Aerial photography collected with a multirotor drone reveals impact of Eurasian beaver reintroduction on ecosystem structure

A.K. Puttock[1*], A.M. Cunliffe[1], K. Anderson[2], R.E. Brazier[1]

[1]Geography, College of Life and Environmental Sciences, Amory Building, Rennes Drive, Exeter, Devon, EX4 4RJ, United Kingdom
[2]Environment and Sustainability Institute, University of Exeter, Penryn, Cornwall TR10 9FE, United Kingdom

*Corresponding author email: A.K.Puttock@exeter.ac.uk

Abstract

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

Key words

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

1. Introduction

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

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

Knowledge of how beavers impact on ecosystem services is vital for providing an evidence base to inform policy developments regarding both the reintroduction of *C. fiber* in the United Kingdom and the wider management of beaver-impacted ecosystems (Burchsted and Daniels 2014). However, much of the available research into the environmental and particularly geomorphological impacts focuses on the North American beaver (*C. Canadensis*) rather than the Eurasian beaver (*C. fiber*). While there are similarities between the two, differences in environment and behaviour, including that *C. fiber* is thought to undertake more limited building activity (Rosell et al. 2005), mean their impacts cannot be presumed to be directly comparable (Gurnell 1998; Rosell et al. 2005).

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

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

This study presents early ‘proof of concept’ research, using a digital camera mounted on a UAV and subsequent data processing to generate orthophotos and digital surface models (DSMs) in order to assess the potential of this approach to characterise the environmental impacts of beaver reintroduction.

2. Materials and Methods

2.1 Study Site

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

2.2. UAV platform and flight details

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

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

2.2. Data processing and analysis

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

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

3. Results

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

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

4. Discussion

Preliminary results presented, demonstrate the suitability of a one day UAV campaign to provide multiple data products characterising ecosystem structure as impacted by beaver activity. Evidence from this study suggests that: once procured and operational, UAVs allow rapid, regular and cost-effective monitoring. This is of particular relevance to monitoring the impact of beavers, with research and field observations noting the rapid rate of ecosystem change, resulting from dam and canal building activities (Collen and Gibson 2000). In particular, UAV surveying mitigated many of the challenges associated with ground-based surveying in these environments, minimising habitat and species disturbance and personal safety risks with physically accessing wetlands. The low-altitude overflights enabled collection of fine spatial resolution imagery (~0.01 m ground sampling distance), better than that readily available from satellite or manned flights (Johnston and Naiman 1990; Butler 2002; Malison et al. 2014) which would preclude the identification of many features visible in the presented imagery. As such, from manual analysis of the orthophoto, features characteristic of the main environmental impacts of beaver activity were readily identifiable. Clearly, UAV surveys offer a valuable means of data acquisition to develop a spatially explicit evidence-base of beaver impacts to inform management and policy decisions.

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

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

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

Acknowledgements

This research was undertaken as part of the Devon Beaver Project led by Devon Wildlife Trust and the University of Exeter, and funded by Westland Countryside Stewards. Additional thanks go to John Morgan, the site owner for hosting the reintroduction project and allowing site access for researchers. The 3D Robotics Y6 was supplied by the University of Exeter's Environment and Sustainability Institute (ESI) environmental monitoring drone lab. Finally, we thank the helpful feedback received from two anonymous reviews and the associate editor.

References

Anderson, K., and Gaston, K. 2012. Unmanned aerial vehicles (UAVs) will revolutionise spatial ecology. Front. Ecol. Environ. **11**(3): 138–146. doi: 10.1890/120150.

Baker, C., Lawrence, R., Montagne, C., and Patten, D. 2006. Mapping wetlands and riparian areas using Landsat ETM+ imagery and decision-tree-based models. Wetlands, **26**(2): 465–474. doi: 10.1672/0277-5212(2006)26[465:MWARAU]2.0.CO;2.

Bemis, S., Micklethwaite, S., Turner, D., James, M.R., Akciz, S., Thiele, S., and Bangash, H.A. 2014. Ground-based and UAV-Based photogrammetry: A multi-scale, high-resolution mapping tool for Structural Geology and Paleoseismology. J. Struct. Geol. **69**: 163–178. doi: 10.1016/j.jsg.2014.10.007.

Blaschke, T. 2010. Object based image analysis for remote sensing. ISPRS J. Photogramm. Remote Sens. **65**(1): 2–16. doi: 10.1016/j.isprsjprs.2009.06.004.

Blundell, J.S., and Opitz, D.W. 2006. Object recognition and feature extraction from imagery: The Feature Analyst approach. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. Available from http://www.isprs.org/proceedings/xxxvi/4-c42/Papers/OBIA2006_Blundell_Opitz.pdf (Accessed 31sr March 2015).

Burchsted, D., and Daniels, M.D. 2014. Classification of the alterations of beaver dams to headwater streams in northeastern Connecticut, U.S.A. Geomorphology, **205**: 36–50. doi: 10.1016/j.geomorph.2012.12.029.

Butler, D.R. 2002. Visualizing Animal Impacts on the Landscape: Remote Sensing in the Geography Classroom. Geocarto Int. **17**(4): 69–76. doi: 10.1080/10106040208542255.

Butler, D.R., and Malanson, G.P. 2005. The geomorphic influences of beaver dams and failures of beaver dams. Geomorphology, **71**(1-2): 48–60. doi: 10.1016/j.geomorph.2004.08.016.

Castillo, C., Pérez, R., James, M.R., Quinton, J.N., Taguas, E. V., and Gómez, J.A. 2012. Comparing the Accuracy of Several Field Methods for Measuring Gully Erosion. Soil Sci. Soc. Am. J. **76**(4): 1319. doi: 10.2136/sssaj2011.0390.

Chabot, D., and Bird, D.M. 2013. Small unmanned aircraft: precise and convenient new tools for surveying wetlands. J. Unmanned Veh. Syst. **01**(01): 15–24. http://www.nrcresearchpress.com. doi: 10.1139/juvs-2013-0014.

Collen, P., and Gibson, R.J. 2000. The general ecology of beavers (Castor spp.), as related to their influence on stream ecosystems and riparian habitats, and the subsequent effects on fish – a review. Rev. Fish Biol. Fish, **10**(4): 439–461. doi: 10.1023/A:1012262217012.

Colomina, I., and Molina, P. 2014. Unmanned aerial systems for photogrammetry and remote sensing: A review. ISPRS J. Photogramm. Remote Sens. **92**: 79–97. doi: 10.1016/j.isprsjprs.2014.02.013.

Conroy, J., and Kitchener, A. 1996. The Eurasian beaver (Castor fiber) in Scotland: a review of the literature and historical evidence. Scottish Natural Heritage Review No. 49. Available from http://www.snh.org.uk/pdfs/publications/review/049.pdf (Accessed 31st March 2015).

Cunningham, J.M., Calhoun, A.J.K., and Glanz, W.E. 2006. Patterns of Beaver Colonization and Wetland Change in Acadia National Park. Northeast. Nat. **13**(4): 583–596. doi: 10.1656/1092-6194(2006)13[583:POBCAW]2.0.CO;2.

DWT. 2013. The Devon Beaver Project The story so far. Devon Wildlife Trust. Available from http://www.wildlifetrusts.org/sites/default/files/files/Beaver report 27-8-13.pdf [accessed 2 February 2015].

Fracz, A., Chow-Fraser, P., and Prairie, Y. 2013. Changes in water chemistry associated with beaver-impounded coastal marshes of eastern Georgian Bay. Can. J. Fish. Aquat. Sci. **70**(6): 834–840. NRC Research Press. doi: 10.1139/cjfas-2012-0431.

Gurnell, A.M. 1998. The hydrogeomorphological effects of beaver dam-building activity. Prog. Phys. Geogr. **22**(2): 167–189. doi: 10.1177/030913339802200202.

Halley, D.J. 2011. Sourcing Eurasian beaver Castor fiber stock for reintroductions in Great Britain and Western Europe. Mamm. Rev. **41**(1): 40–53. doi: 10.1111/j.1365-2907.2010.00167.x.

Hammerson, G.A. 1994. Beaver (Castor-Canadensis) - Ecosystem Alterations, Management, and Monitoring. Nat. Areas J. **14(1)**: 44–57.

Hartman, G., and Tornlov, S. 2006. Influence of watercourse depth and width on dam-building behaviour by Eurasian beaver (Castor fiber). J. Zool(Lond). **268**(2): 127–131. doi: 10.1111/j.1469-7998.2005.00025.x.

Hood, G.A., and Bayley, S.E. 2008. Beaver (Castor canadensis) mitigate the effects of climate on the area of open water in boreal wetlands in western Canada. Biol. Conserv. **141**(2): 556–567. doi: 10.1016/j.biocon.2007.12.003.

James, M.R., and Robson, S. 2014. Mitigating systematic error in topographic models derived from UAV and ground-based image networks. Earth Surf. Process. Landforms, **39**(10): 1413–1420. doi: 10.1002/esp.3609.

Johnston, C.A., and Naiman, R.J. 1990. The use of a geographic information system to analyze long-term landscape alteration by beaver. Landsc. Ecol. **4**(1): 5–19. doi: 10.1007/BF02573947.

Jones, S., and Campbell-Palmer, R. 2014. Scottish Beaver Trial: The story of Britain’s first licensed release into the wild. Available from http://scottishbeavers.org.uk/docs/003_143__scottishbeavertrialfinalreport_dec2014_1417710135.pdf [accessed 3 February 2015].

Kaiser, A., Neugirg, F., Rock, G., Müller, C., Haas, F., Ries, J., and Schmidt, J. 2014. Small-Scale Surface Reconstruction and Volume Calculation of Soil Erosion in Complex Moroccan Gully Morphology Using Structure from Motion. Remote Sens. **6**(8): 7050–7080. doi: 10.3390/rs6087050.

Loeb, R.E., King, S., and Helton, J. 2014. Human pathways are barriers to beavers damaging trees and saplings in urban forests. Urban For. Urban Green. **13**(2): 295-303. doi: 10.1016/j.ufug.2013.12.005.

Lucieer, A., Jong, S.M. d., and Turner, D. 2013. Mapping landslide displacements using Structure from Motion (SfM) and image correlation of multi-temporal UAV photography. Prog. Phys. Geogr. **38**(1): 97–116. doi: 10.1177/0309133313515293.

Malison, R.L., Lorang, M.S., Whited, D.C., and Stanford, J.A. 2014. Beavers (Castor canadensis) influence habitat for juvenile salmon in a large Alaskan river floodplain. Freshw. Biol. **59**(6): 1229–1246. doi: 10.1111/fwb.12343.

McKinstry, M.C., Caffrey, P., and Anderson, S.H. 2001. The importance of beaver to wetland habitats and waterfowl in Wyoming. J. Am. Water Resour. Assoc. **37**(6): 1571–1577. doi: 10.1111/j.1752-1688.2001.tb03660.x.

Met Office. 2015. Holsworthy climate information - Met Office. Available from http://www.metoffice.gov.uk/public/weather/climate/gchchcqqh [accessed 2 February 2015].

Natural England. 2015. Natural England approves trial release of beavers - News stories - GOV.UK. Available from https://www.gov.uk/government/news/natural-england-approves-trial-release-of-beavers [accessed 3 February 2015].

Nyssen, J., Pontzeele, J., and Billi, P. 2011. Effect of beaver dams on the hydrology of small mountain streams: Example from the Chevral in the Ourthe Orientale basin, Ardennes, Belgium. J. Hydrol. **402**(1-2): 92–102. doi: 10.1016/j.jhydrol.2011.03.008.

Ouédraogo, M.M., Degré, A., Debouche, C., and Lisein, J. 2014. The evaluation of unmanned aerial systems-based photogrammetry and terrestrial laser scanning to generate DEMs of agricultural watersheds. Geomorphology, **212**(1): 339-355. doi: 10.1016/j.geomorph.2014.02.016.

Polvi, L.E., and Wohl, E. 2012. The beaver meadow complex revisited - the role of beavers in post-glacial floodplain development. Earth Surf. Process. Landforms, **37**(3): 332–346. doi: 10.1002/esp.2261.

Rango, A., Laliberte, A., Herrick, J.E., Winters, C., and Havstad, K. 2009. Unmanned aerial vehicle-based remote sensing for rangeland assessment, monitoring, and management. J. Appl. Remote Sens. **3**(1): 033542. International Society for Optics and Photonics, doi: 10.1117/1.3216822.

Remondino, F., Spera, M.G., Nocerino, E., Menna, F., and Nex, F. 2014. State of the art in high density image matching. Photogramm. Rec. **29**(146): 144–166. doi: 10.1111/phor.12063.

Rosell, F., Bozer, O., Collen, P., and Parker, H. 2005. Ecological impact of beavers Castor fiber and Castor canadensis and their ability to modify ecosystems. Mamm. Rev. **35**(3-4): 248–276. doi: 10.1111/j.1365-2907.2005.00067.x.

Sawaya, K.E., Olmanson, L.G., Heinert, N.J., Brezonik, P.L., and Bauer, M.E. 2003. Extending satellite remote sensing to local scales: land and water resource monitoring using high-resolution imagery. Remote Sens. Environ. **88**(1-2): 144–156. doi: 10.1016/j.rse.2003.04.006.

Shuman, C.S., and Ambrose, R.F. 2003. A Comparison of Remote Sensing and Ground-Based Methods for Monitoring Wetland Restoration Success. Restor. Ecol. **11**(3): 325–333. doi: 10.1046/j.1526-100X.2003.00182.x.

Singh, K.K., Pal, K., and Nigam, M.J. 2012. Shadow Detection and Removal from Remote Sensing Images using NDI and Morphological Operators. Int. J. Comput. Appl. **42**(10): 37–40. Available from http://www.ijcaonline.org/archives/volume42/number10/5732-7805 [accessed 2 February 2015].

Tamminga, A., Hugenholtz, C., Eaton, B., and Lapointe, M. 2014. Hyperspatial Remote Sensing of Channel Reach Morphology and Hydraulic Fish Habitat Using an Unmanned Aerial Vehicle (UAV): A First Assessment in the Context of River Research and Management. River Res. Appl. **31**(3): 379–391. doi: 10.1002/rra.2743.

Townsend, P.A., and Butler, D.R. 1996. Patterns of landscape use by beaver on the Lower Roanoke river floodplain, North Carolina. Phys. Geogr. **17**(3): 253–269. doi: 10.1080/02723646.1996.10642584.

Turner, D., Lucieer, A., and Watson, C. 2012. An Automated Technique for Generating Georectified Mosaics from Ultra-High Resolution Unmanned Aerial Vehicle (UAV) Imagery, Based on Structure from Motion (SfM) Point Clouds. Remote Sens. **4**(12): 1392–1410. doi: 10.3390/rs4051392.

Verhoeven, G. 2011. Taking computer vision aloft - archaeological three-dimensional reconstructions from aerial photographs with photoscan. Archaeol. Prospect. **18**(1): 67–73. doi: 10.1002/arp.399.

De Visscher, M., Nyssen, J., Pontzeele, J., Billi, P., and Frankl, A. 2014. Spatio-temporal sedimentation patterns in beaver ponds along the Chevral river, Ardennes, Belgium. Hydrol. Process. **28**(4): 1602–1615. doi: 10.1002/hyp.9702.

Whitehead, K., and Hugenholtz, C.H. 2014. Remote sensing of the environment with small unmanned aircraft systems (UASs), part 1: a review of progress and challenges 1. J. Unmanned Veh. Syst. **02**(03): 69–85. http://www.nrcresearchpress.com. doi: 10.1139/juvs-2014-0006.

Wright, J., Jones, C., and Flecker, A. 2002. An ecosystem engineer, the beaver, increases species richness at the landscape scale. Oecologia, **132**(1): 96–101. Springer-Verlag. doi: 10.1007/s00442-002-0929-1.

Figure Captions

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

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

Figures (can be resized for journal formatting)

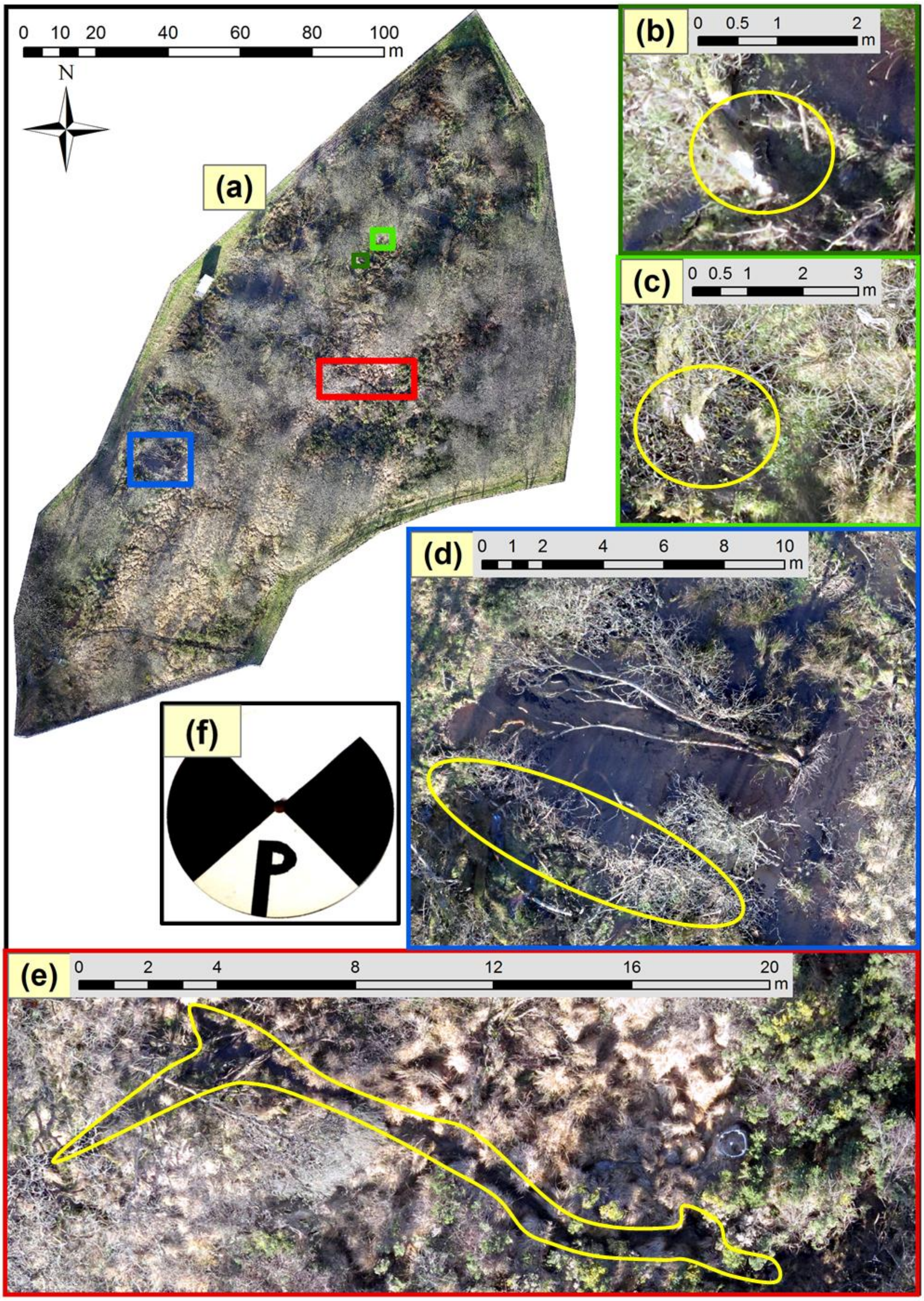

Figure 1.

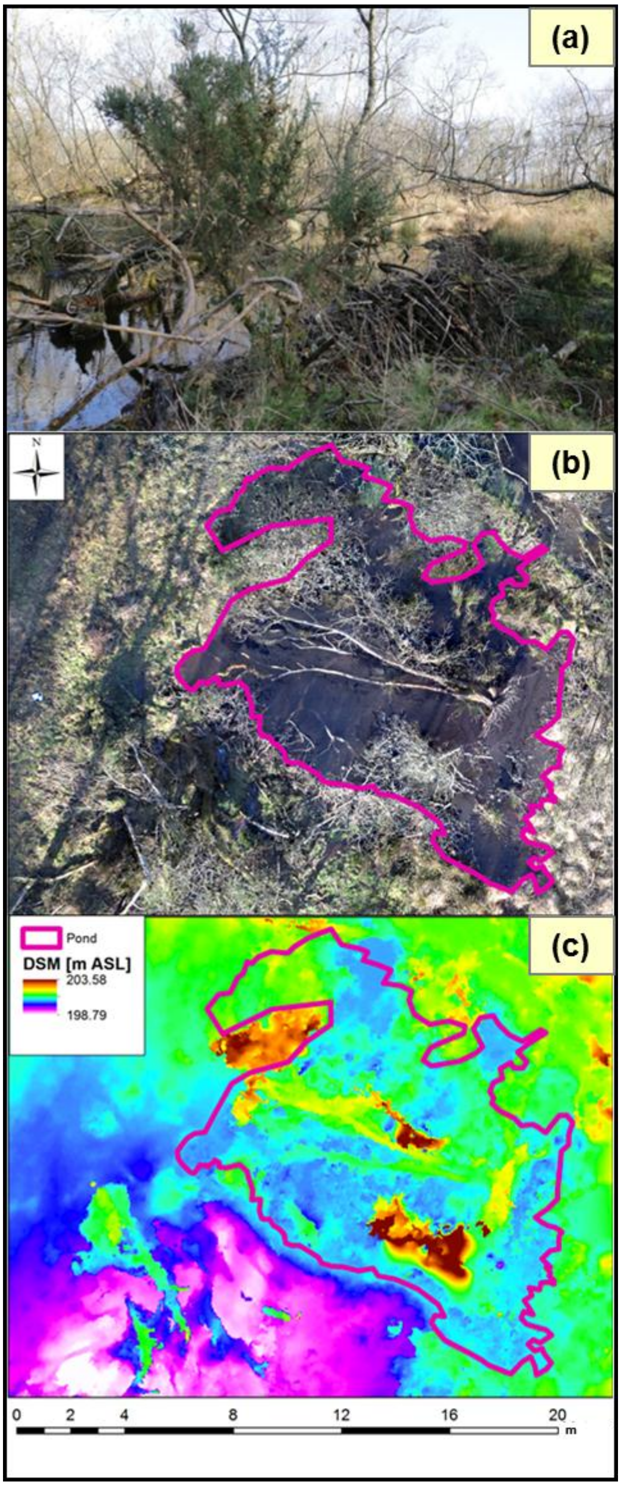

Figure 2.