

1 **Aerial photography collected with a multicopter drone reveals impact of Eurasian beaver**  
2 **reintroduction on ecosystem structure**

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10 **Abstract**

11 Beavers are often described as ecological engineers with an ability to modify the structure and flow  
12 of fluvial systems and create complex wetland environments with dams, ponds and canals.  
13 Consequently, beaver activity has implications for a wide range of environmental ecosystem services  
14 including biodiversity, flood risk mitigation, water quality and sustainable drinking water provision.  
15 With the current debate surrounding the reintroduction of beavers into the United Kingdom, it is  
16 critical to be able to monitor the impact of beavers upon the environment. This study presents the  
17 first proof of concept results showing how a lightweight hexacopter fitted with a simple digital  
18 camera can be used to derive orthophoto and digital surface model (DSM) data products at a site  
19 where beavers have recently been reintroduced. Early results indicate that analysis of the fine-scale  
20 (0.01 m) orthophoto and DSM can be used to identify impacts on the ecosystem structure including  
21 the extent of dams and associated ponds, and changes in vegetation structure due to beaver tree  
22 felling activity. Unmanned aerial vehicle data acquisition offers an effective toolkit for regular repeat  
23 monitoring at fine spatial resolution which is a critical attribute for monitoring rapidly-changing and  
24 difficult to access beaver-impacted ecosystems.

25 **Key words**

26 Eurasian beaver (*Castor fiber*); Ecosystem structure; Wetlands; Unmanned Aerial Vehicle; Structure-  
27 from-Motion; Environmental Monitoring and Management.

28

## 29 1. Introduction

30 Beavers are the classic example of a keystone species, having a disproportionately large habitat  
31 modifying impact than may be expected from their abundance (McKinstry et al. 2001). Beavers are  
32 frequently described as ecological engineers (Hartman and Tornlov 2006), their greatest  
33 geomorphological impact being the construction of dams to impound water (Butler and Malanson  
34 2005). Dam construction increases catchment hydrological storage capacity (Hammerson 1994;  
35 Hood and Bayley 2008), reduces stream velocity and peak discharge, altering flow regimes locally  
36 (Burchsted and Daniels 2014) and downstream (Polvi and Wohl 2012), so there is expected to be a  
37 positive impact on flood risk alleviation (Collen and Gibson 2000). Beavers also construct canals to  
38 facilitate safe access to foraging areas (Gurnell 1998), and the creation of wetlands and reduction in  
39 tree cover can increase biodiversity (See review: Rosell et al. 2005).

40 Eurasian beavers (*Castor fiber*) were once common across Europe. Populations were greatly reduced  
41 by human activities, particularly over-hunting (Collen and Gibson 2000), and were thought to be  
42 extirpated from the United Kingdom by the 16<sup>th</sup> Century (Conroy and Kitchener 1996). Stimulated by  
43 the European Commission Habitats Directive, reintroduction programs have seen the re-  
44 establishment of Eurasian beaver colonies across northwest Europe (de Visscher et al. 2014),  
45 including Scotland (Jones and Campbell-Palmer 2014). In England, beavers are currently classified as  
46 a non-native species and there is currently only one (recently licensed) wild population, subject to a  
47 rigorous, five year monitoring program (Natural England 2015).

48 Knowledge of how beavers impact on ecosystem services is vital for providing an evidence base to  
49 inform policy developments regarding both the reintroduction of *C. fiber* in the United Kingdom and  
50 the wider management of beaver-impacted ecosystems (Burchsted and Daniels 2014). However,  
51 much of the available research into the environmental and particularly geomorphological impacts  
52 focuses on the North American beaver (*C. Canadensis*) rather than the Eurasian beaver (*C. fiber*).  
53 While there are similarities between the two, differences in environment and behaviour, including

54 that *C. fiber* is thought to undertake more limited building activity (Rosell et al. 2005), mean their  
55 impacts cannot be presumed to be directly comparable (Gurnell 1998; Rosell et al. 2005).

56 Studies have highlighted the value of image analysis to quantify landscape alteration by beaver  
57 activity, using data obtained from satellite or conventional aircraft platforms (Johnston and Naiman  
58 1990; Townsend and Butler 1996; Butler 2002; Cunningham et al. 2006; Polvi and Wohl 2012;  
59 Malison et al. 2014). However, the acquisition of these data can be costly and the imagery hitherto  
60 analysed has had a relatively coarse spatial resolution (e.g. 7 m (Johnston and Naiman 1990); 30 m  
61 (Townsend and Butler 1996); 1-4 m (Butler 2002); 2.4 m (Malison et al. 2014)). Ground-based  
62 surveying can generate useful geomorphological information (Nyssen et al. 2011; Burchsted and  
63 Daniels 2014; de Visscher et al. 2014); however, detailed ground-based surveying can be time  
64 consuming, challenging in complex wetland environments, and risks disturbing the study habitat  
65 (Shuman and Ambrose 2003; Chabot and Bird 2013). Beaver activity is a dynamic, year-round  
66 process (Collen and Gibson 2000); in particular the construction and alteration of dams and canals  
67 can rapidly alter channel geomorphology and water storage (Halley 2011; Loeb et al. 2014).  
68 Consequently, infrequent sampling, for example yearly or greater (Johnston and Naiman 1990;  
69 Wright et al. 2002; Polvi and Wohl 2012; Malison et al. 2014), may fail to capture the rate and extent  
70 of ecosystem change.

71 Recent research has highlighted the emerging use of unmanned/uninhabited aerial vehicles (UAVs or  
72 'drones') in spatial ecology (Anderson and Gaston 2012) for environmental monitoring and  
73 management (Rango et al. 2009) including in impenetrable wetlands (Chabot and Bird 2013). UAVs  
74 may offer a cost- and time-efficient surveying option (Castillo et al. 2012, Colomina and Molina  
75 2014), which can also yield 3D models quantifying ecosystem structure, using techniques such as  
76 Structure-from-Motion (SfM) photogrammetry (Turner et al. 2012; Lucieer et al. 2013).

77 This study presents early 'proof of concept' research, using a digital camera mounted on a UAV and  
78 subsequent data processing to generate orthophotos and digital surface models (DSMs) in order to

79 assess the potential of this approach to characterise the environmental impacts of beaver  
80 reintroduction.

## 81 **2. Materials and Methods**

### 82 **2.1 Study Site**

83 Research was undertaken at the Devon Beaver Project site, situated upon a small first order stream  
84 in the headwaters of the Tamar river catchment, within Devon, South West England (DWT 2013).  
85 The site experiences a temperate climate with a mean annual temperature of 14 °C and mean  
86 annual rainfall of 918 mm (Met Office 2015). In March 2011, a pair of Eurasian beavers was  
87 introduced to a 1,600 m<sup>2</sup> enclosure, dominated by a single channel, with land cover of deciduous  
88 willow and birch woodland. Beaver activity at the site has created a complex wetland environment,  
89 dominated by ponds, dams and an extensive canal network (DWT 2013).

### 90 **2.2. UAV platform and flight details**

91 The UAV overflight of the study site was undertaken in December 2014 to minimise occlusion of the  
92 terrain and underlying hydrological system by the deciduous vegetation canopy. Fifteen iron-cross  
93 ground control points (GCP) (Figure 1f, size 0.3 m diameter) were deployed across the site and  
94 geolocated using differential GPS. The UAV platform was a 3D Robotics Y6 hexacopter  
95 (<http://3drobotics.com/>) equipped with a GPS receiver and consumer-grade camera (Canon S100)  
96 and controlled by ArduCopter software (V3.2; <http://copter.ardupilot.com>). The site was gently  
97 sloping with a variation in terrain height of approximately 20 m (~180 m to ~200 m asl). Automatic  
98 flights were designed using Mission Planner (V1.3.11), flying a lawnmower survey pattern with an  
99 average altitude of 25 m and average ground sampling distance of 0.01 m. Flight plans were  
100 designed so that every part of the area of interest was imaged in 10 or more photos. The camera  
101 was triggered at distance intervals to attain 70 % front-lap and 65 % side-lap, capturing 476  
102 geotagged photographs in total. Camera shutter speed (Tv) was faster than 1/800th seconds, ISO

103 (Sv) was 400, aperture (Av) was f3.5 and focus was set at infinity. To minimise shadowing, flights  
104 were completed within a few hours of midday. The AOI was surveyed in three separate flights (due  
105 to platform endurance limits), with a combined flight time of under an hour.

## 106 **2.2. Data processing and analysis**

107 SfM reconstruction and orthophoto stitching was undertaken using Agisoft's PhotoScan (V1.0.4);  
108 PhotoScan is described further in Verhoeven (2011); Remondino et al. (2014) and Kaiser et al.  
109 (2014). Ninety-two percent (436 photos) of the original image set was utilized in the reconstruction,  
110 the remaining images could not be matched due to insufficient tie-points, usually in more densely  
111 vegetated areas. Each GCP appeared in between 7-24 images (average 13); these GCPs, which were  
112 used to guide the reconstruction, had an overall root mean square error (RMSE) in three dimensions  
113 of 0.49 m. This error was dominated by the z component; the RMSE of x and y were 0.21 and 0.12  
114 m, respectively.

115 The resultant point cloud (3D dataset) comprised 114 million individual points with spatial ( $x, y, z$ )  
116 and spectral ( $R, G, B$ ) information. Points were meshed (Delaunay triangulation) using a height field,  
117 and the mesh regularly sampled to derive a digital surface model (DSM) at 0.01 m resolution. The  
118 orthophoto was manually examined to determine whether key environmental features associated  
119 with beaver activity could be identified, features were manually identified and digitized using a  
120 Geographic Information System (GIS) (ESRI ArcMap V10.2).

### 121 **3. Results**

122 Figure 1a presents the georectified orthophoto of the site, indicating the location of several  
123 examples demonstrating beaver activity. Figures 1b and 1c show that the 0.01 m spatial resolution  
124 imagery is suitable to determine different occurrences of woodland disturbance. Figure 1b depicts a  
125 tree that has been completely gnawed through and felled, whilst Figure 1c shows a live tree stem  
126 where early stage nibbling has occurred. Figures 1d and 1e illustrate the capacity of fine-spatial  
127 resolution image data to identify beaver modifications to watercourses and channel geomorphology.  
128 In Figure 1d, a beaver dam is clearly visible along with the extent of impounded surface water.  
129 Extensive canal networks have been created by beavers across the site, facilitating safe access to  
130 new foraging ground, a section of one canal is shown in Figure 1e.

131 Figure 2 provides an example of the quantitative detail that can be extracted from SfM-derived  
132 topographic models. Figure 2a is a photo taken from the ground of the AOI whilst Figure 2b shows  
133 the same area captured from the UAV. Using the airborne orthophoto, it is possible to digitize the  
134 surface area of impounded ponds; for example, the pond depicted in Figure 2b has a surface area of  
135 125 m<sup>2</sup>. The ecosystem structure can be further quantified from the DSM; for example, Figure 2c  
136 depicts a high-spatial resolution DSM of the same pond, from which the maximum height of the dam  
137 face (1.44 m) can be determined. Additionally, because bed surfaces can be visible through the  
138 water, with further processing it may be possible to quantify bathymetry from a digital terrain model  
139 (Tamminga et al. 2014).

### 140 **4. Discussion**

141 Preliminary results presented, demonstrate the suitability of a one day UAV campaign to provide  
142 multiple data products characterising ecosystem structure as impacted by beaver activity. Evidence  
143 from this study suggests that: once procured and operational, UAVs allow rapid, regular and cost-  
144 effective monitoring. This is of particular relevance to monitoring the impact of beavers, with

145 research and field observations noting the rapid rate of ecosystem change, resulting from dam and  
146 canal building activities (Collen and Gibson 2000). In particular, UAV surveying mitigated many of the  
147 challenges associated with ground-based surveying in these environments, minimising habitat and  
148 species disturbance and personal safety risks with physically accessing wetlands. The low-altitude  
149 overflights enabled collection of fine spatial resolution imagery (~0.01 m ground sampling distance),  
150 better than that readily available from satellite or manned flights (Johnston and Naiman 1990; Butler  
151 2002; Malison et al. 2014) which would preclude the identification of many features visible in the  
152 presented imagery. As such, from manual analysis of the orthophoto, features characteristic of the  
153 main environmental impacts of beaver activity were readily identifiable. Clearly, UAV surveys offer a  
154 valuable means of data acquisition to develop a spatially explicit evidence-base of beaver impacts to  
155 inform management and policy decisions.

156 Whilst the analysis presented, yielded promising results, further work is required to determine the  
157 full potential and limitations of this monitoring approach (Whitehead and Hugenholtz 2014). The  
158 manual identification of features is useful as an illustrative example of the suitability of the  
159 application. However, whilst practical for small areas, it presents a barrier to upscaling monitoring to  
160 greater spatial or temporal scales (Blundell and Opitz 2006; Blaschke 2010). Automated classification  
161 of water surfaces (Sawaya et al. 2003; Baker et al. 2006) is hindered by occlusion due to vegetation  
162 cover, while spatially variable illumination (Singh et al. 2012) makes it challenging to automatically  
163 identify freshly chewed trees, indicative of recent woodland disturbance. Further work is required to  
164 explore the suitability of automated classification of the derived information products; this is likely  
165 to yield a semi-automated system presenting candidate areas to an operator, expediting feature  
166 identification. The use of SfM photogrammetry in environmental research is still an emerging field  
167 and the spatial uncertainty of the approach is determined by flight and site specific factors that need  
168 deeper empirical investigation (Bemis et al. 2014; James and Robson 2014). Previously, terrestrial  
169 Light Detection and Ranging (LiDAR) scanning has been used to assess results produced from SfM

170 (Ouédraogo et al. 2014; Kaiser et al. 2014). The combined use of these two techniques on control  
171 areas of the site, may allow the use of SfM to be evaluated.

172 Beaver-impacted sites are complex, characterised by extensive vegetation cover and large areas of  
173 standing water, making it a challenging environment to reconstruct as a 3D model using SfM.  
174 However, the derived 3D models have great potential to extract terrain models characterising  
175 topographic and vegetation structure, pond bathymetry, channel morphology and to support  
176 hydrological modelling. These techniques offer exciting possibilities for investigating beaver-impacts  
177 (and other environmental applications) over the short time periods that environmental change can  
178 occur.

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340 **Figure Captions**

341 **Figure 1.** Georectified orthophoto at 0.01 m resolution, depicting (a) the enclosure; (b) the gnawed-  
342 through stump and trunk of a felled tree; (c) the partially nibbled trunk of a standing tree; (d)  
343 one of the new dam structures and resultant pond; (e) section of canal network (f) iron-cross  
344 GCP targets with black and white segments (size 0.3 m diameter). Yellow annotations highlight  
345 features discussed in results. All sub-figures are orientated north, whilst scale is presented in  
346 metres (m) for each sub-figure.

347 **Figure 2.** Close-up of the pond depicted in Figure 1d, (a) photograph of the dam structure taken from  
348 the ground control marker a few metres west of the dam, (b) digitized extent of surface water,  
349 and (c) digital surface model of the dam and impounded pond (with digitized extent of pond  
350 from 2b).

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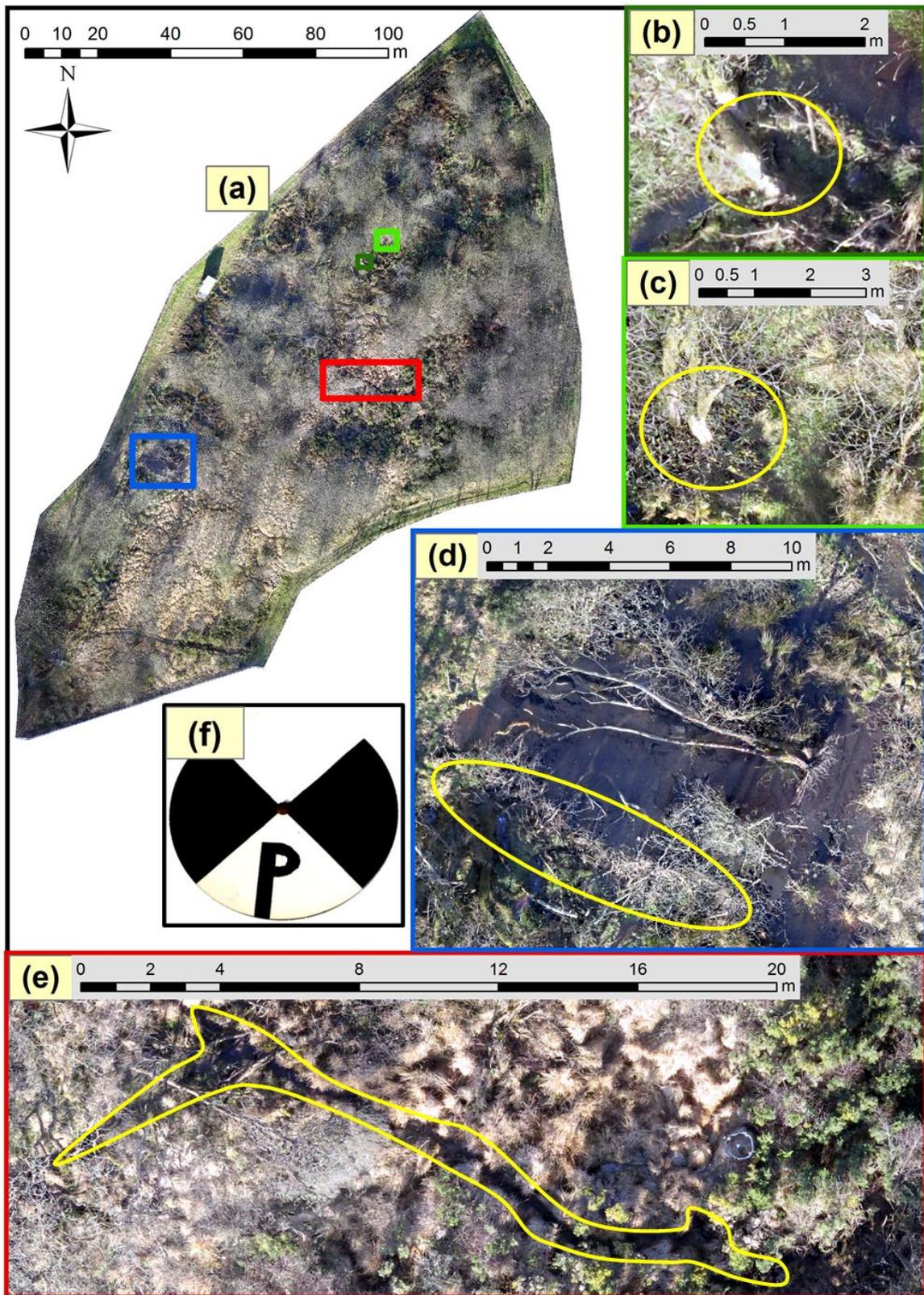
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370 **Figures** (can be resized for journal formatting)

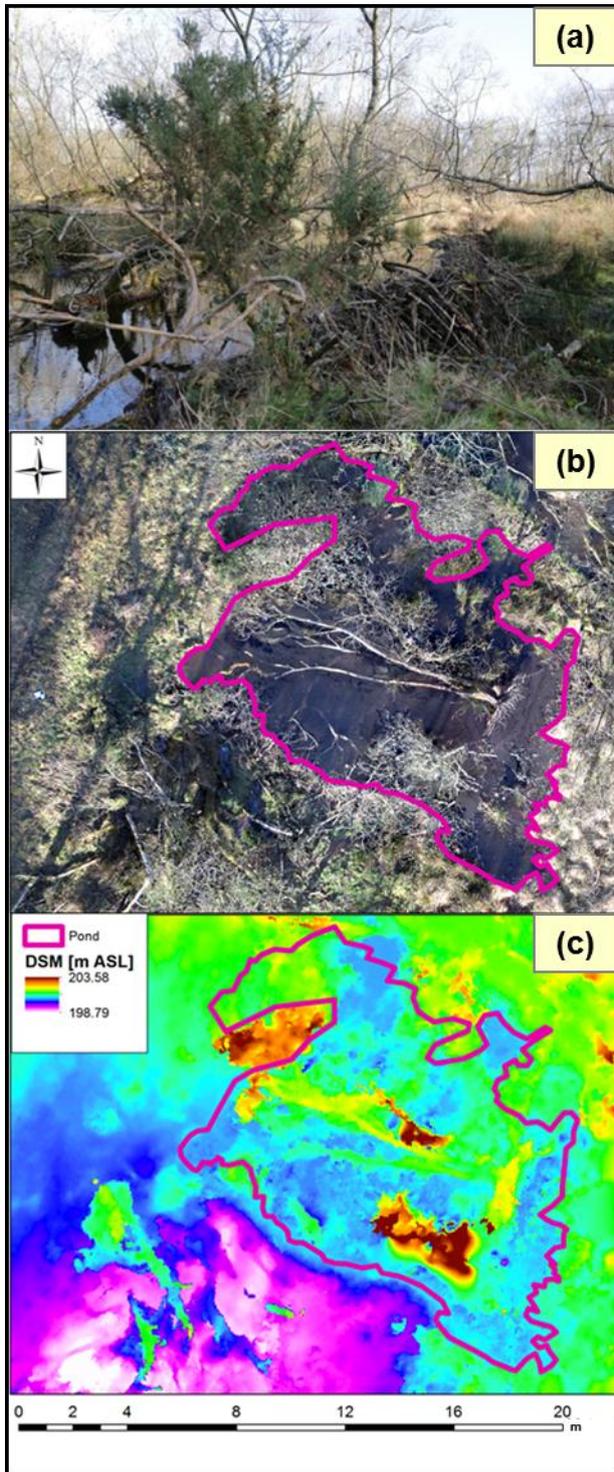


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372 **Figure 1.**

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376 Figure 2.

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