopy that grows rapidly, particularly in the first 15 years following deposition (Figure 6A).
605 The median canopy height increased from 0.24 to 6.85 m (6.61 m growth) on the 2004PI
606 surfaces, from 1.64 to 9.76 m (8.72 m growth) on the 2000PI surfaces and from 22.79 to
607 25.04 m (2.83 m growth) on the 1980EI surfaces between 2005 and 2013. These data
608 suggest that after the first couple of years following deposition, an annual growth increment
609 of over 1 m per year above the aggrading island surface is achieved in the study reach over
610 at least a 15 year period. Since the growth develops from a deposited tree, which then
611 becomes buried, the actual annual growth rate from the elevation at which the tree was
612 deposited is slightly greater than this in these early years.

613 As islands aggrade, they also extend laterally through aggradation and coalescence. This
614 lateral aggradation can be clearly seen in the vegetated area surrounding the studied 2000
615 and 2004 pioneer islands in Figure 1 (compare the 2002 and 2015 images at the sampling
616 locations), and is supported by increases in vegetation canopy height and emergence of a
617 vegetation canopy between pioneer islands (Figure 6A). The annual growth rate of trees on
618 the 2000 and 2004 pioneer islands is quite constant when measured on a time scale of 3 to
619 5 years, with no apparent marked changes between particular years (Figure 6A). The time
620 scale is probably long enough to filter out the impact of annual changes in temperature and
621 precipitation, masking the controls highlighted by Raple et al., 2017. More importantly, once
622 the trees have survived initial deposition and early establishment, which is affected by
623 access to groundwater and thus river stage (e.g. Francis, 2007), there seems to be a
624 negligible impact of local bed elevation on their rate of growth. This comparable growth rate
625 regardless of elevation indicates high water availability in the study reach, which is mainly
626 characterised by groundwater upwelling (Doering et al., 2007). On other reaches of the
627 Tagliamento, such a constant rate of growth may not occur, since there are notable
628 differences between reaches (Gurnell, 2016) that highlight sensitivity to changes in moisture
629 availability, and such sensitivity to relative elevation with respect to groundwater may be an
630 important factor in island development across other river environments.

631 As sediments accumulate around the growing *P. nigra* trees, their properties change (Figure
632 4). While unvegetated bar surfaces are characterised by gravel deposits, higher surfaces
633 show increasingly fine deposits. Well-vegetated island surfaces (1980EI, 2000PI and
634 2004PI) show predominantly sandy surface sediments containing varying amounts of silt,
635 clay and organic material, whereas sparsely-vegetated surfaces of the youngest pioneer
636 islands (2014PI) and areas between the older pioneer islands (2000btwn, 2004btwn) show
637 coarser gravel-sand mixtures (Figure 4). Thus sediments fine with increasing elevation and
638 vegetation cover, presumably because finer sediments on sparsely-vegetated elevated
639 surfaces between pioneer islands are subject to flow funnelling and higher shear stresses
640 during major inundating flood events that may mobilise finer sediments. The role of fine
641 sediments is relevant for island development, but not crucial for island initiation. Deposited
642 trees are able to trap fine sediments soon after they sprout and grow branches and leaves.
643 For example, after less than 2 years and a few moderate floods, the grain size distribution of
644 the 2014PI surfaces show a clear fining. The subsequent growth of shrubs and then herbs
645 and grasses forms a vegetated surface that is increasingly efficient at trapping fine
646 sediments and organic matter as islands age.

647 The number of plant species and the vegetation composition of islands also changes with
648 increasing age (Figure 8). Focussing on the vegetation survey conducted in 2011 and
649 following a warm spring, the number of species in the standing vegetation increases steadily
650 from 1 year old (2010PI) through seven year old (2004PI) to 11 year old (2000PI) islands as
651 new species progressively colonise the developing island surfaces (Figure 8A). The 2016
652 vegetation survey, following a cool spring, recorded fewer species than the 2011 survey,
653 with little difference in the number of species on two year (2014PI) and 12 year (2004PI)
654 pioneer islands. The largest number of species were observed on 16 year old pioneer

655 islands (2000PI), with established islands (1980EI) showing less species than all of the
656 pioneer islands (Figure 8A). This suggests that as islands aggrade, new species appear until
657 the tree canopy closes and the trees and shrubs out-compete many other species, following
658 typical seral trajectories wherein species are excluded by dominant competitors and diversity
659 peaks in the mid-seral stages; though this trend is also likely to be an expression of the
660 intermediate disturbance hypothesis (Connell, 1978; Tabacchi et al., 1998; Bendix and
661 Hupp, 2000) whereby the largest number of species are supported on surfaces subject to an
662 intermediate level of flood disturbance. However, the reduction in species present on
663 established island surfaces is likely to be counteracted by species colonising areas of wood
664 and sediment deposition, sprouting and aggradation at and near island edges that create
665 new local island-margin patches, particularly at the sheltered downstream island tail, that
666 may emulate the vegetation development processes observed on pioneer islands.

667 The supposition concerning canopy closure and competition is also supported by the
668 average C, S and R scores of the species that are present. With increasing surface age, the
669 vegetation becomes increasingly dominated by competitor species, whereas the youngest
670 pioneer islands show a balance of competitor, stress-tolerator and ruderal species (Figure
671 8B). Furthermore, the proportion of species associated with wetland, arable, wasteland and
672 bedrock terminal habitats decreases and the proportion with woodland and scrub terminal
673 habitats increases with surface age (Figure 8D), as a more stable 'climax' riparian woodland
674 emerges. The change in vegetation cover, height and composition with increasing island age
675 is accompanied by an increase in the organic content, roots and fungal hyphae as the fining
676 surface sediments start to develop into soils with increasing island age (Figure 6).

677 These observations support the island development model proposed by Gurnell et al. (2001)
678 and provide considerable detail on the functioning of that model over annual to decadal
679 timescale.

680

681 **Influential processes over days to months**

682 Large flood events are crucial to the island model, and so it is unsurprising that the largest
683 flood in the period 2000 to 2017 (on 5th November 2000, Figure 2) was responsible for
684 initiating numerous, widely distributed pioneer islands in the study reach. The flood event in
685 2004 (on 31st October, Figure 2) was more localised than the 2000 event with trees released
686 by erosion of the floodplain around a tributary being deposited across a relatively small area
687 of the river bed (Francis et al., 2008). However, the resulting pioneer islands have grown
688 rapidly to the present, despite the occurrence of a larger flood in 2012 (on 12th November,
689 Figure 2). This survival can probably be attributed to a four year period without significant
690 floods following the 2004 event, which allowed these 2004 pioneer islands to establish and
691 aggrade sufficiently to resist erosion. The occurrence of the large flood in 2012 may also
692 explain why trees deposited by smaller flood peaks on 30th October 2008, 25th December
693 2009 and 1st November 2010 (Figure 2) have not developed into longer-term pioneer
694 islands. However, it will be interesting to observe whether any of the 2014 pioneer islands
695 (deposited on 6th November) are able to survive in the longer term, given the relatively low
696 flows since their deposition (Figure 2).

697 Information gained from the field campaigns in 2016 and 2017 provides indications of the
698 potential importance of several processes in island development. Between these two field
699 campaigns, there were three small flood events on 14th July, 6th and 19th November 2016
700 (Figure 9), with a maximum water elevation of 0.25m (detrended elevation) on 14th July
701 2016. This maximum elevation would have inundated all unvegetated surfaces and most of
702 the 2014PI, 2004PI and 2004btwn surfaces (Figure 3). The vegetation cover on the latter
703 three surfaces (2014PI, 2004PI, 2004btwn) is likely to have retained sediment from these
704 floods as they receded, and since the floods are relatively small, the transported sediment is
705 likely to have been quite fine, partly explaining the sediment fining on these surfaces

706 between the two sampling campaigns (Figure 5). However, these flood events cannot
707 explain sediment fining on higher surfaces. Gurnell et al. (2008) proposed wind storms as
708 being another important mechanism for transporting sediments along the Tagliamento river
709 corridor that can be intercepted and deposited on vegetated surfaces. This proposal was
710 founded on a unique sequence of events which resulted in the production of very fine
711 surface crusts, whose properties suggested wind as the most likely transporting agent. Wind
712 storms transporting dense dust particles are quite common on the Tagliamento and their
713 importance may be underestimated on other braided rivers where vast areas of exposed
714 sediments can provide fine sediment for wind transport. Between field campaigns, there was
715 a wind speed maximum of 26.3 m/s on 13 July and a period from 8th to 12th November 2016
716 when daily maximum wind speeds exceeded 15 m/s, with a maximum of 23.1 m/s on 10th
717 November 2016. Moreover, almost no precipitation occurred in December 2016 and January
718 2017, whereas several days had a maximum wind speed larger than 10 m/s, suggesting dry
719 conditions may have favoured wind transport. Wind transport may explain the deposition of
720 finer sediments on surfaces that were not inundated between the field campaigns,
721 particularly as the wind-deposited crusts sampled by Gurnell et al. (2008) within the study
722 reach had an average D90 grain size of 6.7 ϕ , which compares favourably with the increases
723 in D90 illustrated in Figure 5. These observations suggest that wind as well as water may
724 play a role in the aggradation and fining of surface sediments as islands increase in age and
725 surface elevation on the Tagliamento and possibly other braided rivers.

726 Finally, the winter seed bank data has some relevance for both short and long term
727 processes of island development. It is unsurprising that there is low similarity between the
728 species in the seedbank and established vegetation (Figure 7) as a lack of similarity has
729 been observed in the riparian seed bank and standing vegetation of other river systems,
730 which have also shown a high seasonal variability in seed bank composition (e.g. Gurnell et
731 al., 2006, 2008). However, the lack of similarity between the winter seedbank and vegetation
732 composition in the present study is particularly stark. Since the seed bank was sampled in
733 winter, it is not surprising that it mainly contained species that are associated with a
734 persistent seed bank (Figure 8C). However, there is evidence that at least some of the seed
735 species that were sampled have been transported into the sampling locations. In particular,
736 some aquatic species are present in the seed bank but not in the standing vegetation. Whilst
737 this is not surprising given their habitat requirements (there are no water bodies on the
738 islands and aquatic species are rarely found in the ponds adjacent to pioneer and
739 established islands), their presence illustrates that they have been dispersed into the
740 sampled surface sediments. Their most likely source is a tributary stream that enters the
741 Tagliamento main stem at the upstream end of the study reach and supports a variety of
742 aquatic plant species, or they may have arrived from other upstream water bodies. Although
743 water transport may explain the presence of these seed species on the 2004PI and
744 2004btwn surfaces, their presence on higher surfaces (Figure 8D) cannot be explained by
745 water transport but could be explained by remobilisation and deposition by wind. Both wind
746 and water are recognised as important means of seed dispersal (Fenner and Thompson,
747 2005) and both are likely to be associated with deposition of seeds on island surfaces by
748 events that occur over periods of hours to days, transporting seeds from their source areas
749 and also remobilising them from other parts of the river bed and margins. In addition, larger
750 vegetative propagules may be transported and deposited by floods to add to living plants
751 and propagules co-deposited with soils attached to uprooted, deposited trees. One final
752 point that relates to both dispersal mechanisms and aggradation, is that the 2004 islands
753 stand out as not only having the highest decadal aggradation rates (Figure 3); the highest
754 seed abundance (Figure 6) and highest number of species (Figure 8A) in their seedbank;
755 and a remarkable development in their standing vegetation (Figures 7 and 8); but in the
756 short term (between 2016 and 2017 sampling) they were affected by both wind and water
757 dispersal processes (Figure 9), enabling enhanced sediment delivery, surface aggradation
758 and the delivery and retention of plant propagules from a wide variety of locations and thus a
759 potentially substantial species pool. Such fine-scale patterns of propagule deposition and

760 plant colonisation are likely to add to the complexity of island development and contribute to
761 the shifting habitat mosaic found at multiple scales within the Tagliamento's island-braided
762 reaches (e.g. Ward et al., 2002a).

763

764 **Management Applications and Concluding Remarks**

765 The recognition of islands as important landscape elements that are indicative of river
766 ecosystem function and health (Tockner et al., 2003; Beechie et al., 2006) has led to
767 increased interest in incorporating such landforms and their underlying processes into river
768 restoration and management efforts. For example, Wyrick and Klingeman (2011) note that
769 despite their widespread occurrence and ecological importance, islands are rarely
770 incorporated into river restoration concepts. They propose a process-based island
771 classification scheme that can identify island types, their formative processes and the
772 relationship between island formation and river processes in general. As Wyrick and
773 Klingeman (2011) indicate, any incorporation of islands and island-building processes in
774 river restoration and management need to be cognizant of both the mechanisms and
775 timescales of development that we have begun to explore here. In particular, our data and
776 similar measurements from other river systems can contribute to the refinement and testing
777 of numerical models that are increasingly incorporating physically based
778 vegetation/morphology feedbacks and could provide important means of forecasting likely
779 evolutionary trajectories of vegetated landforms under different environmental conditions
780 (e.g. van Oorschot et al., 2016; Zen et al., 2016).

781 Gurnell et al. (2001, updated 2012, 2016) presented a conceptual model of island
782 development based on observations along the braided, gravel-bed Tagliamento River. Since
783 then, the expanding literature on river island development, has primarily focused on the
784 formative physical processes of island development, their morphological evolution,
785 sedimentary environments, or aspects of their ecology and biodiversity (e.g. Mikuš et al.
786 2013; Picco et al. 2015; Raška et al. 2016; Vanbergen et al., 2017). In this paper we have
787 integrated these different perspectives and considered them across different timescales.
788 Although the datasets are not as comprehensive as we would like, this is often the case with
789 ecological data in complex and dynamic ecosystems, but we nevertheless consider them
790 sufficient to provide valuable information on elements of island development where
791 knowledge is notably sparse.

792 First, we have provided support to the view that when islands are initiated by the sprouting of
793 deposited trees (the 'regeneration from living wood' pathway; Gurnell et al., 2001), the
794 elevation of the tree deposition site matters (see also Francis, 2007). Trees are only
795 uprooted, transported and deposited in sizeable numbers during relatively large flood events
796 (e.g. Comiti et al., 2016), with deposition occurring during the peak and falling limb of these
797 flood events (e.g. MacVicar et al., 2009). Depositionary location governs both water access
798 (the lower the elevation, the closer to the water table) and likelihood of disturbance and
799 removal prior to establishment (the higher the elevation, the less likely they will be
800 disturbed). Therefore, if trees are deposited at low elevation, where they have access to
801 water to support rapid growth, river flows in the first two to three years following deposition
802 are critical to their survival. If no major floods occur in this early period after deposition the
803 trees can develop significant root and shoot biomass to anchor them and enable them to
804 trap transported sediments, increase their surface elevation and thus reduce the level of flow
805 disturbance to which they are subsequently subjected. These early developmental
806 processes and timeframes are likely to be applicable to all island braided rivers where island
807 development is initiated by sprouting of uprooted trees, and highlight the importance of
808 regenerating trees having sufficient access to water and limited fluvial disturbance during
809 initial years of establishment if island formation is to be facilitated.

810 Second, we have shown that once early establishment has occurred, islands aggrade their
811 surfaces and develop a vegetation canopy at a remarkably steady rate over a decadal time
812 scale. As islands aggrade and above-ground vegetation biomass and canopy height
813 increase, there is also a steady fining of surface sediments and an increase in their organic
814 content, including living material such as roots and fungal hyphae. This steady development
815 reflects the fact that the study reach is subject to groundwater upwelling and thus possesses
816 a fairly consistent and reliable moisture supply to support growth of the main tree species
817 driving island initiation and development along the Tagliamento: *Populus nigra*. Thus, in the
818 case of the study reach, *P. nigra* acts as a true ecosystem engineer (Jones et al., 1994,
819 Gurnell, 2014), and our observations are likely to be applicable to other river reaches where
820 water table fluctuations operate within a relatively small range and where *Populus nigra* or
821 other riparian Salicaceae that are similarly sensitive to moisture availability and groundwater
822 depth are driving pioneer island development. In reaches where major water table
823 fluctuations occur, survival of deposited trees will be more sensitive to the elevation at which
824 they are deposited, as will their subsequent rate of establishment. The initial establishment
825 and growth of islands and the development of their surface sediments and vegetation cover
826 as well as their ability to withstand subsequent flood events will vary not only with the river
827 flow regime but also with the groundwater regime (e.g. Bätz et al., 2016) and any
828 confounding climatic trends (low rainfall, high evaporation). Detailed analyses to compare
829 island and associated dynamics in reaches subject to different groundwater / water
830 availability conditions are needed to more fully investigate the integrated biological and
831 geomorphological implications for island evolution, and how this may relate to management
832 and restoration.

833 Third, we found the maximum number of plant species, seed bank species, and seed
834 abundance to be associated with island surfaces of intermediate age and elevation,
835 reflecting seral trajectories and patterns of disturbance. This further highlights the
836 importance of allogenic disturbances and complex dynamics that shape the ecology of
837 building islands, which may serve to confound easy prediction of, for example, plant
838 community development. In an early study, Nagel et al. (1980) observed that river islands
839 along the lower energy, regulated Platt River in Nebraska (USA) presented similar trends of
840 soil development and aggradation with island age, but also that although plant diversity and
841 abundance of perennials increased with island age, island communities remained broadly
842 similar and at early seral stages. Expectations around ecological development and
843 succession of river islands, for example if used as indicators of ecosystem health or in
844 restoration efforts, should therefore take into account the complexity of factors determining
845 assemblages, which will vary between reaches and river systems. In our case for example,
846 islands of intermediate age had a rather particular initiation and evolution history, and more
847 work would be needed to establish the transferability of our findings to other contexts.

848 Finally, our most speculative finding relates to the importance of climatic conditions in
849 influencing island evolution at event to seasonal timescales. We have observed significant
850 fining of surface sediments on all vegetated surfaces over a period of approximately six
851 months. Whereas some of this fining can be attributed to deposition of fine sediments
852 transported by small flood events on inundated vegetated surfaces, many of the surfaces
853 showing fining were not inundated. Based on earlier observations (Gurnell et al., 2008), we
854 have suggested wind as a potentially important agent for transporting fine sediments that
855 become trapped by vegetation, particularly during dry periods. Aeolian fine sediments and
856 dusts (including organic particulates) have been found to be more pervasive and ecologically
857 important in ecosystems than usually assumed, for example contributing to river nutrient
858 loads, especially in more arid basins (e.g. McTainsh and Strong 2007). McGowan et al.
859 (1996) note that dust entrainment may be particularly prevalent along alpine river valleys,
860 where the topography can channel high wind speeds. On the study reach and higher up the
861 river, fine deposits on exposed bars, especially at high elevations, may represent a source of
862 fine sediments that become trapped by vegetation. Wind is also recognised as a major agent

863 for seed transport; most notably in the present context for the transport of the abundant
864 short-lived seeds of the Salicaceae, alongside and in combination with water (e.g. Boland
865 2014, 2017). Wind may therefore have agency in island aggradation and also the delivery of
866 seeds from terrestrial and riparian species pools, though further work is needed to confirm
867 this. Furthermore, we have provided some support for a potentially important role of
868 temperature conditions in the annual cycle of vegetation development and flowering.
869 Species which only show above-ground biomass seasonally could be an important influence
870 on seasonal fine sediment trapping and retention of surface moisture through the late spring
871 and summer months. Thus, while flood and low flow events are clearly the key controls on
872 island evolution, various climatic variables may be extremely important for fine sediment
873 retention, soil development and other short term facets of island evolution, and should be
874 considered in any management or restoration context. However, more research is needed to
875 verify and quantify these influences

876

877 **ACKNOWLEDGMENTS**

878 Figure 1 includes two images from Google Earth, both from the same supplier: Image ©
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893

894

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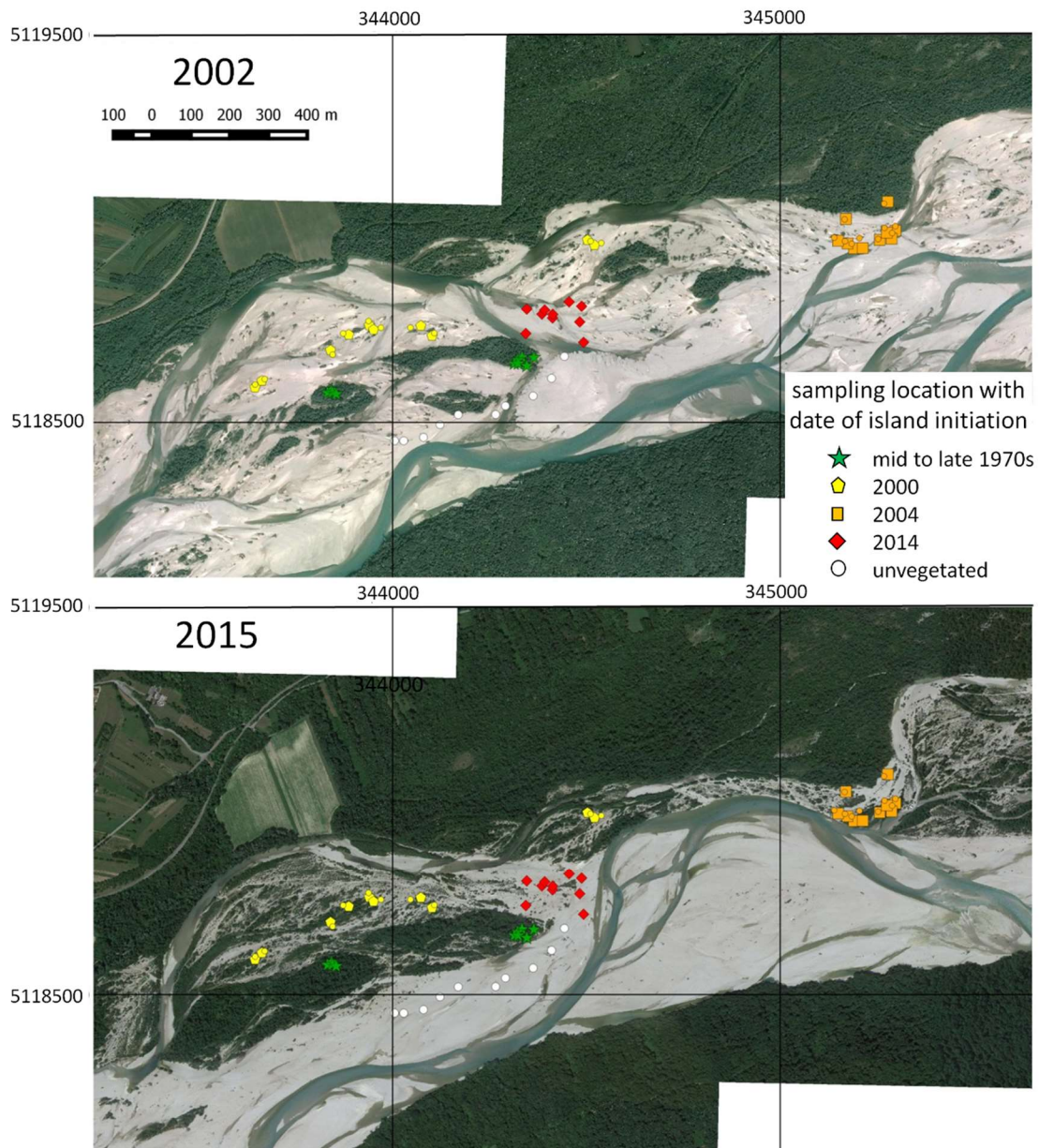
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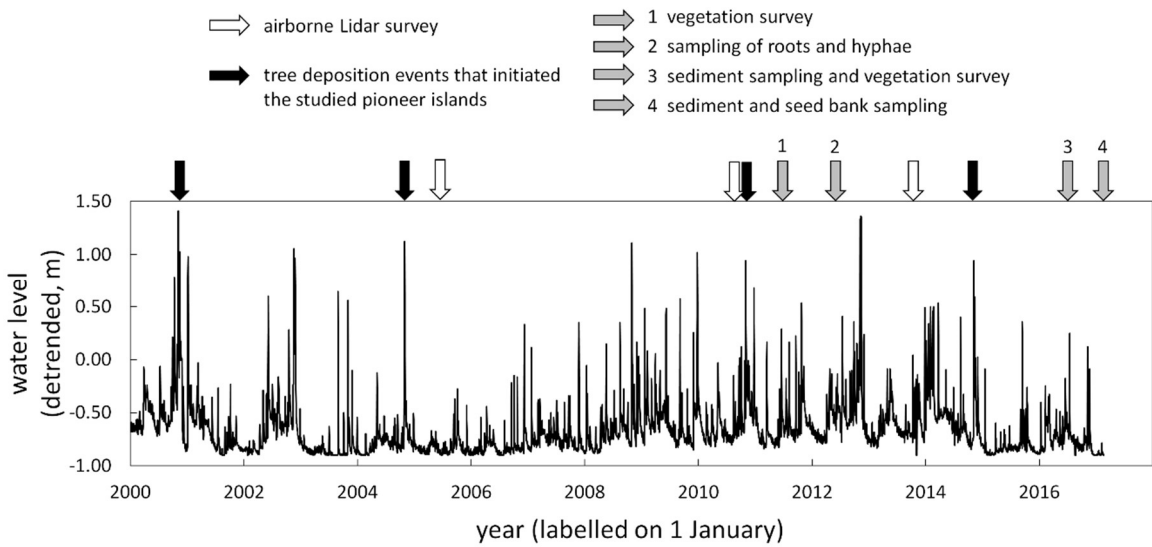
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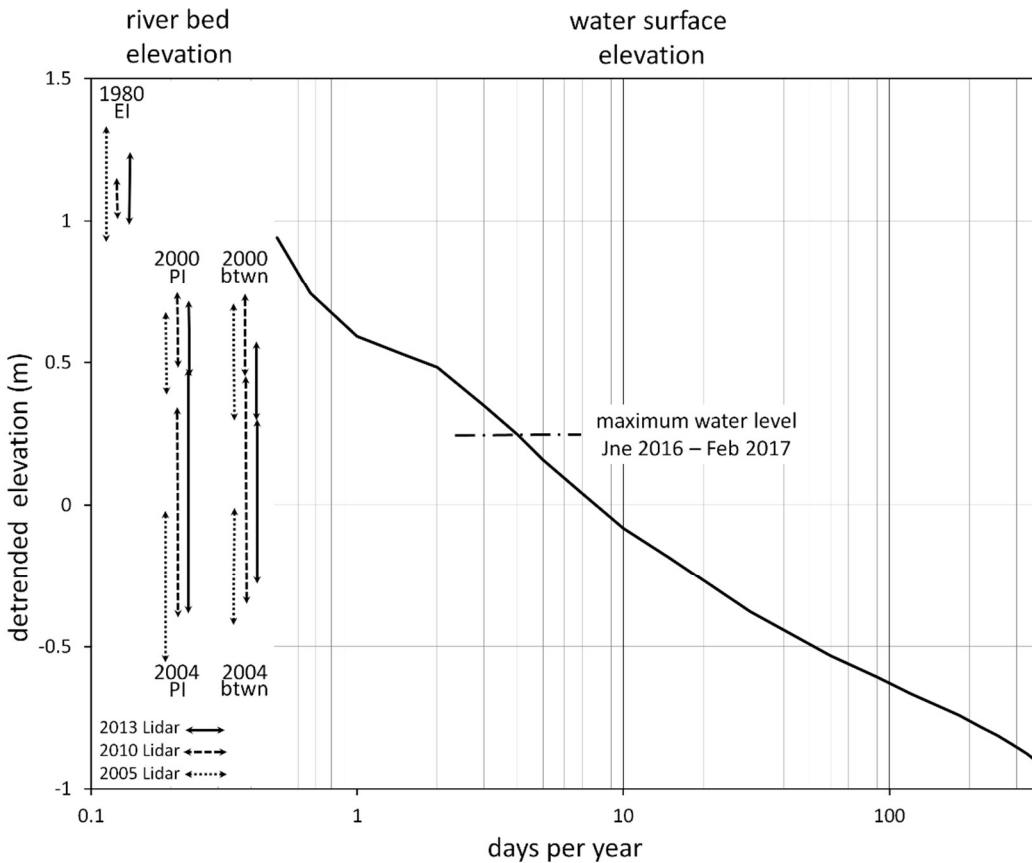
1069 Figure 1. Distribution of sampling locations used in 2016 and 2017 according to date of
 1070 surface initiation, overlain on images of the study reach captured in 2002 and 2015. The
 1071 images are overlain with coordinates for WGS84 UTM zone 33 to indicate the study area
 1072 location. Images were obtained from Google Earth, Image © 2017 DigitalGlobe, and were
 1073 captured on 21 July 2002 and 12 July 2015.

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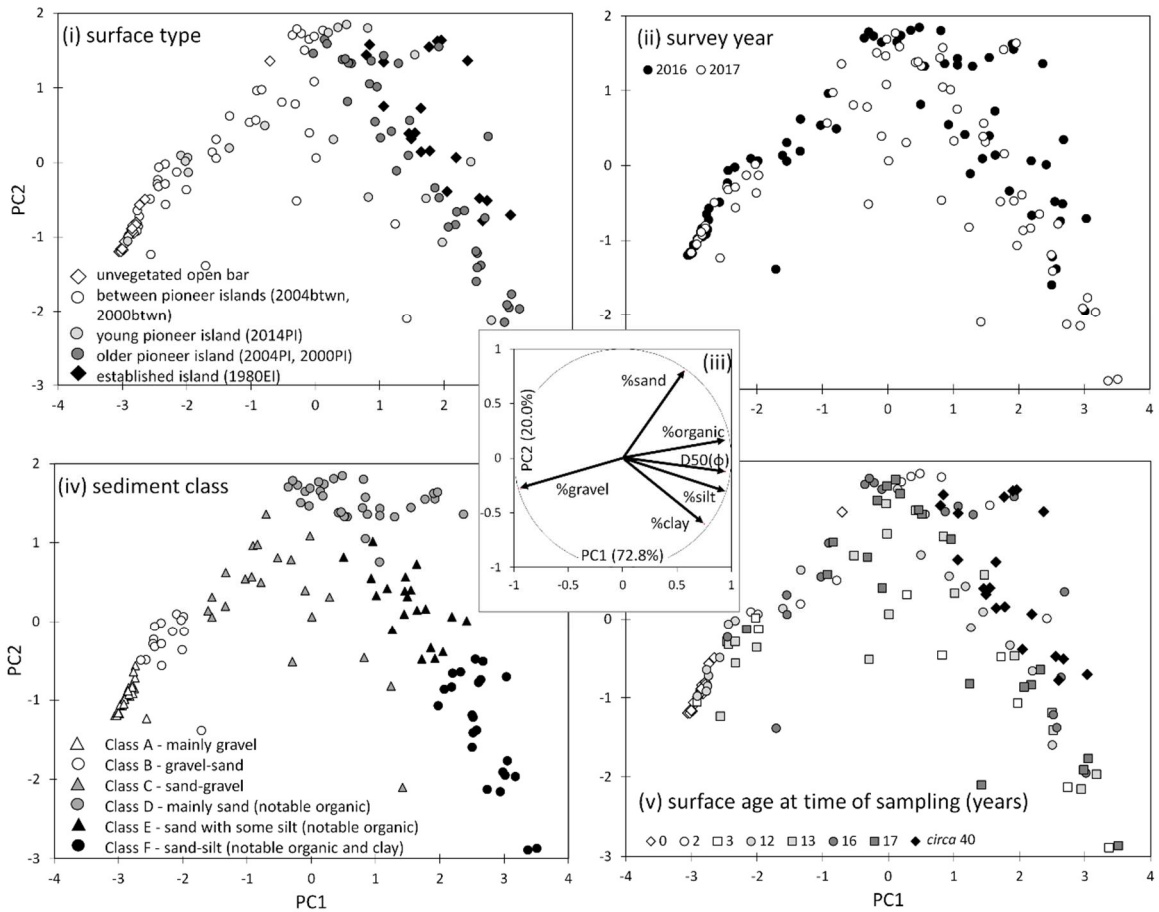
1076 Figure 2. Data sets and events described in this paper in relation to variations in water level
 1077 in the study reach between January 2000 and February 2017 inclusive.



1078

1079 Figure 3. Water level (detrended elevation in m) - frequency relationship in the study reach
 1080 estimated for the period 2000-2017, compared with the interquartile range of the detrended
 1081 elevation of sampling locations on 1980EI, 2000PI, 2000btwn, 2004PI, 2004btwn surfaces in
 1082 2005, 2010 and 2013 and the maximum river stage between June 2016 and February 2017
 1083 sampling campaigns.

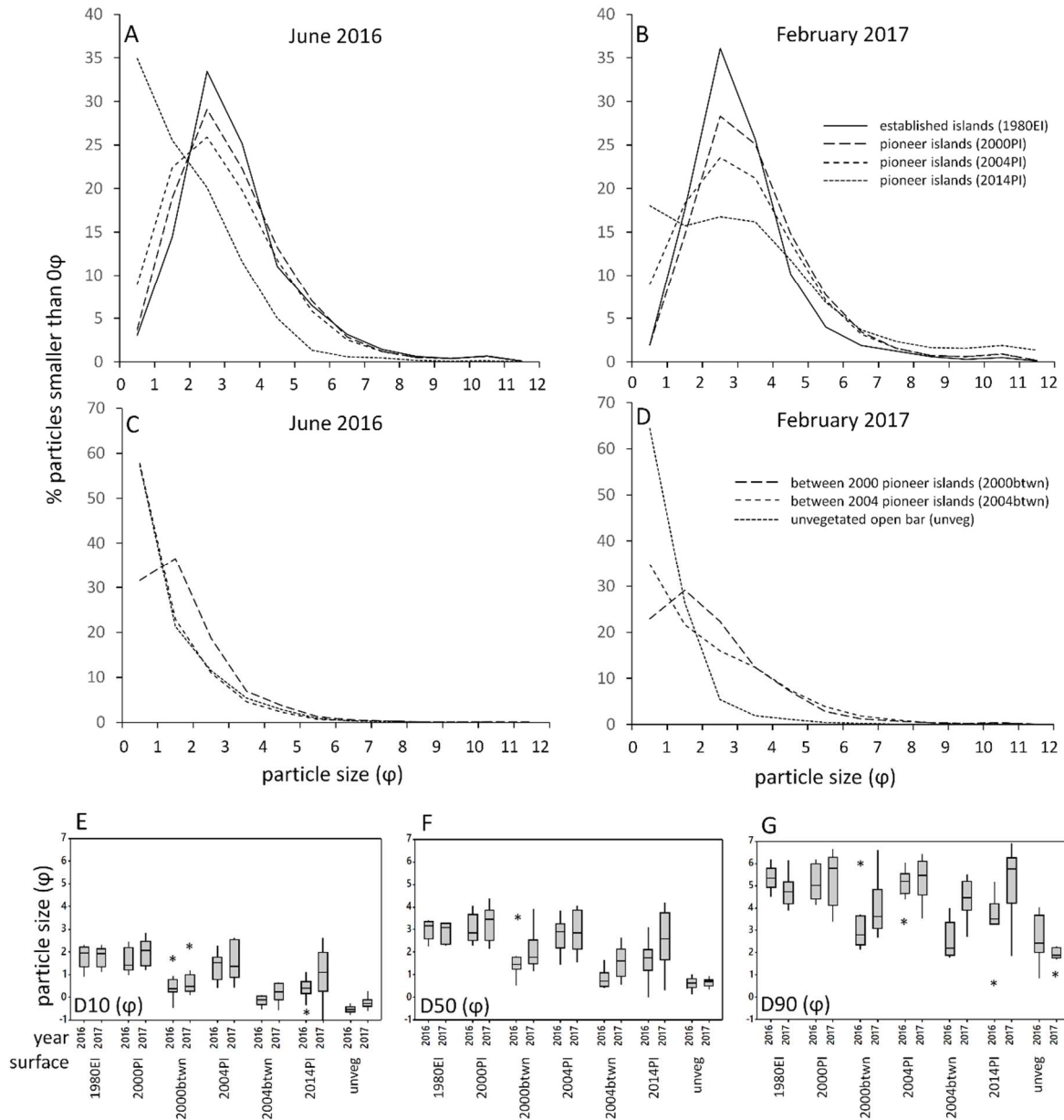
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1086 Figure 4. Surface sediment sampling locations and times plotted in relation to their scores on
 1087 the first two PCs of a PCA. The PCA was applied to the %organic, D50, %gravel, %sand,
 1088 %silt, %clay content of each sample: (iii) illustrates the loadings of these six variables on the
 1089 first two PCs. The samples are coded according to (i) the sampled surface, (ii) the survey
 1090 year, (iv) sediment class (derived from AHC of %organic, D50, %gravel, %sand, %silt,
 1091 %clay), (v) surface age at the time of sampling.

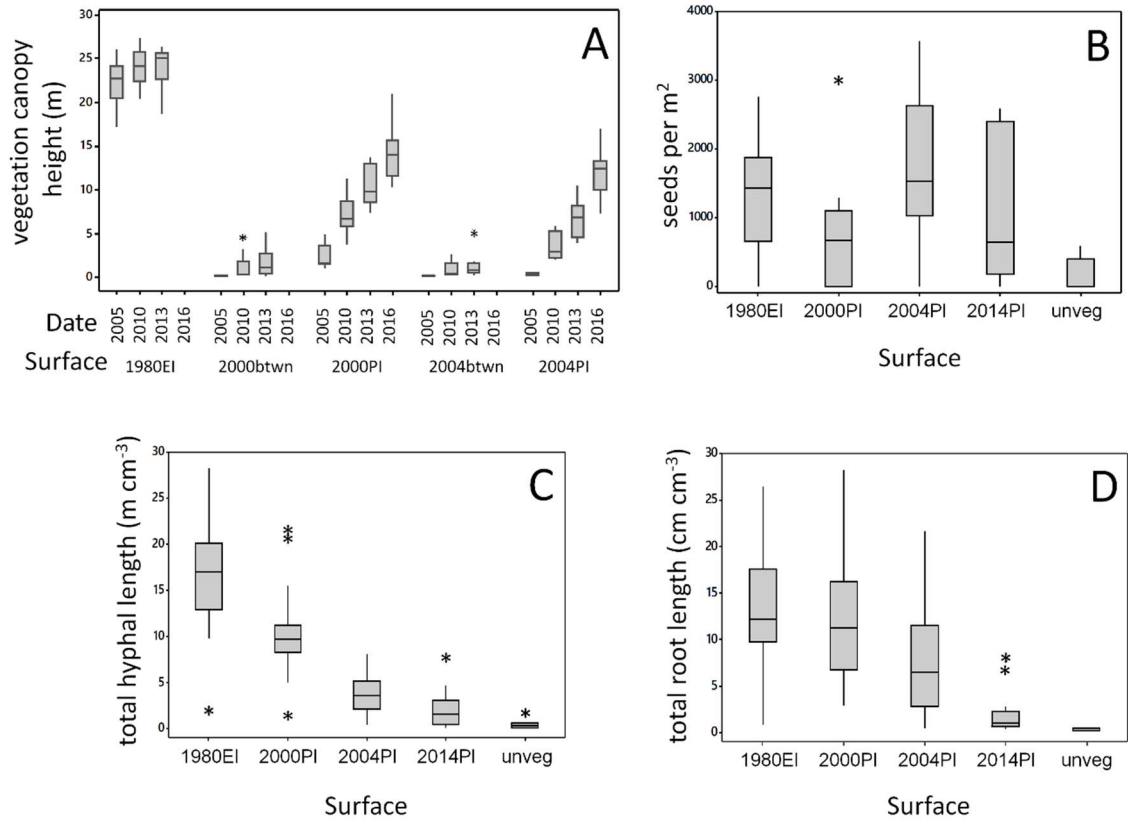
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1094 Figure 5. A, B, C, D: Particle size distributions for the <1 mm (0ϕ) fraction of island surface
 1095 (A, B) and unvegetated and between island (CD) surface sediment samples obtained in
 1096 June 2016 (A,C) and February 2017 (B,D). The data are presented as percentages of the
 1097 sample within 1ϕ bins (<1 , $1-2$, $2-3$, ..., $10-11$, $>11\phi$). E, F, G: D10, D50 and D90 percentile
 1098 particle sizes estimated for the 139 distributions contributing to the averages shown in A, B,
 1099 C, D. Note that some D10 estimates are larger ($<0\phi$) because the $<1\phi$ bin contains such a
 1100 large percentage of the particles in these coarse samples.

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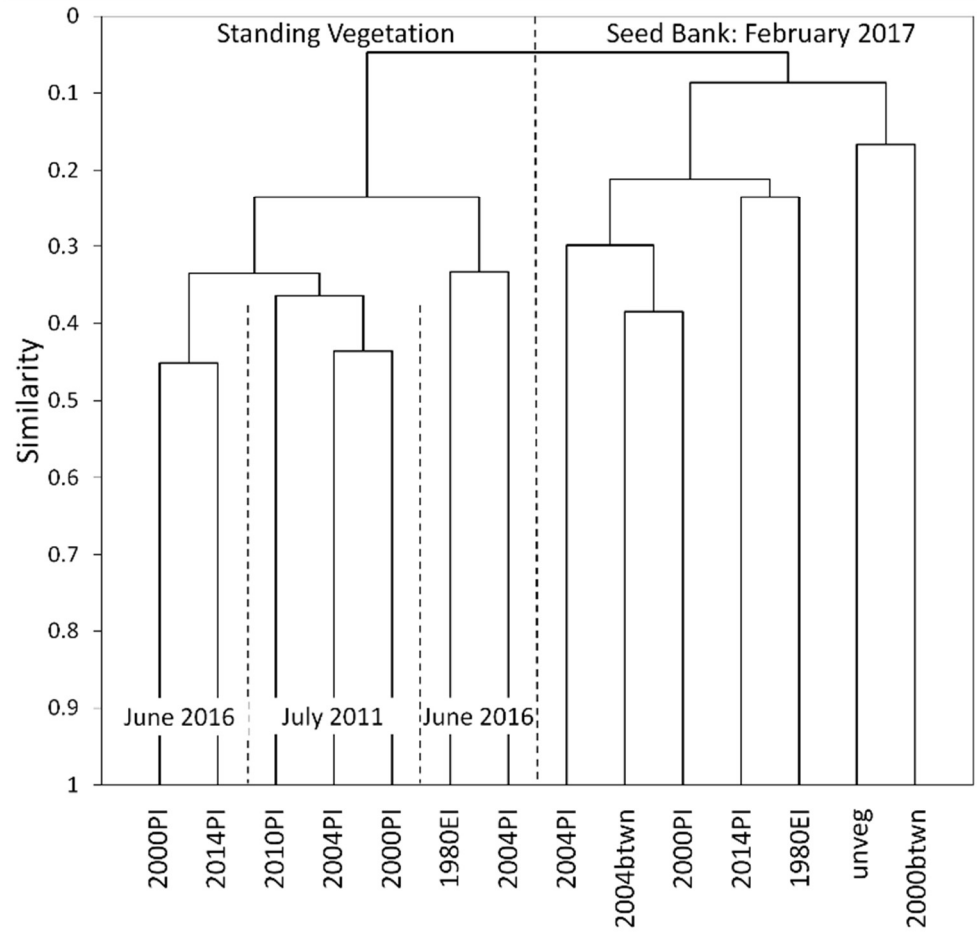


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1103 Figure 6. A. Box plots of canopy height at sampling locations on 1980, 2000 and 2004 island
 1104 surfaces and between 2000 and 2004 islands, extracted from Lidar surveys captured in
 1105 2005, 2010, 2013 and field measurements in 2016 (2000PI, 2004PI only). B. C. D. Some
 1106 living components of the organic material in island and unvegetated bar surface sediments
 1107 (1980EI, 2000PI, 2004PI, 2010PI, 2014PI, unveg): A. seeds per m² sampled in February
 1108 2017, B. total hyphal length sampled in July 2012, C. total root length sampled in May 2012
 1109 (data for B and C from Mardhiah et al., 2014).

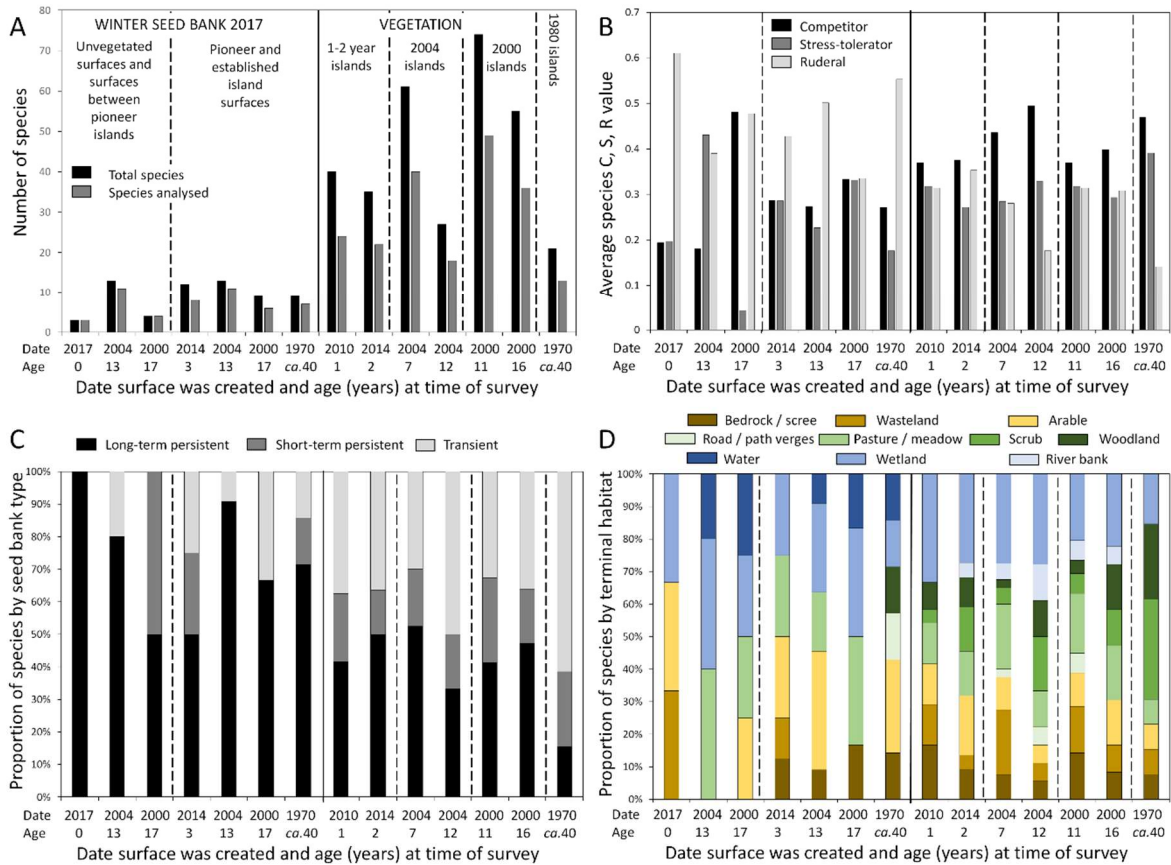
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1980EI	established island (after mid 1970s)		
2000PI	pioneer island (2000)	2010PI	ca.1 year old pioneer islands (2011 survey)
2000btwn	between 2000 pioneer islands	2014PI	1.5 year old pioneer island (2016 survey)
2004PI	pioneer island (2004)	unveg	unvegetated bar surface
2004btwn	between 2004 pioneer islands		



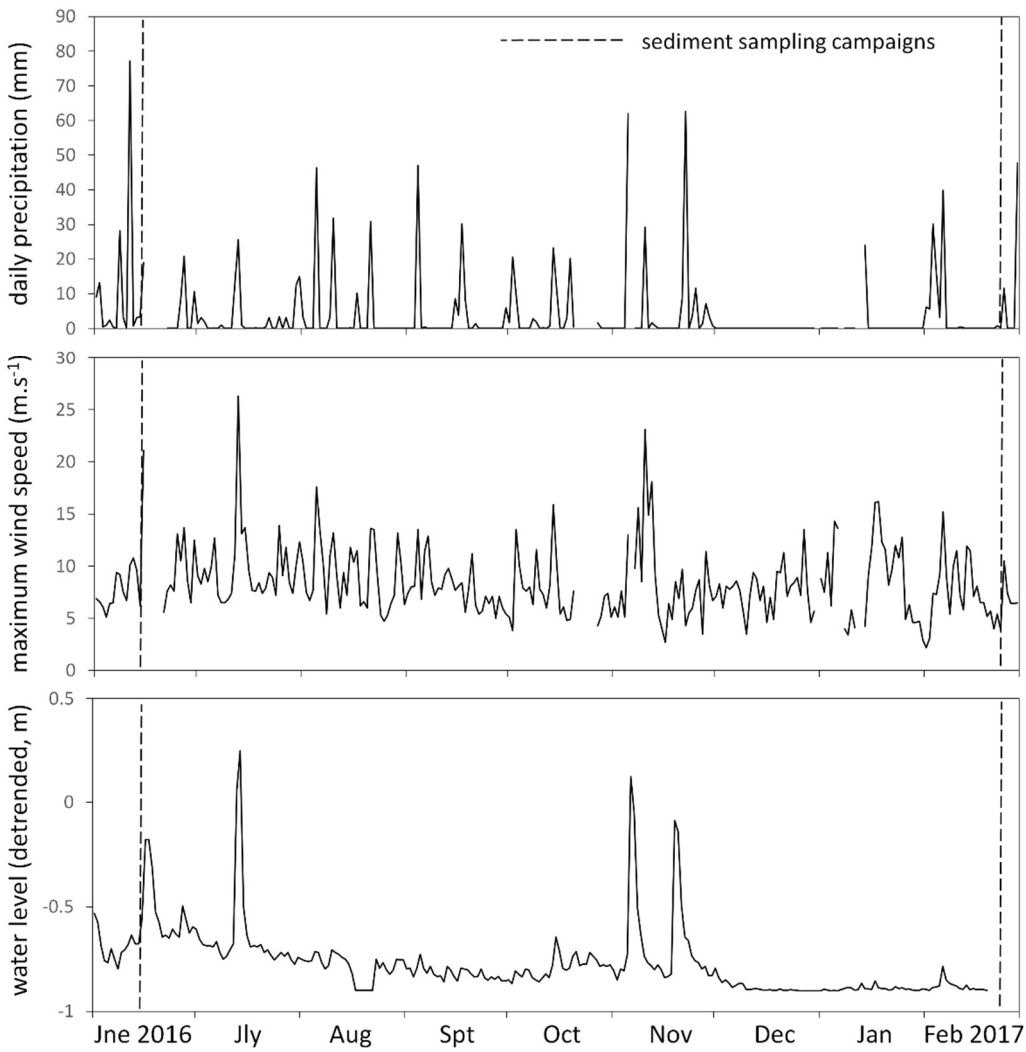
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1112 Figure 7. Similarity in the species composition of the standing vegetation (July 2011, June
 1113 2016) and seed bank (February 2011) observed on surfaces of different type and age.
 1114 Agglomerative Hierarchical Cluster analysis was performed with the Jaccard coefficient as
 1115 the similarity measure and clustering determined using the unweighted pair group average.



1116

1117 Figure 8. Standing vegetation and seed bank species composition on surfaces of different
 1118 age, based on surveys of the standing vegetation in 2011 and 2016, and the winter seed
 1119 bank in 2017. A. Number of species present, B. Average C, S, R scores, C. Proportions of
 1120 species with long-term persistent, short-term persistent, and transient seed banks, D.
 1121 Proportions of different most common terminal habitats



1122

1123 Figure 9. Daily total precipitation, maximum wind speed, and maximum detrended water
 1124 level between field campaigns in June 2016 and February 2017.

1125

1126 **TABLES**

1127 Table 1. Generalised linear models for detrended surface elevation and vegetation canopy
 1128 height in relation to sampled surfaces (1980EI, 2000PI, 2000btwn, 2004PI, 2004btwn) Lidar
 1129 survey years (2013, 2010, 2005) and interactions between surfaces and years

	DF	F-value	P-value	Bonferroni pairwise comparisons (P<0.05)
Bed elevation				
Surface	4	77.60	<0.001	1980EI > 2000PI, 2000btwn > 2004PI, 2004btwn
Lidar date	2	3.55	0.031	2013, 2010 > 2005
R ² (adjusted) = 65.8%				
Vegetation Canopy				
Surface	4	940.62	<0.001	1980EI > 2000PI > 2004PI > 2000btwn,2004btwn
Lidar date	2	64.24	<0.001	2013 > 2010 > 2005
Surface*Lidar date	8	8.99	<0.001	1980EI(2013,2010,2005) > 2000PI(2013) > 2000PI(2010),2004PI(2013) > 2004PI(2010) > 2000PI(2005),2000btwn(2013,2010,2005),2004PI(2005), 2004btwn(2013,2010,2005)
R ² (adjusted) = 96.36%				

1130

1131

1132 Table 2. Centroid values for sediment classes discriminated using AHC (Euclidean distance,
 1133 Ward's clustering algorithm) applied to six sediment properties of 139 surface sediment
 1134 samples, with significant differences between classes in relation to the six contributing
 1135 sediment properties (Kruskal Wallis tests).

Sample size and sediment property	A mainly gravel	B gravel-sand	C sand-gravel	D mainly sand (notable organic)	E sand with some silt (notable organic)	F sand-silt (notable organic and clay)	Significant differences between classes*
sample size	23	25	16	36	28	41	
%organic	0.3	0.8	1.4	5.0	4.8	6.0	D,E,F>A,B C>A
D50(ϕ)	-1.4	-1.7	1.3	2.1	2.9	3.7	E,F>C,D>A,B
%gravel	80.6	58.5	26.3	0.5	0.4	0.1	A,B,C>D,E,F A>C
%sand	19.0	38.5	64.9	91.0	76.8	59.8	C,D,E,F>A,B D>C,F
%silt	0.5	2.9	8.4	8.4	21.7	37.5	E,F>B,C,D>A C,D>B
%clay	0.0	0.1	0.4	0.1	1.2	2.7	E,F>A,B,C,D

1136 * Kruskal Wallis tests, df = 5, P < 0.0001, multiple pairwise comparisons using Dunn's
 1137 procedure with Bonferroni corrected significance level (P = 0.003)

1138

1139 Table 3. Eigenvalues, percentage variability explained, and variable loadings on the first
 1140 three Principal Components of a PCA applied to six sediment properties of 139 surface
 1141 sediment samples.

1142

	PC1	PC2	PC3
Eigenvalue	4.371	1.201	0.197
Variability (%)	72.843	20.010	3.282
Cumulative %	72.843	92.854	96.136
Loadings			
%organic	0.921	0.157	-0.336
D50(ϕ)	0.946	-0.123	0.161
%gravel	-0.937	-0.280	0.001
%sand	0.568	0.790	0.182
%silt	0.926	-0.304	-0.059
%clay	0.754	-0.605	0.146

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1144

1145 Table 4. Generalised linear models for each of the ten, fifty and ninety percentiles (D10,
 1146 D50, D90) of the 0 ϕ and finer mineral sediment fraction of 139 particle size distributions,
 1147 with sampling year (2016, 2017), surface (1980EI, 2000PI, 2000btwn, 2004PI, 2004btwn,
 1148 2014PI, unveg) and interactions between year and surface as the explanatory variables
 1149 (percentile expressed in ϕ units, statistical significance of differences between groups
 1150 explored using the Bonferroni method).

	DF	F-value	P-value	Bonferroni pairwise comparisons (P<0.05)
D10				
Surface	6	44.27	<0.001	1980EI, 2000PI, 2004PI > 2014PI, 2000btwn > 2004btwn, unveg
Year	1	8.51	0.004	2017 > 2016
R ² (adjusted) = 66.8%				
D50				
Surface	6	35.11	<0.001	1980EI, 2000PI, 2004PI > 2014PI, 2000btwn > 2004btwn, unveg
Year	1	8.88	0.003	2017 > 2016
R ² (adjusted) = 60.6%				
D90				
Surface	6	26.00	<0.001	1980EI, 2000PI, 2004PI > 2000btwn, 2004btwn > unveg 2014PI > unveg
Year	1	9.37	0.003	2017 > 2016
Surface*Year	6	5.41	<0.001	1980EI(2016,2017), 2000PI(2016,2017), 2004PI(2016, 2017), 2014PI(2017), 2000btwn(2017), 2004btwn(2017) > 2000btwn(2016), 2004btwn(2016), unveg(2016,2017)
R ² (adjusted) = 57.2%				

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