Channel evolution engineered by a native riparian sedge, *Carex nudata*, following passive restoration

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Introduction

Until the latter part of the 20th century, fluvial geomorphology focused primarily on physical processes within rivers. The relationship between physical processes and biological components such as plants was portrayed as largely unidirectional with biological components conceived as passive features responding to flood disturbance and flow patterns (Hughes 1997). Increasingly, however, vegetation is recognized as having significant effects on the evolution of river morphology (Vaughan et al. 2009). Plants may affect flow, erosion and sedimentation in complex ways (Rodrigues et al. 2007; Rodrigues et al. 2006). Corenblit et al. (2007) have proposed the concept of biogeomorphic succession to describe the interplay between vegetation and physical river processes in the linked development of channel morphology and riparian plant communities.

The Middle Fork John Day River (MFJDR) in northeastern Oregon has become a remarkable natural laboratory for examining the coupled evolution of plant communities and river morphology. Historically, the MFJDR was heavily degraded by dredge mining, tree removal and cattle grazing. However, in the late 1990s vegetation was released from cattle grazing pressure following reformation of grazing practices by the U.S. Forest Service (USFS) and the establishment of conservation areas dedicated to salmon population recovery. In the midst of much resource-intensive active restoration, one of the most surprising developments was the unaided explosion of the native riparian sedge, *Carex nudata,* now the most prominent species along the stream-side greenline. A model of passive restoration, the explosion of *C. nudata* caught our attention given that anecdotal evidence suggested that river morphology may be changing in response to *C. nudata's* expansion.

Found in varying densities in rivers throughout Oregon and California, *C. nudata* derives its common name, torrent sedge, from its ability to grow in the middle of fast rivers due to its remarkably strong, dense root system (Levine 2000). *C. nudata*'s life history traits are consistent with a disturbance-adapted strategy (Chapter 2). *C. nudata* is tussock-forming, not rhizomatous, and propagates primarily by seeds that are river-dispersed (Wilson et al. 2008). Seeds are dispersed and immediately germinate during summer low flows, placing newly established *C. nudata* at the leading edge of opened substrate. The diameter of a mature (>10 yrs) tussock at its base can be >.5 m, and the diameter of its leaf crown may be 1-2 m. *C. nudata* tussocks, grouped together, may form a "fringe," a linear patch at the base of cut banks, typically where layers of course substrate are exposed and colonized as the bank erodes. *C. nudata* individuals may also form a fringe along the edge of gravel bars or alternatively, be found in a dispersed pattern across a bar. *C. nudata* patches can also form islands. As a significant obstacle, *C. nudata* tussocks may alter patterns of flow, erosion and deposition. The differing morphology among reaches with and without *C. nudata* suggest that *C. nudata* may be classed as an ecosystem engineer, an organism capable of altering the environment around it, modifying its habitat (Jones, Lawton, and Shachak 1994; Gurnell and Petts 2006).

The emerging field of inquiry around plant-river interactions has described different patterns of vegetation effects upon rivers and a complexity of interactions varying with plant and river types. A widely described pattern is the capacity of plants to stabilize substrate, affecting the direction of channel evolution. Flume experiments have demonstrated the ability of vegetation to shift a braided channel to a sinuous, single thread channel via the stabilization of unconsolidated material (Gran and Paola 2001; Tal and Paola 2007). Similar conversions of broad, braided channels toward narrowed single thread channels have been observed in natural experiments where dams have reduced downstream peak flows, allowing vegetation expansion (Birken and Cooper 2006; Hicks et al. 2007). Through a variety of processes – protecting the bank toe from fluvial shear stress, increasing bank cohesiveness via root strength, reducing soil pore pressure via transpiration – vegetation may stabilize banks, often leading to channel narrowing (Anderson, Bledsoe, and Hession 2004; Pollen-Bankhead and Simon 2010; Rodrigues et al. 2007; Simon and Collison 2002). By disturbing and reducing vegetation, cattle grazing has generally led to wider stream channels (Kauffman and Krueger 1984; Magilligan and McDowell 1997; Trimble and Mendel 1995). Conversely, the removal of cattle grazing has often led not only to increases in vegetation but also shifts in plant composition toward more bank-stabilizing species and potentially narrower channels (Clary 1999; Green and Kauffman 1995; Hough-Snee et al. 2013; Kauffman, Krueger, and Vavra 1983; Platts and Nelson 1989).

Plants may also facilitate the development of specific features within rivers. In low energy river systems in England, Gurnell et al. (2006) found that by trapping sediment, the aquatic macrophyte, *Sparganium erectum*, could induce either in-channel shelf formation (below water surface) or bench formation (along channel edges) depending on a channel's stream power. In the high energy, braided Tagliamento River of Italy, trees including *Populus* or *Salix* spp. have been characterized as ecosystem engineers that drive island formation (Edwards et al. 1999; Gurnell and Petts 2006). Gurnell et al. (2001) describe alternative pathways of island formation with varying rates of development and persistence dependent on the mode of island formation by 1) diffuse vegetation establishment on a bar, 2) propagule establishment in the lee of dead wood or 3) vegetative regeneration from transported living wood.

The effects of plants within a given system may not be generalizable, rather different plant species and communities within a system may have differing effects. In a vegetated secondary channel of the anabranching Loire River, Rodrigues et al. (2006) demonstrated that differing forms and degrees of resistance to flow among riparian tree species could lead to complex patterns of erosion and sedimentation, challenging simple generalizations. In the high energy Tech River, Corenblit et al. (2009) found differential patterns of erosion and aggradation associated with differing plant communities along an elevation gradient with increasing distance away from the river's base flow. Corenblit et al. (2009) postulated that communities of shrubs and pioneer tree seedlings at intermediate elevations instigate positive feedbacks that stabilize landforms and promote succession. By presenting high roughness at distances where flows are still sufficient to carry significant sediment, sediment accumulated at high rates, promoting additional establishment of tree seedlings.

While a growing body of evidence has demonstrated the capacity of vegetation to mediate stream evolution, certain plant guilds (, aquatic macrophytes; trees and shrubs such as *Populus*, *Salix* and *Tamarix* spp.) and river types (low energy rivers with fine sediments, high energy braided rivers) have been studied extensively while other plant types and systems have received relatively little attention. (Gurnell et al. 2010; Gurnell, Bertoldi, and Corenblit 2012). *C. nudata* represents a plant form and an ecological role distinct from the plant guilds that have been studied extensively. In contrast to aquatic macrophytes, *C. nudata* does not typically present significant roughness via its leaf area when inundated given that *C. nudata* loses its leaves in winter prior to early spring peak flows. Instead, as a tussock forming sedge it builds a solid obstruction with its mass of dense roots, senescent material and captured sediment. *C. nudata* individuals might be described best as organic boulders that grow and reproduce, situated in a narrow band at the leading edge of intense fluvial-vegetative interaction.

In this study, we aimed to describe the channel morphology of river reaches with *C. nudata* and the patterns of erosion and deposition relative to *C. nudata*. We then aimed to propose a conceptual model of stream evolution in rivers with *C. nudata*. Observing *C. nudata* patterns of establishment, a variety of questions and hypotheses emerged. Across gravel bars, does the diffuse distribution of *C. nudata* enhance deposition via roughness? Do *C. nudata* fringes at the base of banks arrest bank erosion? Along the stream-side face of *C. nudata* fringes, does scour or deposition occur? Are *C. nudata* islands loci of upstream scour and downstream deposition? How did these ubiquitous *C. nudata* islands get there in the first place?

We structured our investigation around two methodologies, repeated topographic surveys and historic aerial imagery analysis, overlapping in their aim to address four broad questions.

1) What morphological features distinguish channels with *C. nudata* patches?

2) What patterns of erosion and deposition are associated with *C. nudata* features?

To address the first two questions, we conducted repeated topographic surveys at 7 focused sites, repeated these surveys after two years and used digital elevation model (DEM) differencing to assess patterns of erosion and deposition.

3) How has planform – channel boundaries, bank tops and islands – evolved with the establishment of *C. nudata* patches in channels?

To address this question, we integrated the change analysis from our repeated topographic surveys with an analysis of historic aerial imagery at these sites.

4) What are the primary pathways of *C. nudata* island genesis?

To address this question, we tracked islands in a 10 km stretch of river through a series of historical aerial imagery.

Integrating these lines of investigation, we will propose a conceptual model of stream evolution in rivers with *C. nudata*. In light of emerging inquiry around plant-river interactions, *C. nudata* may serve as a model of bidirectional relationships between vegetation and physical river processes and the potential role of plants as ecosystem engineers in rivers (Corenblit *et al.* 2007). Furthermore, understanding the relationship between stream evolution and the expansion of particular plant species following passive restoration is critical for managers and restoration practitioners.

Methods

Study Area

The Middle Fork John Day is one of four branches of the John Day River, a tributary to the Columbia River and the third longest free-flowing river in the contiguous United States (Fig 1). The headwaters of the MFJDR arise in the Blue Mountains of northeastern Oregon, where the climate is generally characterized by cold winters and dry, warm summers. Seventy percent of the precipitation falls between November and March, primarily as snow. Therefore, hydrology is strongly driven by snowmelt with spring peak flows with intermediate flows after fall rains, complete river ice in winter and late summer flows sustained by groundwater (OWRD 1986). The river is generally sinuous and alternates between unconstrained reaches across floodplain meadows (400-500 m wide) and constrained reaches. The first part of our study, the repeated topographic surveys, was located within a broad alluvial valley while the second part of our study, the extensive survey of *C. nudata* islands, included both reach types. The repeated survey sites were all located within the Oxbow Conservation Area (OCA) owned by the Confederated Tribes of Warm Springs (CTWS) whereas the extensive survey of islands, crossed through both U.S. Forest Service land and the OCA. Elevation at the OCA is around 1100 m. In the alluvial valley of the OCA, the river bed is dominated by coarse gravels and cobbles; median sediment size (D_{50}) is typically 50-80 mm (McDowell 2001). The constrained canyon reaches can include a significant component of boulders. Low summer flow channel widths range from 3 to 13 m, and typical measured slopes range from .003 to .008. Pool-riffle channel reach types predominate with occasional plane-bed types. Mean annual discharge at the nearest gage (14 km downstream from surveyed sites) is 3.7 m^3/s and Q_2 flow is 21.2 m^3/s.

Repeated Topographic Surveys

We surveyed 7 sites in 2012 and 2014. We examined changes in bed morphology by constructing digital elevations models (DEMs) from these surveys and then differencing these DEMS to produce DEMs of differences (DoDs). Five of the surveyed sites were “full surveys” or “fringe sites” and two surveys were partial surveys or “island sites.” The full survey, fringe sites were placed within meander bends with a cut bank on the outside bend and gravel bar on the inside and all included a fringe of *C. nudata* at the base of the bank. Surveys included and extended beyond the banktop on one side and on the other side, surveys extended beyond the exposed gravel bar usually to the elevation where shrubs and trees became dominant (and surveying difficult). Sites were chosen to represent a range of *C. nudata* channel types we had observed, e.g. dense, continuous fringes vs. sparse patchy fringes. Sites ranged from 24-42 m in length with an average site width across the river was 15.5 m, such that average site areas ranged from 320-560 m^2. While the fringe sites often included islands, we surveyed two sites specifically focused on an individual island. At these island sites, partial surveys extended just beyond the water's edge on each side of the river but did not include bank tops. Average island site length was 8 m and average width 9 m.

Topographic surveys were derived entirely from rtkGPS (Topcon GR-3) surveys. Full (fringe site) surveys comprised between 1000-3900 points (2200 average). The average kernel point density was derived from a moving 1 m radius window. We surveyed points across a .7-1.5 m grid-based sampling scheme, capturing inflection points along grid lines and then infilling this grid with feature-based surveys of higher point density in areas of topographic complexity. In particular, we surveyed the linear break features of bank tops and bank bottoms at higher density, and we conducted high density radial surveys around mature *C. nudata* tussocks, starting at each tussock's highest point and extending outward at least 1 m. Grid survey points were extended beyond the boundaries of the intended analytical window (the DEM) such that there would be no issue with boundary effects.

We constructed DEMs in ESRI's ArcGIS using a two-stage process. Survey points were used to derive a triangular irregular network (TIN) which was then resampled onto a grid (DEM) with .1 m resolution. When deriving the TIN, we treated linear features such as bank tops as hard breaks and used a hard clip polygon around the points used in the TIN construction. We used the natural neighbors method when converting the TIN into a DEM.

A key issue when differencing DEMs is accounting for uncertainty. While early DoD analyses used uniform estimates of error and limits of detection, many authors have demonstrated that uncertainty can vary spatially. Accounting for the spatial variability of uncertainty is critical such that changes in elevation are not attributed in areas where uncertainty is high nor ignored where change may be small, but uncertainty is minimal. Uncertainty may vary as a function of slope and topographic complexity, survey point density and instrument error (aka point quality). We assessed two different methods for accounting for uncertainty, the completely quantitative functions of Milan et al. (2011) that focus on topographic complexity, and the fuzzy inference systems (FIS) of Wheaton et al. (2010) that account for slope, point density and point quality. The Wheaton et al. (2010) FIS yielded more conservative estimates of change at our sites, and we proceeded with a modified version of their FIS. That is, we dropped point quality from our FIS, because instrument uncertainty (vertical root mean square error, VRMS) showed little spatial variation across our sites and was generally low (average VRMS = .007 m). Given that we surveyed very high point densities in areas of high complexity, point densities much higher than those reported in Wheaton et al. (2010), we also modified the point density and slope membership functions and logic: we added a "very high" point density class that allowed areas of moderately high slope to be classed as "average" uncertainty rather than the "high" or "extreme" uncertainty assigned to all slopes other than "low" and "moderate" in Wheaton et al. (2010).

Using our modified version of the Wheaton et al. (2010) FIS, we created error surfaces for the old (2012) and new (2014) DEMs for each site. For each grid cell within the DEM, propagated error can be calculated as the root mean square of the error associated with the old and new error surfaces, and a critical threshold error, U_{crit}, can be determined by:

$$U_{crit} = t(\sqrt{(\delta z_{new})^2 + (\delta z_{old})^2} \quad (1)$$

where δz_{new} and δz_{old} are the individual errors in the new and old DEMs, respectively and t is a critical student's t-value at a chosen confidence interval. We used a 90% confidence interval. Any changes in elevation with absolute values greater than the critical threshold error are represented as significant change in the DoD. We did not apply the Wheaton et al. (2010) Bayesian spatial coherence function to the DoD which can expand the areas deemed significant change as we perceived its results to be too liberal.

Aerial imagery analysis

In addition to the repeated topographic surveys at the 5 full sites, we also investigated historic changes in planform and vegetation at each site using historic aerial imagery. We compared sets of aerial imagery from 2013, 2006, 2001 and 1989 with resolutions of .1 m, .15 m, .48 m and .48 m, respectively. The 2013 and 2006 imagery were true color, the 2001 imagery black and white and the 1989 imagery color infrared. All imagery was taken during the summer low flow ranging from late July to early September. The 2013 imagery was developed by the University of Oregon in collaboration with the U.S. Bureau of Reclamation, the 2006 imagery was developed by Watershed Sciences, Inc. and the 1989 imagery by the National Aerial Photography Program (NAPP). To interpret planform evolution, we digitized *C. nudata* patch boundaries in the 2013 imagery and then for all imagery years, the channel boundaries and banktop lines at each site. Given the low resolution of the 1989 and 2001 relative to the rates of bank retreat, it was only feasible to conduct a qualitative assessment of bank movement.

We used this same set of imagery to assess pathways of *C. nudata* island genesis over a 10 km stretch of river that included our surveyed sites. For the 2013 imagery, we digitized all *C. nudata* islands, defined as any mature *C. nudata* individual or cluster around which water pixels were continuously visible between the tussock and bank. We then classified the status of each island in the earlier 2006, 2001 and 1989 imagery. Classes included information on whether the *C. nudata* patch identified as an island in 2013 was present or not, whether it was mature or much smaller in size (a clue to how long it had been in its current position)) and whether it was in a midchannel position or attached to the edge of a bank or gravel bar, and if it was in a midchannel position, the nature of the material on which it was established, if visible (e.g. midchannel gravel bar vs. discrete boulders). We deduced the origin of the islands from changes in status across time periods. For instance, if a mature *C. nudata* present in 2013 was completely absent in 2006, not even visible as a juvenile, it was assumed to have been uprooted between 2006-2013 and transported to its new 2013 position (and often, it was possible to identify the 2006 location from which had been uprooted). The resolution of the 1989 and 2001 imagery did not allow identification of individual *C. nudata* tussocks. However, it was possible to identify midchannel bars, vegetation patches and bank lines, and thus determine whether 2013-delineated *C. nudata* locations were in midchannel or bank positions in 2001 and 1989.

Results

Topographic surveys: initial surveys (2012)

Our initial topographic surveys (2012) revealed an overall channel morphology that we will describe as a compound channel. Among our five full topographic surveys (bank-to-bank: cut bank to gravel bar), three sites could be classed as a compound channel (BEBU_F01, BUTI_F01, BUTI_F03; Fig. 2a,c,e) in which fringes of *C. nudata* tussocks established at the base of banks created natural levees bounding the summer low flow channel (Fig. 3a,b,c,e,f,i,j). The *C. nudata* bank fringes also defined a higher elevation margin between the cut bank and the fringe which becomes inundated during fall and spring high flow events at which time the channel boundaries are defined by the outer cut bank and opposite inner bank. This bank-to-fringe margin ranged from approximately 1.5-5 m across our sites. Instead of a compound channel, one site (BUTI_F02) illustrated an island morphology type in which the space between the cut bank and the *C. nudata* patch was inundated across all flows, including summer low flows, and the thalweg was positioned between the cut bank and islands (Fig 2d; Fig 3g,h). One site (BEBU_F02) could be characterized as island morphology in the upstream portion of the site and as a compound channel in the lower portion of the site (Fig 2b; Fig 3c,d). It should also be noted that at two of the three sites we classify as compound channels (BEBU_F01, BUTI_F01), the *C. nudata* bank fringe included discontinuities that gave way to *C. nudata* island patches, but the thalweg never passed between ("behind") these islands and the bank, such that the margin between the bank and the *C. nudata* fringe was always at a higher elevation than the channel "in front" of the *C. nudata* fringe. In some segments, *C. nudata* also formed a well-defined fringe with elevated topography along the gravel bar edge (Fig. 3b,d,e,i), whereas in most cases, *C. nudata* was dispersed and less topographically effective across the gravel bar.

In addition to the overall channel morphology defined by *C. nudata* (compound channel and island types), microtopographic features were also associated with *C. nudata* fringes and islands. *C. nudata* tussocks, themselves, created individual small hummocks or linear levees (Fig. 2). Deeper areas were often found along the thalweg-facing edge of the *C. nudata* fringe and at the upstream face and edges of *C. nudata* islands (Fig. 2, 4).

DEMS of difference: 2012-2014

The most striking pattern of change was the significant bank erosion that occurred across all of the full survey sites. Significant bank erosion occurred not only in segments without *C. nudata* in front of the bank, but also in segments with *C. nudata* fringes in front of the bank (Fig

5). Due to the large volume of bank erosion, the overall volume of erosion was greater than depositional volume. Apart from bank erosion, overall change across sites was varied and often minimal. Microtopographic changes that did occur were often in proximity to *C. nudata* features, e.g. small patches of scour along the thalweg-facing edges of *C. nudata* fringes and the upstream and lateral edges of islands (Fig 5, 6). Theses scour patches did not occur consistently along the fringes or islands but were found only along specific *C. nudata* edges at certain sites (e.g. BEBU_F01, BEBU_F02, BUTI_F01, BUTI_I01; Fig. 5a,b,c; Fig. 6b). In some cases, spaces between islands or along the edges of islands or fringes were also loci for deposition (BEBU_F02, in particular, also BEBU_F01, BUTI_F02; Fig. 5a,b,d). Outside the low flow channel, small patches of deposition were sometimes associated with *C. nudata* tussocks in the bank fringes or islands or among patches of dispersed *C. nudata* on the gravel bars (e.g. BEBU_F01, BEBU_F02, BUTI_F03; Fig 5a,b,e). Most deposition (apparent in the "raw" DoDs) was below the limits of detection. In general, microtopographic changes that did occur, while not widespread, were typically in proximity to *C. nudata* patches rather than dispersed evenly across the sites.

A few in-channel changes bear specific mention. At BUTI_F02, the uprooting and transport of an entire *C. nudata* tussock left a scour hole where it was previously located and apparent "deposition" at its new location (Fig 5d). At BEBU_F01, continuous *C. nudata* fringes in front of both the bank and gravel bar create a "chute" that empties into a deep pool. The 2012-2014 DoDs display as scour patch at the downstream end of this chute right before it empties into the deep pool where patches of deposition are apparent (Fig 5a).

Historic change (pre-2012) at survey sites

Consistent with the bank erosion revealed by our 2012-2014 DoDs, historic aerial imagery showed significant bank retreat across all sites and time intervals (1989-2001,2001-2006, 2006-2013). The most eye-opening change occurred at the site with island type morphology, BUTI_F02. In 2006, the *C. nudata* islands in our 2012 survey were not islands, but rather were "attached" to the bank as a *C. nudata* fringe at the base of the bank. Therefore, between 2006-2012, the bank not only eroded "backward" behind the *C. nudata* fringe, but the margin between the fringe and bank also eroded downward, allowing the thalweg to shift from in front of the fringe in 2006 to behind the fringe where our surveys located it in 2012 between the bank and islands (Fig 7). At another site, BUTI_F01, the one island at this site is in line with the rest of the fringe and was also revealed to be "attached" to the bank in 2006 (i.e. no water behind it), also suggesting downward scour between the bank and the fringe along this segment between 2006-2012 (Fig 8). However, in this case, the thalweg remains "in front" of the island. At all three of the full BUTI sites, the current *C. nudata* fringes and islands all established post-1989 in a pattern suggesting relatively synchronous establishment proximate to the 2001 bank boundaries (imagery in 2001 is not sufficiently clear to identify vegetation).

In contrast with the BUTI sites, establishment of *C. nudata* patches started earlier and was more complex in the BEBU reach. At BEBU_F01, the large midchannel island was already well-established in the 1989 imagery (Fig 9). The left bank fringe and the upper portion of the gravel bar fringe (right bank) likely established between 1989-2001 as these patches are in line with the 1989 bank and channel boundaries and faint vegetation coloring along these edges is apparent in 1989, as is a small (1-2 m) gravel margin at the base of the left bank. Bank retreat and gravel bar expansion between 1989-2001 led to the emergence of the downstream pool below the left bank fringe and the current boundary of the gravel bar. The lower portion of the gravel bar *C. nudata* fringe (right bank) and left bank pool-bounding *C. nudata* established 2001-2006 (Fig. 9).

At BEBU_F02, the large cluster of *C. nudata* islands in the upstream portion of the site formed in three phases and revealed an additional pathway of island formation (Fig 10). One row of islands evolved from *C. nudata* patches that established in front of the 1989 bank. The broad, vegetated margin in front of the bank across the middle section of the site was also present in 1989, abeit narrower, and the apex defined by the *C. nudata* patch was also apparent in 1989, but without the image “texture” associated with mature *C. nudata*, suggesting it had just established. A second row of islands evolved from *C. nudata* patches that established as a bank fringe between 2001-2006. Finally, between 2006-2013, this island cluster grew at the upstream end with the addition of two more *C. nudata* “blocks” (one a single tussock and the other 2+ tussocks) that were uprooted from *C. nudata* bank fringes upstream of the site and transported to their present location where their transport was arrested, and they re-established.

Island genesis: large extent analysis of historic imagery

From field observations, we had observed *C. nudata* established on midchannel gravel bars and on large mid-channel boulders, suggesting these establishment modes as two pathways of island genesis. Our site-based historic aerial imagery suggested two additional pathways: 1) the retreat of banks away from *C. nudata* bank fringes leaving these patches “detached” as islands and 2) the uprooting and transport of *C. nudata* blocks from channel edges to midchannel positions. Through our extensive analysis of historic aerial imagery (10 km river length), we found not only further evidence for all of these pathways, but also additional pathways: 1) establishment in shallow riffles, presumably on clasts breaking water surface but not visible as large boulders nor aggregated as midchannel bars, and 2) “detachment” of *C. nudata* gravel bar fringes via erosion behind these fringes along the inner bend of the river (Fig. 11, 12).

Over 10km, our census counted 440 islands consisting of 1,754 mature *C. nudata* tussocks and covering 4,728 m^2 of river surface area (Table 1). This would suggest that on average, 4.4 islands occur every 100m and, if we assume an average island width of 2 m, these islands would stretch along 24 m of every 100 m of river length. Among the island census, 19% were already well-established by 1989, preventing assessment of their origin. Image quality issues (e.g. shadows) and artificial pathways (excavation around *C. nudata* patches) excluded additional islands, leaving 298 islands (68%) with a clear determination of origin via natural processes.

Island formation via the movement of channel boundaries away from *C. nudata* patches, either at the base of banks or along gravel bars, accounted for a plurality of islands (47%) and a majority by island area (51.6%) or by total number of tussocks (58.2%) (Table 2). Bank-derived islands were greater in number (87) than gravel bar-derived islands (42) but the larger average area of gravel bar-derived islands led to a greater overall area (29.2% vs. 18.1%). Transported *C. nudata* blocks made up 11.1 % of all islands but were the smallest in size (1.8 m^2 average), making this class the least important by overall area (1.9%). Boulder-established *C. nudata* made up the 2nd largest class of islands by number (61 islands, 20.5%) but were also relatively small (2.4 m^2 average), such that they accounted for only 4.6% of island area. In contrast, islands originating on midchannel gravel bars were not numerous (20 islands, 6.7%), but being the largest in size, this class covered largest overall area (36.5%).

Discussion

Channel morphology and patterns of change relative to C. nudata

At each stage of our investigation, our results produced surprises that up-ended initial expectations. The first and foremost surprise was the continuing, significant retreat of banks behind *C. nudata* bank fringes. Vegetation has often been shown to slow bank retreat. Meta-analyses have found that channels with vegetation are typically narrower than those not fully vegetated (Anderson, Bledsoe, and Hession 2004). The expansion of vegetation, in general, following flow reductions by dams has led to the conversion of braided channels to single channels and channel narrowing (Hicks et al. 2007). In the arid southwestern U.S., the introduction and expansion of the non-native, *Tamarix* spp, has likewise led to dramatic narrowing of channel widths (Birken and Cooper 2006). Across the western U.S. in grassland systems, studies of cattle grazing effects have often found that channels where grazing has been excluded or reduced are narrower (by bankfull width or wetted width) and have lower width to depth ratios than intensively grazed channels (Clary 1999; Kauffman and Krueger 1984; Magilligan and McDowell 1997). Differences in width associated with differing grazing treatments have often been associated with shifts in plant species composition away from ruderal grasses in grazed areas toward hydrophytic, bank-stabilizing species such as densely rooted, rhizomatous sedges in areas with reduced or eliminated grazing(Green and Kauffman 1995; Hough-Snee et al. 2013; Kauffman, Krueger, and Vavra 1983; Platts and Nelson 1989). Therefore, it was surprising to find that bank retreat continues to occur behind *C. nudata*. We should be clear, however, that our data does not establish whether bank retreat rates are continuing at rates similar to or slower than those prior to *C. nudata* expansion. Furthermore, continued bank retreat does not necessarily mean that low flow wetted widths or width to depth ratios have remained the same.

Nevertheless, the finding of continued bank erosion highlights the point that vegetation effects cannot be generalized. The particular form and ecology of a plant are critical to understanding the effects of plants on channel morphology. In the case of *C. nudata*, its dispersal strategy results in establishment in a narrow band along the leading edge of colonizable substrate most prone to disturbance. Once established, it does not expand significantly further up a bank or further back on a bar. In some cases, we have observed successive vegetation establishing behind *C. nudata* (especially on gravel bars) but the margin between *C. nudata* and the bank often remains sparsely vegetated and unprotected from further erosion. Whether a bank continues to erode or is stabilized following *C. nudata* colonization may depend on the rate of erosion relative to the rate of colonization by additional species behind the *C. nudata* fringe. In addition to its strong, dense root mass, the other critical aspect of *C. nudata*'s morphology is its tussock form. Given this morphology, *C. nudata* forms irregular patches characterized by hummocks, discontinuities and gaps that may allow further erosion.

The nature of flow patterns and associated erosion patterns around *C. nudata* warrant further investigation beyond the speculation offered here. For instance, a key question is whether the continued erosion observed for banks behind *C. nudata* might still slower than banks without *C. nudata* due to the stabilization of the bank toe by *C. nudata*. Understanding flow velocity patterns around *C. nudata* fringes at different discharges would also permit better interpretation of the bank retreat patterns documented here. Nevertheless, the key point remains that vegetation effects on banks and channel geomorphology cannot be generalized but may reflect the particular ecology and form of the key species in play.

In contrast to the large volume of bank erosion occurring at our sites, patches of erosion and deposition (2012-2014) across the rest of the channel bed was relatively minimal. To some extent this was puzzling because our initial topographic surveys revealed much micro-topographic variation around *C. nudata* features. For instance, deepened in-channel areas and a steep "wall" of roots in front of the *C. nudata* fringe (or along island fronts and edges) was a common feature such that we expected to see continued deepening in these areas. Continuing scour in such areas would offer further evidence of the association between *C. nudata* and this process. However, significant continuing scour was only found in small patches and the patterns of deposition and erosion around *C. nudata* were not consistent enough to allow ready interpretation. Nevertheless, the small patches of scour and deposition that were evident at our sites were typically in proximity to patches of *C. nudata* pointing to *C. nudata* as the critical organizer of morphological change in theses channels.

To some extent it was not surprising that we did not detect more widespread change. Streambeds in the MFJDR are characterized by clast sizes that are relatively coarse relative to the stream power experienced in these reaches. Furthermore, during the 2012-2014 survey period, the spring 2013 peak flows were below average, and the 2014 peak flow was a 1.6 return interval event. It may be that significant stream bed change occurs primarily during exceptional peak flows or can only be detected over longer time periods. It should also be noted that in our spatially variable estimates of error, the areas around *C. nudata* have much higher error estimates and limits of detection given the steepness around *C. nudata* features. Finally, it is also possible that the most significant changes in streambed topography occur earlier in the *C. nudata* establishment and growth life cycle. That is, our sites (and much of the MFJDR now) are currently occupied by mature *C. nudata* tussocks. It is possible that most morphological adjustments occurred shortly after the *C. nudata* established such that a new equilibrium has now been established and many of the topographic features we observe across the streambed are products of that initial adjustment.

Following the finding that significant bank erosion was continuing behind *C. nudata* fringes, the next big surprise was the revelation that *C. nudata* islands could originate from bank fringes "detached" from their banks via backward and downward erosion behind the fringe. Based on field observations in which we had observed *C. nudata* establishing in riffles, on boulders and around midchannel bars, we had assumed that *C. nudata* islands originated in mid-channel positions. The island origin census revealed another unexpected pathway, "detachment" of gravel bar fringes, and revealed that island origin via "detachment" from moving channel boundaries is the predominant mode for island genesis in the MFJDR. The diversity of island genesis pathways creates a diversity of island types. Establishment of *C. nudata* on large boulders or on clasts in riffles results in small islands typically consisting of 1-2 *C. nudata* tussocks. Islands derived from the uprooting and transport of *C. nudata* blocks are also typically small, but in many cases these small islands may be deposited at the front of and augment existing island clusters (e.g. the BEBU_F02). Islands originating via detachment from channel boundaries are larger and often linear in shape, reflecting the linear pattern of establishment of the initial *C. nudata* fringe. However, successive cycles of linear cohort establishment and detachment may lead to larger clusters of islands (e.g. BEBU_F02). Islands derived from midchannel gravel bars were the largest among all island types and distinct in form, less linear and broader in shape than fringe-derived islands. Analysis of historic imagery suggested that midchannel gravel bars exhibit significant growth over time. Presumably, establishment of *C. nudata* around the edges facilitates further deposition downstream and midchannel islands often exhibited additional colonization and stabilization by other plant species. *C. nudata* islands originating on midchannel bars are essentially depositional features whereas *C. nudata* islands originating from bank fringes are essentially erosional features. While we have observed other plant species establishing and growing within bank-derived *C. nudata* island tussocks (including shrubs and trees!), overall island area expands slowly and almost exclusively through the growth and expansion of individual *C. nudata* tussocks.

The evolution of *C. nudata* islands from bank detachment offers an intriguing contrast with several other studies of island evolution. In classic studies of the high energy, braided Tagliamento River in Italy, Gurnell et al. (2001) describe different modes of island formation instigated by shrub and tree species (*Salix* and *Populus* spp.) including 1) stabilization of existing bars via dispersed colonization by tree seedlings; 2) enhanced substrate deposition, bar formation and subsequent colonization behind deposited dead trees; and 3) the transport, deposition and resprouting of a live tree followed by enhanced deposition, bar formation and colonization behind the resprouting tree. In each of these cases, island formation takes place either on an existing depositional feature or via the creation of a depositional feature behind deposited vegetation (dead or alive). In the MFJDR system, while *C. nudata* may facilitate island formation via the colonization of depositional features, island formation via erosional processes around substrate stabilized by *C. nudata* appears to be the dominant mode.

Conceptual model of river system with C. nudata

Integrating the morphological patterns described by the site surveys and temporal patterns of current and historic change, we can build a conceptual model of channel evolution with *C. nudata* in the MFJD River system. *C. nudata* is remarkably effective at stabilizing substrate and building elevated topography along the edge of the low flow channel where it initially establishes. However, it is less effective in arresting the erosion of banks such that the boundaries of the bankfull channel may continue to migrate even though the low flow channel boundaries may be stabilized. The differing rates at which banks retreat and the differing directions of vertical change (aggradation vs downward erosion) in the margin between the bank and the fronting *C. nudata* fringe set up the potential for multiple alternative pathways of channel evolution (Fig. 13).

If bank retreat continues without consistent net erosion or aggradation in the bank-fringe margin, a compound channel morphology develops (Fig 13b,e.). With the low flow channel boundaries locked in by *C. nudata*, a compound channel would likely have narrower channel widths during low flows than channel segments without *C. nudata*. Our 2012 topographic surveys also suggested deepened areas at the face of the *C. nudata* bank fringe, but the DoDs showed inconsistent evidence for continued scour (2012-2014) at the front of the *C. nudata* fringe face. If bank retreat continues rapidly with downward erosion in the bank-fringe margin, a channel with island morphology develops (Fig 13f). The thalweg may also shift into the space between the bank and fringe-derived island as was the case for our survey site, BUTI_F02, but not the case for islands in the upper portion of the BEBU_F02 site. Prior to island formation, deepened areas may have developed on the face of the bank fringe but it is unclear whether this island edge (facing the inner bend) continues to scour or aggrades. If bank retreat behind a bank fringe is slowed sufficiently for other vegetation to colonize the bank-fringe margin and this margin aggrades, a stabilized bank morphology and potentially narrower channel emerges (Fig 13d). None of our survey sites provided evidence of the bank stabilization pathway, but we have observed segments in the MFJDR in which gentle, vegetated slopes behind a *C. nudata* fringe suggest this pathway.

The pathway along which the channel evolves may depend upon a variety of factors including the bank material, river curvature and pattern of *C. nudata* establishment. A key difference between the island-dominated BUTI_F02 site and the compound channel sites was the bank material. In general, MFJDR banks consist of cohesive materials (typically silty clay loams in the upper portions) with coarser materials common in lower lens near or below the low flow water surfaces. However, in some banks the lower portions may be occupied by clays or alternatively, the coarse materials may extend much farther up the bank profile. In contrast with our other survey sites, the BUTI_F02 island site included a much higher percentage of coarse materials that extended upward through much of the bank, presumably making it less cohesive and more prone to erosion. Our sites were also distinguished by differences in *C. nudata* establishment pattern. The two sites with the most well-developed compound channel morphology (BEBU_F01, BUTI_F01) also had the most continuous, well-developed bank fringes, whereas BUTI_F02 was fronted by a shorter, less continuous fringe which may have allowed greater erosion behind it. River curvature is also likely a critical factor in driving erosion rates and development pathways, but our sites were all characterized by moderate curvature and did not display significant differences among sites with one exception. In BEBU_F02, curvature within the surveyed area does not appear significantly different, but the site is located immediately downstream of a strong curve which is migrating and resulting in more rapid bank retreat at the upstream portion of this site where island morphology developed (Fig 10). Heterogeneous patterns of bank material, *C. nudata* establishment and river curvature may interact to produce an array of alternative pathways of channel evolution.

The pathways described above all depend upon the establishment of a *C. nudata* fringe in front of a bank. Another pathway is made possible not by the establishment of a bank fringe but by the establishment of a gravel bar fringe leading to the evolution of islands on the inside bend of the river (Fig 13g). These islands were typically derived from fringes at the upstream end of a gravel bars, and the key factors in driving this pathway appeared to be river characteristics, particularly curvature, immediately upstream of the gravel bar. That is, upstream bank erosion (typically associated with a strongly curved upstream meander) results in the migration of the channel boundary immediately upstream of the gravel bar such that the straightest flow path is directed behind the *C. nudata* fringe at the upstream end of the bar. While a gravel-bar derived island site was not among our survey sites, we can presume downward erosion behind the fringe leading to its detachment from the gravel bar.

Within this array of alternative pathways, there is also the potential for a segment without a *C. nudata* bank fringe to continue along a pathway of simple channel morphology not dissimilar to a channel without *C. nudata*. Gravel bars opposite such banks might still experience change via enhanced deposition with *C. nudata* colonization, but our DoDs found only limited evidence for aggradation in dense patches of *C. nudata* (e.g. BUTI_F03, Fig 5e).

Implications for restoration

Throughout the Pacific Northwest, enormous investments are being made in river restoration projects aimed at improving habitat for salmon populations listed as threatened or endangered under the Endangered Species Act (ESA). The Middle Fork John Day River, in particular, has been targeted as a high priority for restoration and monitoring, designated as an Intensively Monitored Watershed (IMW). Restoration has included such capital intensive projects as placement of engineered log jams, often with deepened pools where log jams have been placed in outer bends. Preceding these active restoration projects, however, passive restoration was initiated through the reforms in cattle grazing timing/intensity or the withdrawal of cattle grazing from river banks. Following these reforms, the expansion of *C. nudata* has been perceived positively by managers and restoration practitioners, but the specific effects of *C. nudata* on channel morphology and planform have not been understood. The results of our investigation suggest that the expansion of *C. nudata* throughout the system is resulting in systemic changes to channel morphology that are enhancing channel complexity, a key goal of restoration efforts. In contrast to active restoration, the changes associated with *C. nudata* are less localized (i.e. restricted to the neighborhood of a specific restoration intervention such as an engineered log jam), but rather occur throughout the system. Furthermore, these changes in pattern have resulted from the restoration of natural processes, processes that are self-perpetuating, rather than simply the construction of desired patterns. Finally, these changes have required relatively minimal investment apart from the reduction or withdrawal of the disturbing factor and the management required to maintain that reduction (e.g. fencing maintenance and cattle rotation).

With the expansion of *C. nudata* throughout the system, different channel segments have the potential to evolve along different channel evolution pathways. The array of alternative pathways (both with and without *C. nudata*) results in a complex mosaic of channel forms at the scale of the riverscape. The *C. nudata*-associated forms such as the compound channel and island types also exhibit complexity at the reach scale. A diversity of habitat types may be associated with this complexity. For instance, in compound channel segments, the elevated margin between the *C. nudata* fringe and bank would likely experience lower velocities during high flows than the main channel, a potential refuge for juvenile fish. In general, the complex array of irregularly shaped islands and fringes with discontinuities and erosion behind them creates slower backwater eddies at all flows. Margins along the *C. nudata* fringes and islands can offer deepened edges, micro-habitats that are also shaded by overhanging *C. nudata* leaves during summer. McDowell and Goslin (2015) estimated that overhanging *C. nudata* leaves create fish cover (shade, predator protection etc.) over 5% of river surface area in the Oxbow Conservation Area, a figure similar to the amount of fish cover produced by engineered log jams. These deepened, shaded margins often face the main flow, but in some cases, changes in river path (e.g. with the creation of islands) may leave these deepened, shaded margins facing away from the main flow with slower velocities. As C.nudata expands and builds features throughout the river system, it induces complexity at both the scale of the river-scape via a mosaic of different channel forms and at the scale of individual reaches via an array of micro-topographic features and associated habitats.

Restoration projects often proceed by seeking to replicate desired patterns apparent in healthy ecosystems, but many investigators and restoration practitioners increasingly recognize that restoring the processes that create these patterns is more critical and self-sustaining that simply reproducing patterns. We have had the privilege of participating in collaborative monitoring efforts with restoration practitioners and managers in the MFJDR, and much excellent work with an eye to restoring processes has been undertaken. Nevertheless, recent restoration projects that employ *C. nudata* offer an excellent example of the differences between restoring patterns vs. processes. Several segments of the MFJDR were dredged for gold in the early 20th century leaving behind straightened channels with embankments of tailings. These segments have been the focus of engineering projects in which a new, meandering channels are constructed. In addition to the logs and engineered log jams that are placed in the new channel, *C. nudata* is transplanted from the soon-to-be-abandoned dredged channel and placed in the newly constructed meandering channel. *C. nudata* tussocks (usually one or two) are typically placed in mid-channel positions with the intention of reproducing the pattern of islands elsewhere in the MFJDR and are also placed as dispersed individuals on gravel bars. Engineered log jams are typically placed in the outside bends of the meanders, both for the purpose of creating complex habitat and also stabilizing the newly constructed banks. Placement of engineered log jams in the outer bends of meanders is also a common practice in the natural segments of the MFJDR (see left side of Figure 9 as an example). It remains to be seen whether *C. nudata* transplants placed as islands will remain in place, and it seems likely that they will not. As documented in our island genesis census, the majority of islands have originated from establishment and growth along the edges of the channel, solidifying their foothold before the boundaries of the channel around them move. While bank erosion and retreat are often perceived by managers as processes of concern that should be slowed or arrested, gradual bank retreat coupled with the expansion of vegetation and vegetation-built features is critical to the emergence of islands and complex forms in this system. Placement of log-jams in outer bends both prevents colonization of these banks by *C. nudata* as well as arresting boundary movement, thus short-circuiting the very process that created the complex pattern that the restoration design is attempting to reproduce via transplants. It should be noted that many of these projects were initiated around the same time as the research presented here and were designed prior to a full understanding of how *C. nudata* effects channel change.

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Figure List

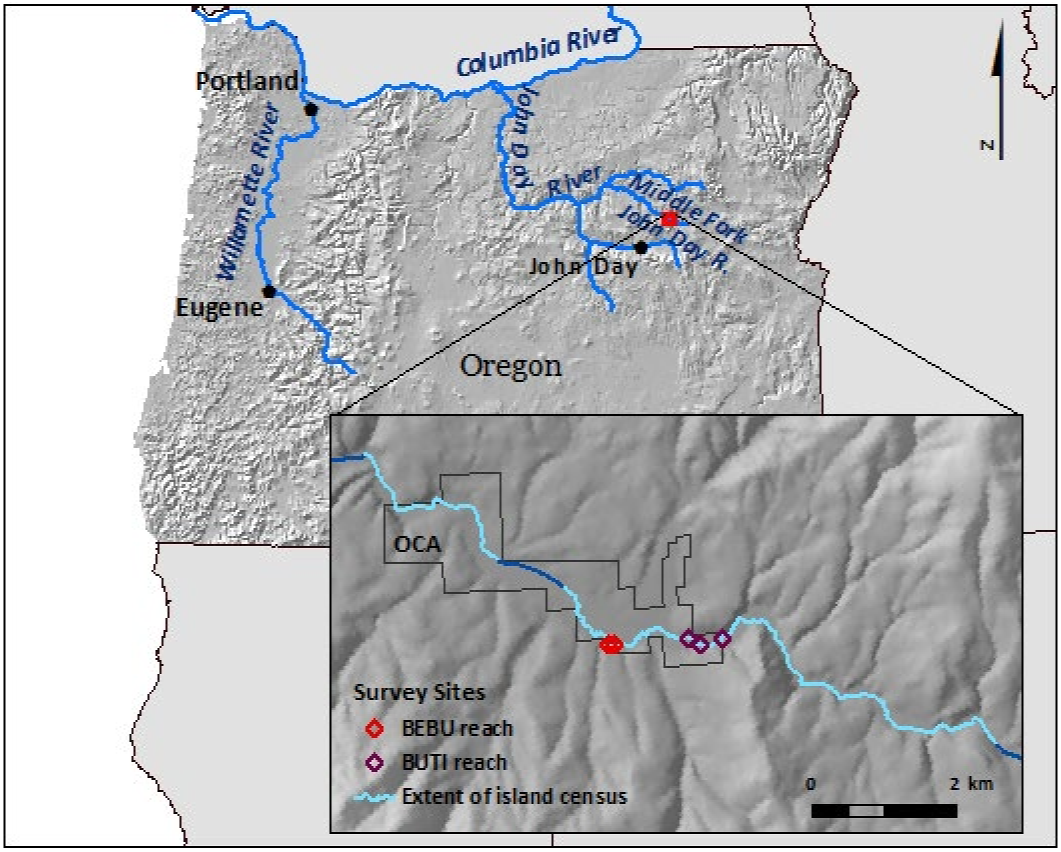

Figure 1. Location of Middle Fork John Day River (MFJDR). Inset focus map shows the location of the 5 full survey sites in the BEBU and BUTI reaches of the MFJDR and the extent of the 10 km river length census of C. nudata islands. Surrounding land ownership is U.S. Forest Service except the polygon with black outline represents the Oxbow Conservation Area (OCA) owned by the Confederated Tribes of the Warm Springs. Note the straight stretch of river (dark blue) not included in the island census extent (cyan). This stretch is the straightened, gold-dredged channel that was recently re-engineered as a meandering channel as discussed in the "restoration implications" section of the discussion.

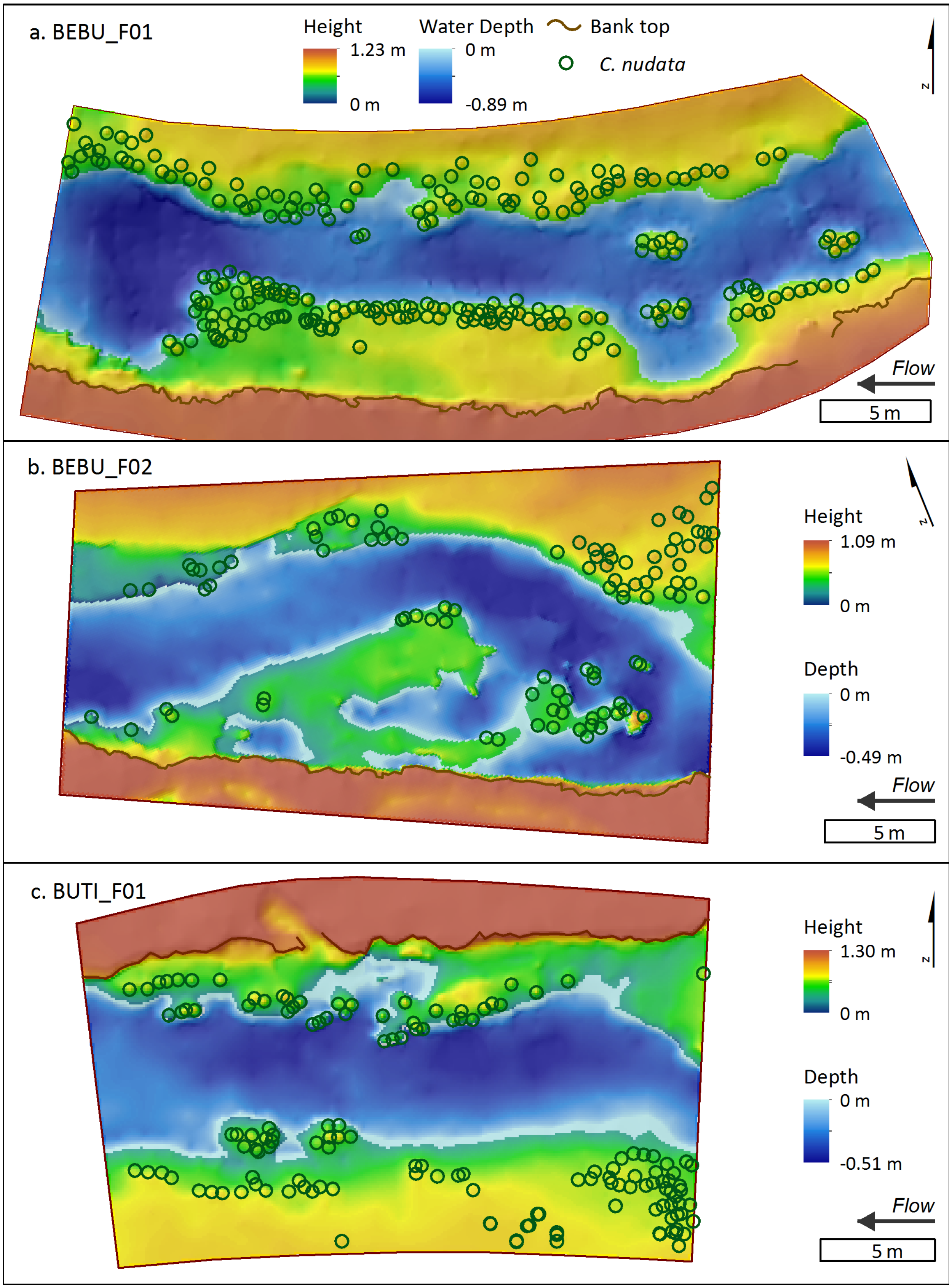

Figure 2. Digital elevation models (DEMs) of full survey sites, 2012. Height is relative to lowest water surface elevation. Green circles indicate *C. nudata* positions. Thick dark line represents bank top. Flow is from right to left.

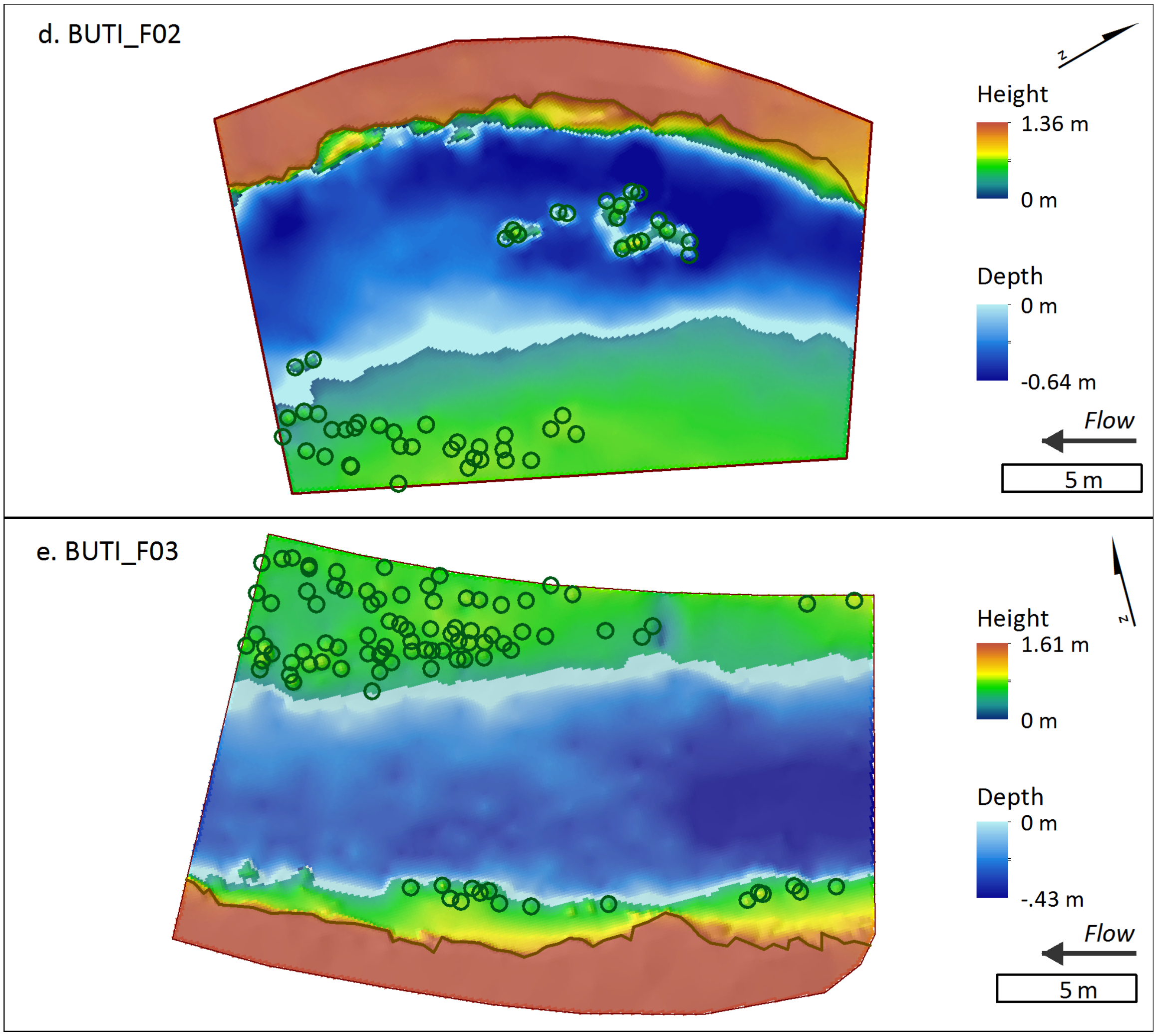

Figure 2 cont. Digital elevation models (DEMs) of full survey sites, 2012. Height is relative to lowest water surface elevation. Green circles indicate *C. nudata* positions. Thick dark line represents bank top. Flow is from right to left.

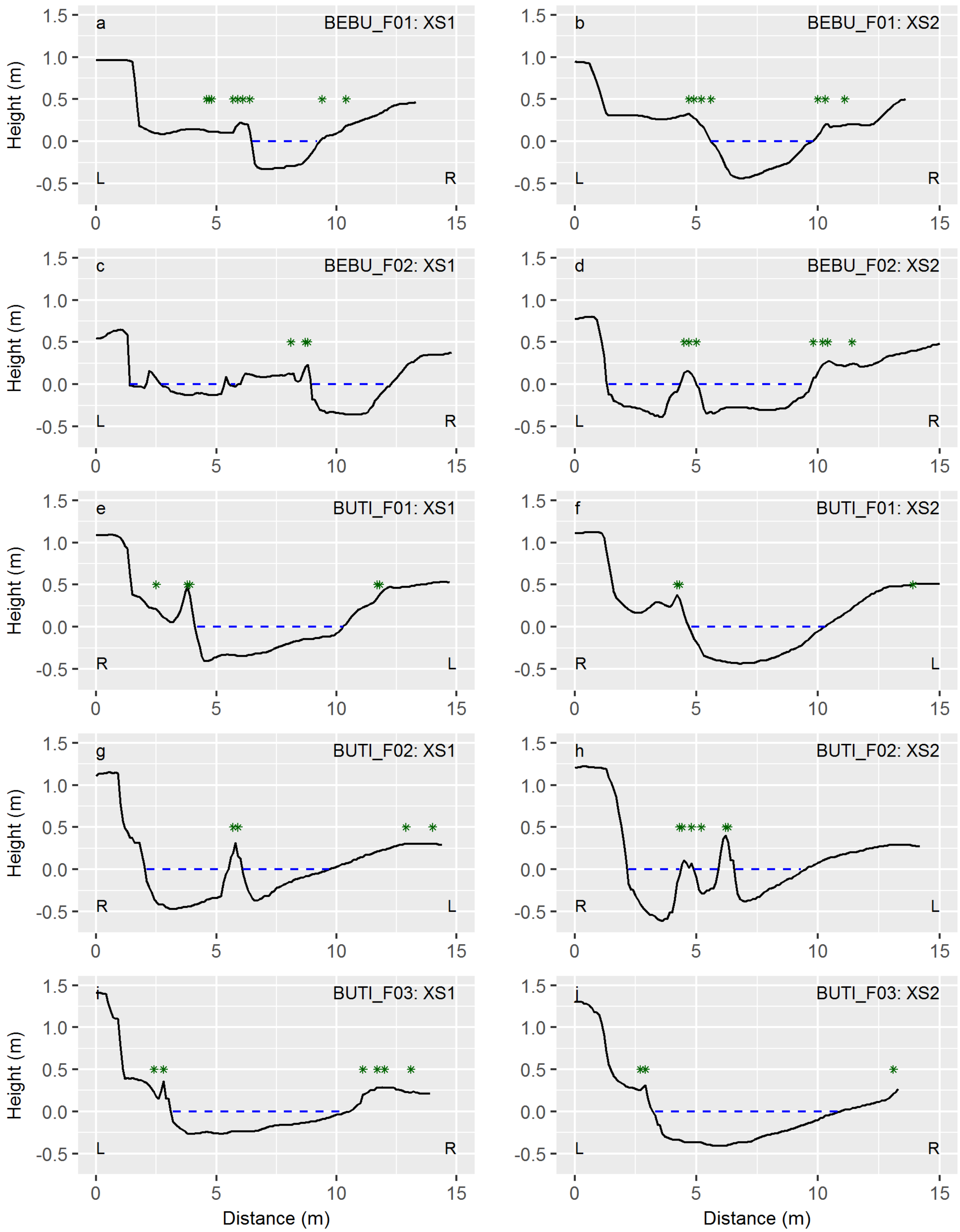

Figure 3. Cross sections from 2012 DEMs. Two cross sections are shown for each full survey site. Green asterisks indicate *C. nudata* locations within .5 m of cross section line.

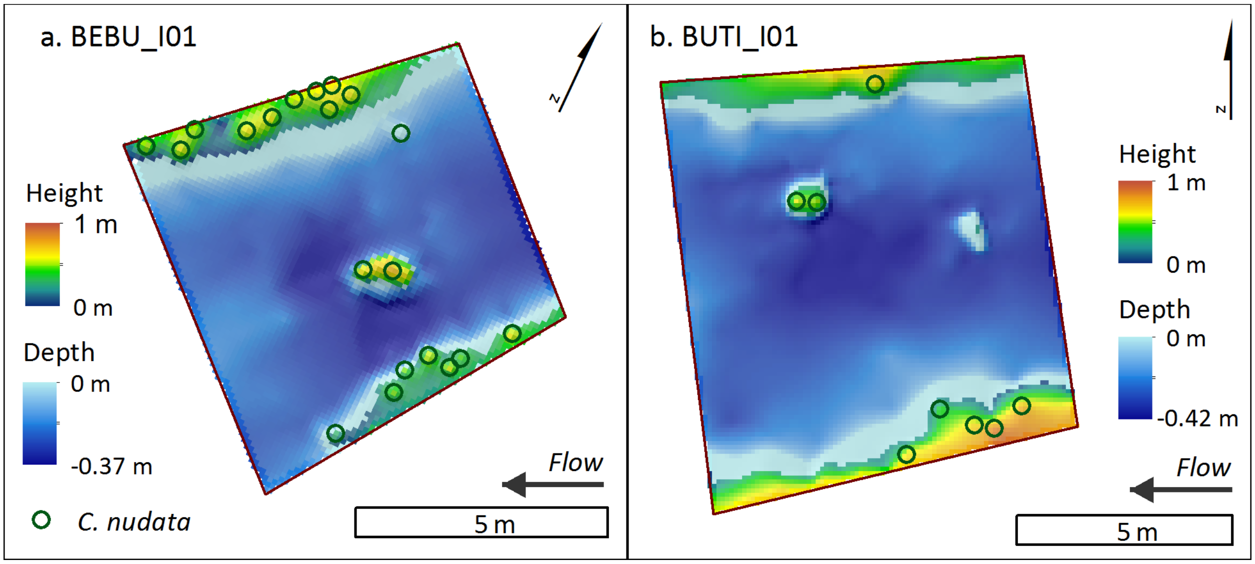

Figure 4. Digital elevation models (DEMs) of island-only survey sites, 2012. Height is relative to lowest water surface elevation. Green circles indicate *C. nudata* positions. Flow is right to left.

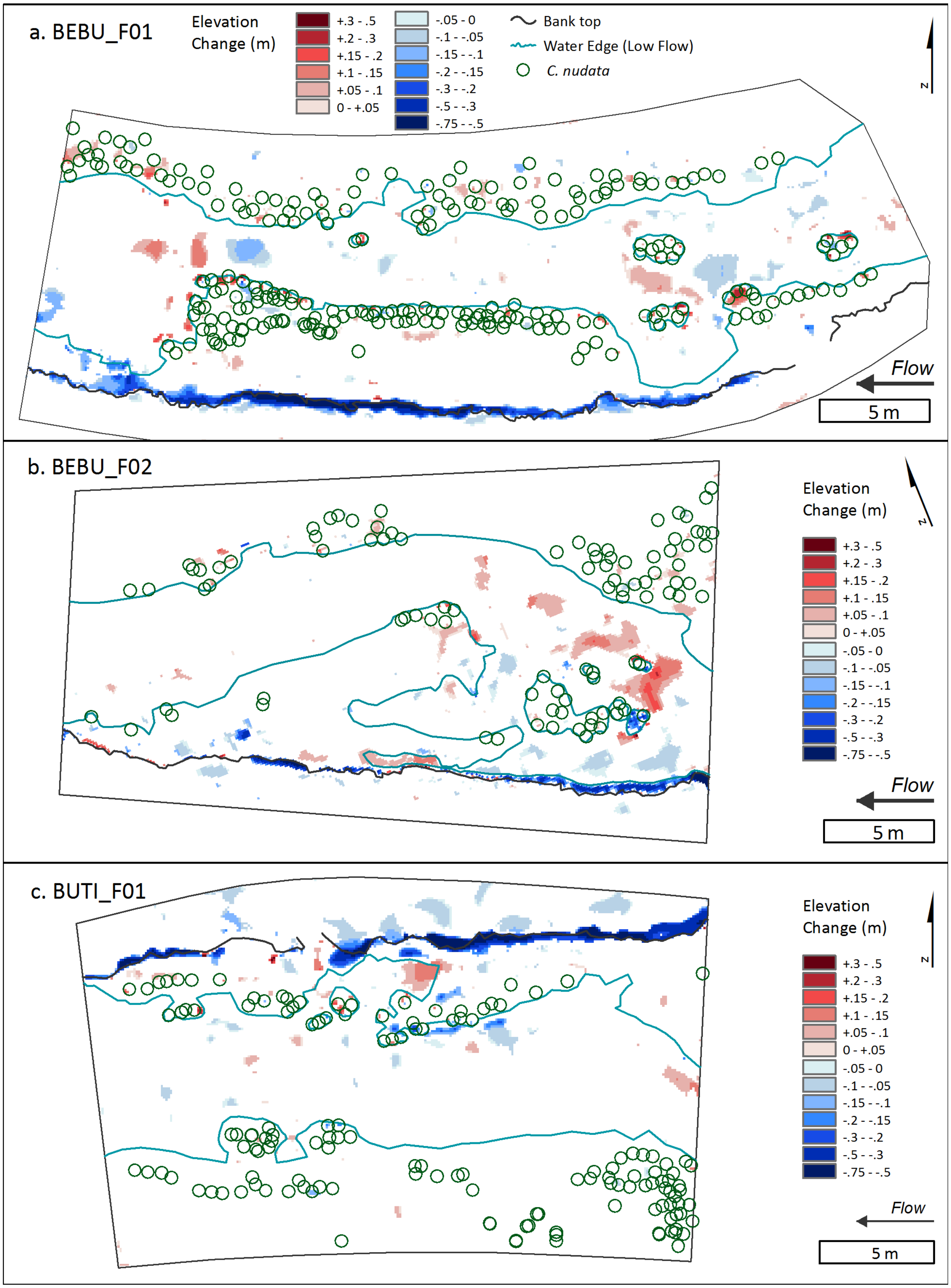

Figure 5. Elevation change at full survey sites, 2012-2014, after accounting for spatially variable uncertainty using an FIS and a 90% confidence interval. Green circles represent *C.nudata* locations, the thick black line the bank top and blue lines the low flow water's edge.

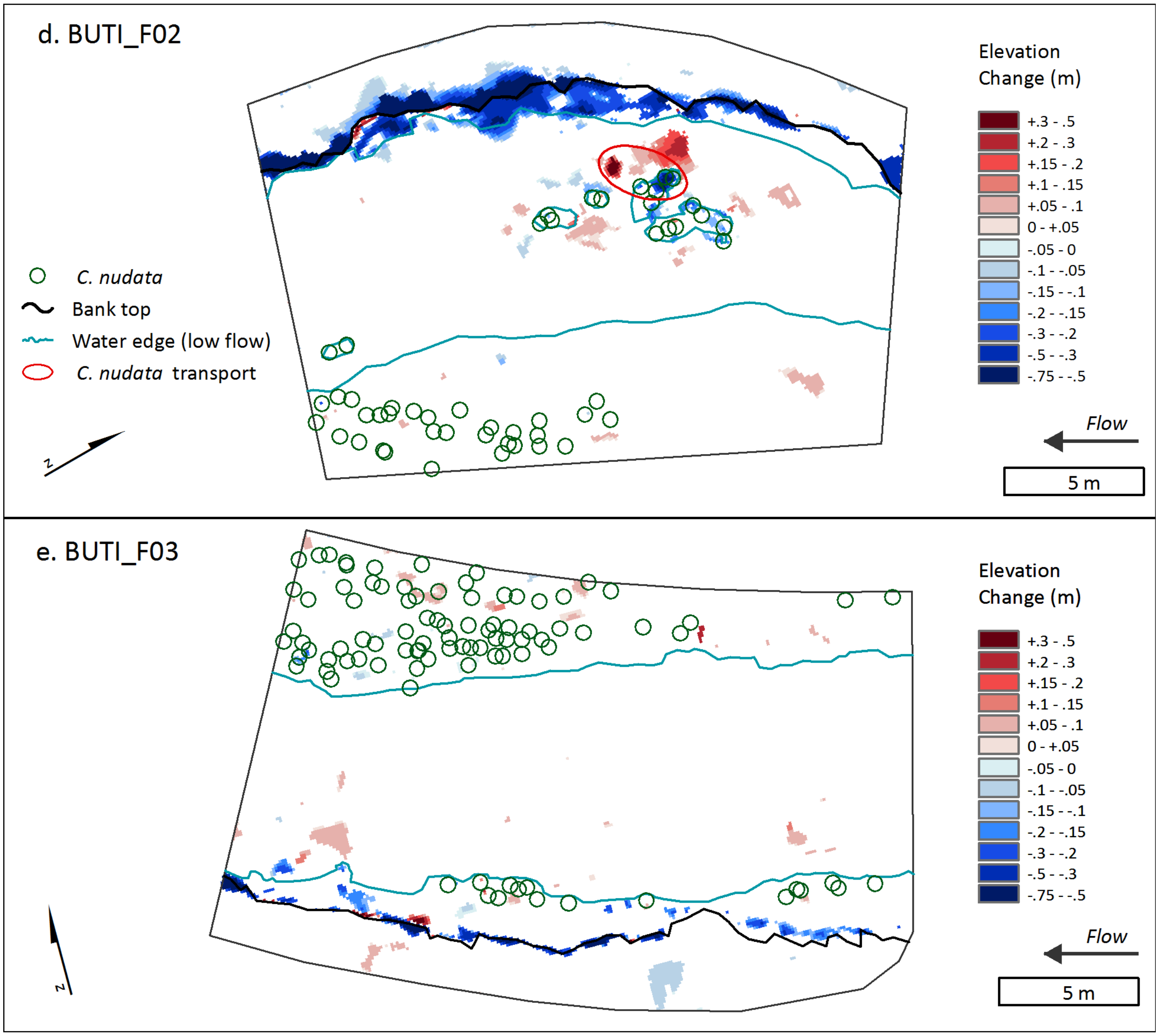

Figure 5 cont. Elevation change at full survey sites, 2012-2014, after accounting for spatially variable uncertainty using an FIS and a 90% confidence interval. Green circles represent *C.nudata* locations, the thick black line the bank top and blue lines the low flow water's edge.

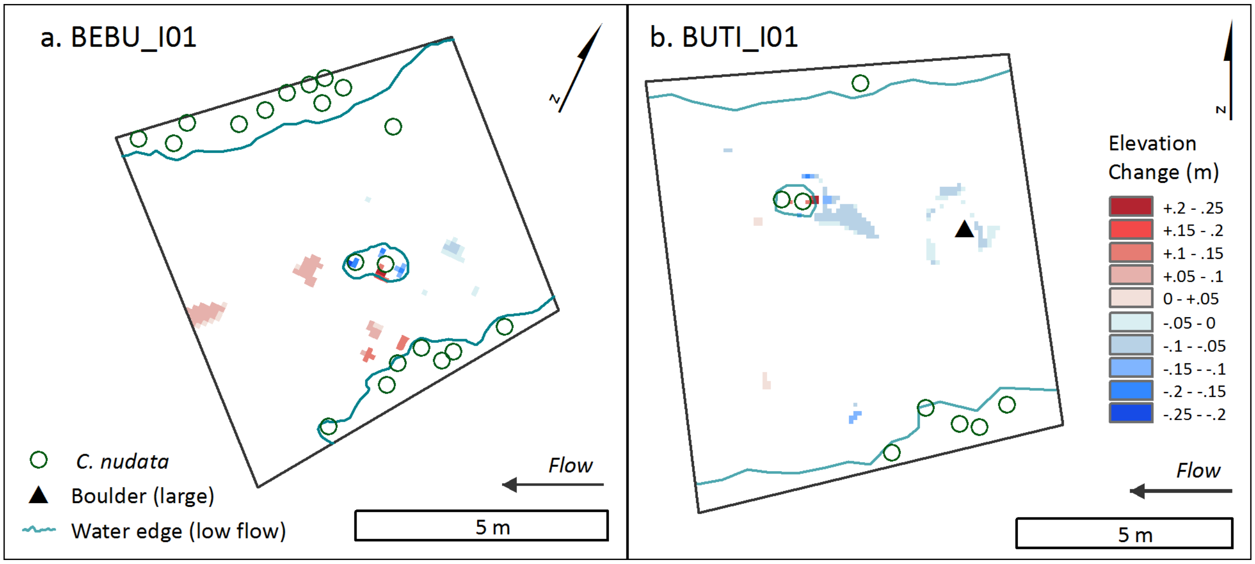

Figure 6. Elevation change at island-only survey sites, 2012-2014, after accounting for spatially variable uncertainty using an FIS and a 90% confidence interval. Green circles represent *C.nudata* locations and blue lines the low flow water's edge.

Figure 7. Historic imagery and island genesis from a) 2006 to b) 2013 at BUTI_F02. Black polygon outline indicates survey site boundary; red outline indicates *C. nudata* island boundary in 2013. Flow is from top to bottom of image.

Figure 8. Historic imagery and island genesis from a) 2006 to b) 2013 at BUTI_F01. Black polygon outline indicates survey site boundary; red outline indicates *C. nudata* island boundary in 2013. Flow is from right to left of image.

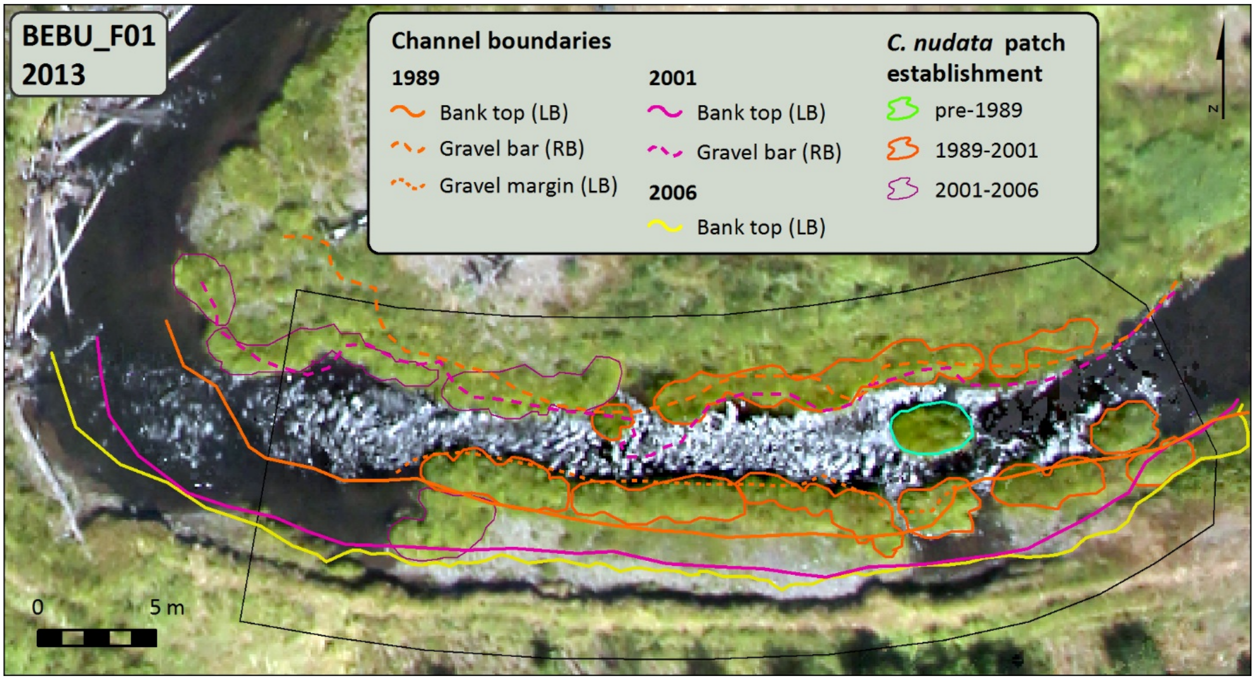

Figure 9. 2013 imagery for BEBU_F01 overlaid with *C. nudata* cohort boundaries, bank top lines and gravel margins from 1989, 2001 and 2006. Black polygon outline represents survey site boundary. Flow is from right to left of image. Note engineered log jam at left of image.

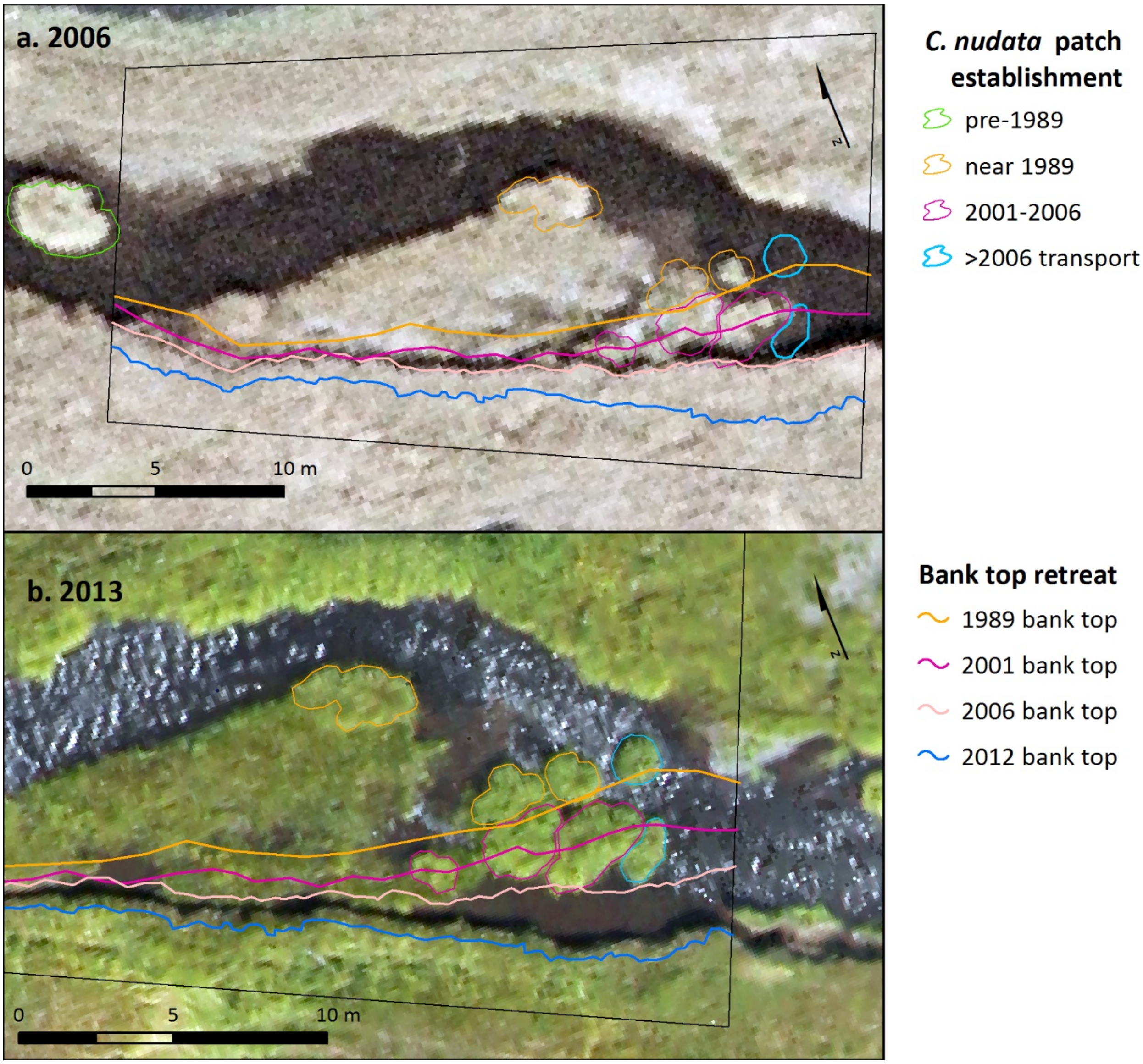

Figure 10. a) 2006 and b) 2013 imagery for BEBU_F02 overlaid with *C. nudata* cohort boundaries and bank top lines from 1989, 2001, 2006 and 2012. Black polygon outline represents survey site boundary. 2012 bank top line is from actual survey rather than aerial imagery interpretation which places it behind apparent bank top in 2013 given the presence of overhanging vegetation in the 2013 imagery. Flow is from right to left of image.

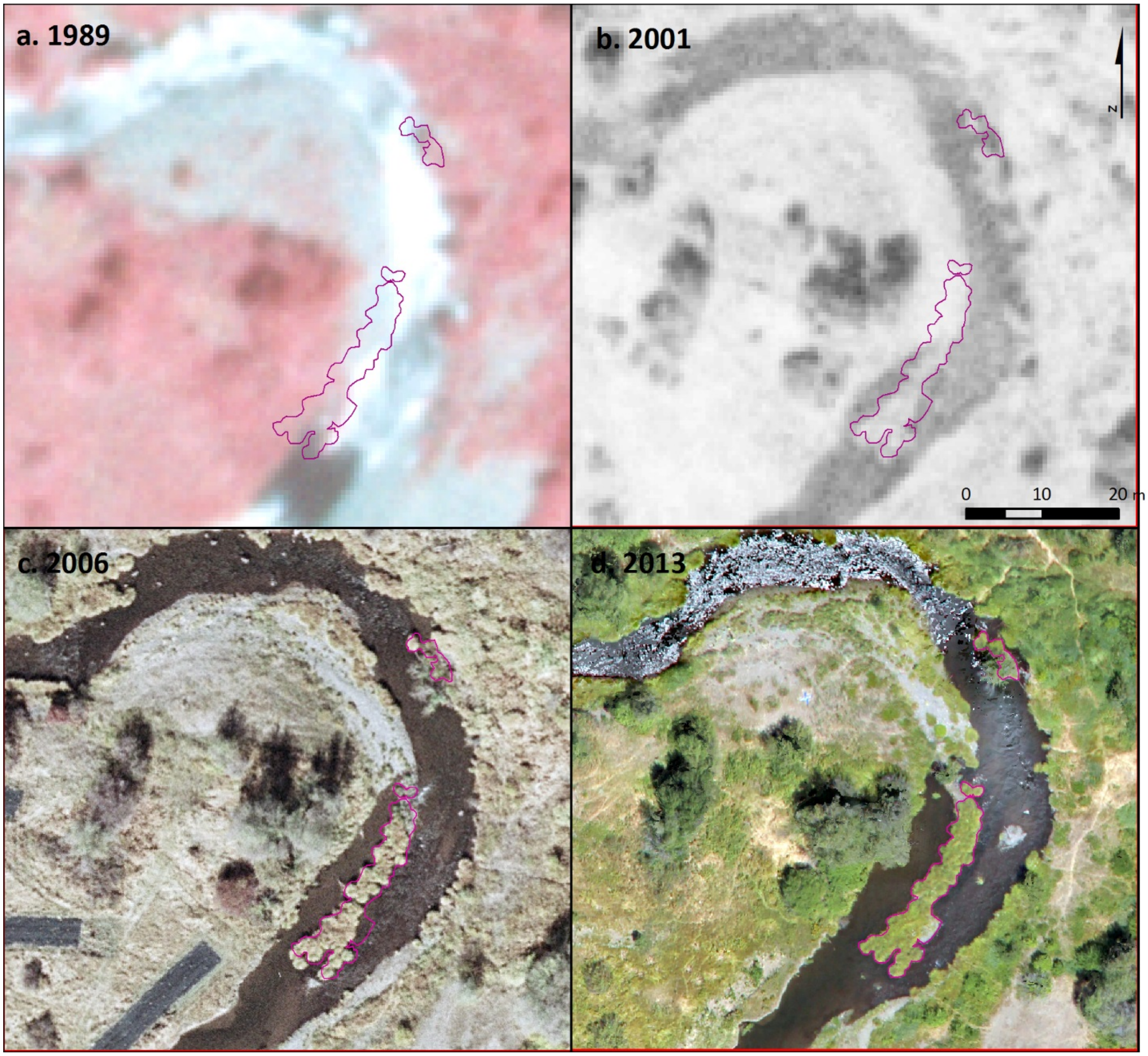

Figure 11. Island genesis from gravel bar fringes, example 1. Historic imagery from a) 1989 (top left, vegetation represented as red in color infrared image), b) 2001 (top right), c) 2006 (bottom left) and d) 2013 (bottom right). Magenta polygon outline represents boundary of *C. nudata* islands in 2013. Flow is from bottom to top of images.

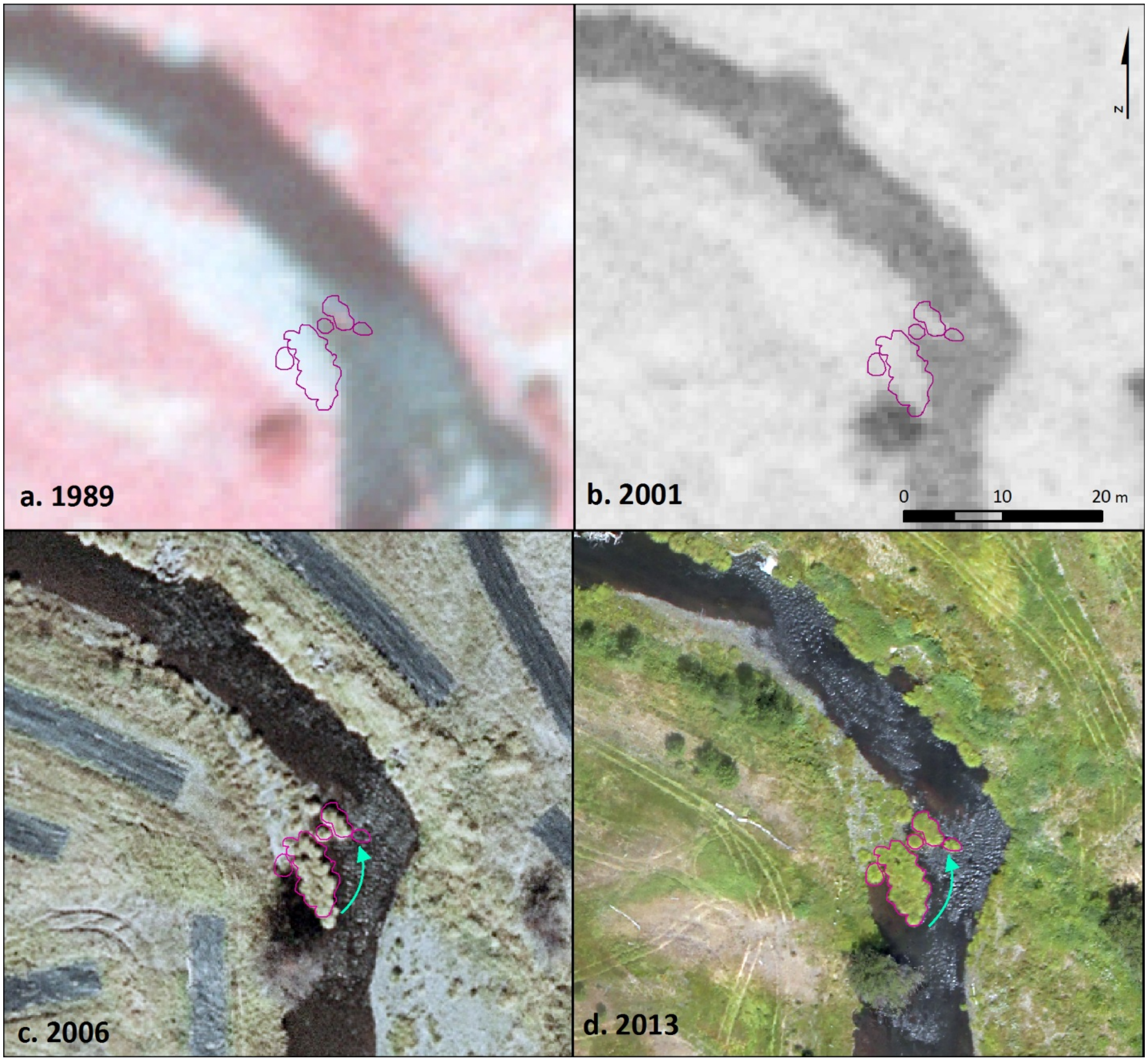

Figure 12. Island genesis from gravel bar fringes, example 2. Historic imagery from a) 1989 (top left, vegetation represented as red in color infrared image), b) 2001 (top right), c) 2006 (bottom left) and d) 2013 (bottom right). Magenta polygon outline represents boundary of *C. nudata* islands in 2013. Light turquoise arrow in c) and d) represents uprooting and transport of *C.nudata* tussocks to a new position in 2013. Flow is from bottom to top of images.

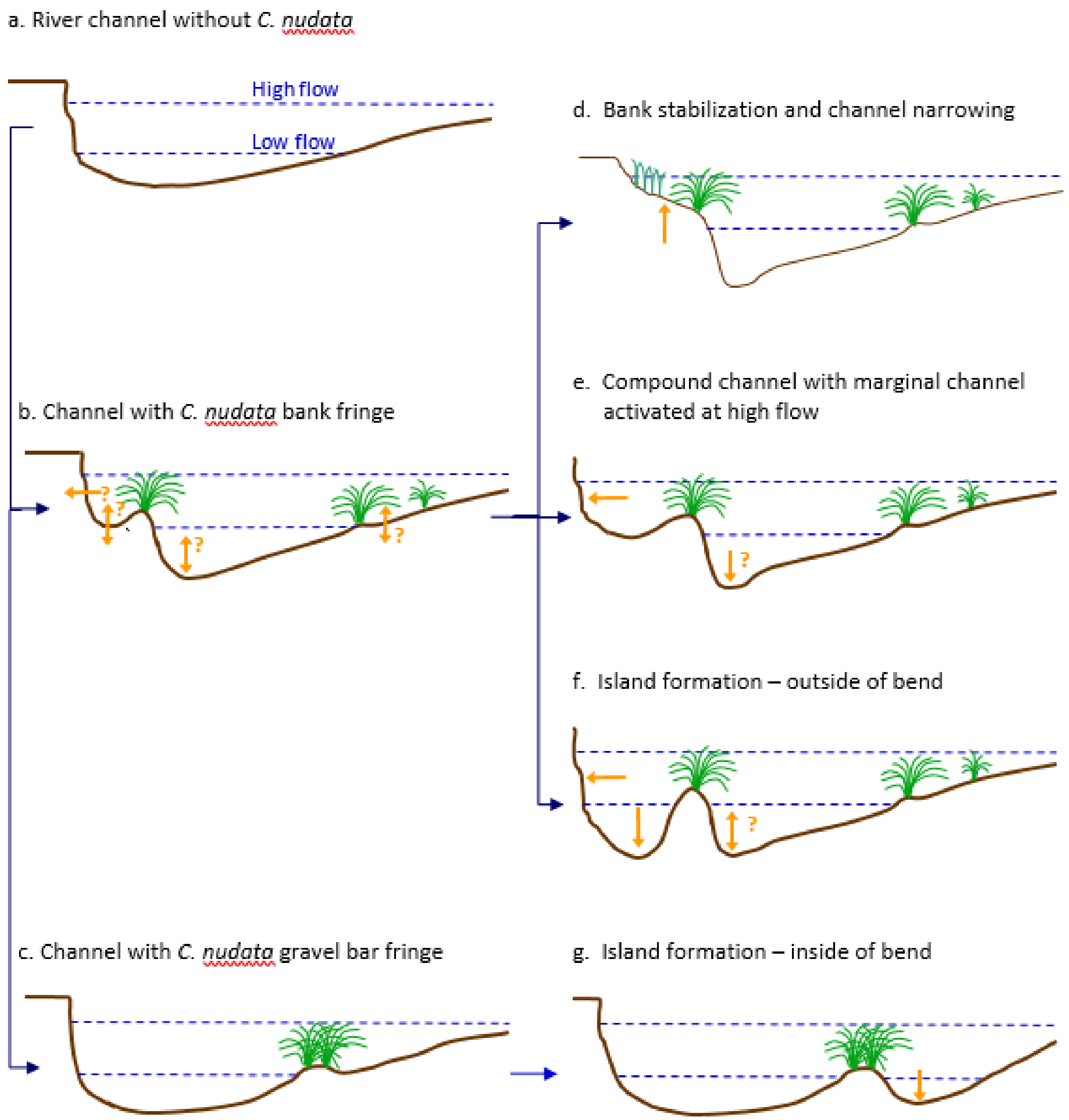

Figure 13. Conceptual model: alternative pathways of channel evolution in river with *C. nudata*. The directional arrows with questions marks in b) the early stage channel with *C. nudata* bank fringe represent the areas of directional change which we aimed to address in our change analyses. Arrows in the right panel indicate directions of change that can be clearly inferred or (with question marks) have incomplete evidence or mixed indicators.

Table 1. Island genesis analysis: islands with natural origin determined relative to all islands

	N	%	Tussocks / Island (Mean)	Area (m^2) / Island (Mean)
Uncertain: pre-1989	85	*19.3*	6.0	16
Uncertain: post-1989	47	*10.7*	2.1	4.2
Artificial origin	10	*2.3*	1.7	2.5
Origin determined, natural	298	*67.7*	3.8	11
Total	**440**		**1754**	**4728**

Table 2. Island genesis analysis: origin classes.

			Tussocks / Island (n)		Area / Island (m^2)	
Origin	N	%	Mean (Min-Max)	%	Mean (Min-Max)	%
Mid-channel establishment						
1. Midchannel bar	20	*6.7*	12.8 (1- 38)	*22.6*	58 (.5- 268)	*36.5*
2. Riffle	44	*14.8*	1.8 (1- 9)	*7.1*	4.0 (.3- 21)	*5.5*
3. Boulder	61	*20.5*	1.5 (1- 6)	*7.9*	2.4 (.1- 9.2)	*4.6*
Subtotal		***41.9***		***37.5***		***46.6***
Channel boundary movement						
4. Bank	87	*29.2*	3.3 (1- 22)	*25.5*	6.6 (.1- 66)	*18.1*
5. Gravel Bar	42	*14.1*	7.4 (1- 42)	*27.5*	22 (.3- 221)	*29.2*
6. Bank | Gravel Bar	11	*3.7*	5.4 (1- 15)	*5.2*	13 (2.1- 45)	*4.3*
Subtotal		***47.0***		***58.2***		***51.6***
C. nudata movement						
7. Transported, post-uproot	33	***11.1***	1.5 (1- 4)	***4.2***	1.8 (.3- 4.5)	***1.9***
Total	298		1132		3168	