Assessing climate change associated sea level rise impacts on sea turtle nesting beaches using drones, photogrammetry and a novel GPS system.

Running head: Climate change and drone-based photogrammetry

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Abstract

Climate change associated sea level rise (SLR) is expected to have profound impacts on coastal areas, affecting many species including sea turtles which depend on these habitats for egg incubation. Being able to accurately model beach topography using digital terrain models (DTMs) is therefore crucial to project SLR impacts and develop effective conservation strategies. Traditional survey methods are typically low-cost with low accuracy or high-cost with high accuracy. We present a novel combination of drone-based photogrammetry and a low-cost and portable real-time kinematic (RTK) GPS to create DTMs which are highly accurate (<10 cm error) and visually realistic. This methodology is ideal for surveying coastal sites, can be broadly applied to other species and habitats, and is a relevant tool in supporting the development of Specially Protected Areas. Here we applied this method as a case-study to project three SLR scenarios (0.48, 0.63 and 1.20 m) and assess the future vulnerability and viability of a key nesting habitat for sympatric loggerhead (*Caretta caretta*) and green turtle (*Chelonia mydas*) at a key rookery in the Mediterranean. We combined the DTM with 5 years of nest survey data describing location and clutch depth, to identify (1) regions with highest nest densities, (2) nest elevation by species and beach, and (3) estimated proportion of nests inundated under each SLR scenario. On average, green turtles nested at higher elevations than loggerheads (1.8 m vs. 1.32 m, respectly). However, because green turtles dig deeper nests than loggerheads (0.76 m vs. 0.50 m, respectly), these were at similar risk of inundation. For a SLR of 1.2 m, we estimated a loss of 67.3% for loggerhead turtle nests and 59.1% for green turtle nests. Existing natural and artificial barriers may affect the ability of these nesting habitats to remain suitable for nesting through beach migration.

Introduction

Climate change is recognised as a major driver of ecosystem transformation worldwide (Hoegh-Guldberg and Bruno, 2010), and is likely to cause shifts in species ranges and phenology, and potentially threaten the survival of entire species and habitats (Baker et al., 2006, Bellard et al., 2012, Hawkes et al., 2007, Thomas et al., 2004). Global sea level rise, due to ocean thermal expansion, melting of glaciers and ice caps, aggravated by increased storm activity (Pachauri et al., 2014), is expected to have impacts on coastal tropical areas, and to profoundly affect species which depend on these habitats. The latest Intergovernmental Panel on Climate Change (IPCC) projections on global sea level rise (SLR) range from 0.47 m (95% CI: 0.26-0.55 m) to 0.63 m (95% CI: 0.45 – 0.82 m) by 2100 (Stocker et al., 2013), while semi-empirical models, including ice melt, project even more extreme sea level rise for the same period (>1m SLR, Grinsted et al., 2010, Nicholls et al., 2010, 2011, Horton et al., 2014, DeConto and Pollard, 2016, Vousdoukas et al., 2018, Chown et al., 2017). Although global sea level has varied a great deal during glacial/interglacial cycles (Fairbanks, 1989), current SLR is happening at an unprecedented rate (Pachauri et al., 2014), some argue, potentially too rapidly for species to adapt to new conditions (Jezkova & Wiens, 2016).

All marine turtle species depend on temperate to tropical sandy beaches for reproduction. Nesting turtles generally display natal philopatry; returning to the beach where they hatched to lay their eggs (Meylan et al., 1990). This makes them potentially vulnerable to SLR and enhaced storm activity (Poloczanska et al., 2009), as areas of beach can be lost or degraded by coastal erosion or flooding. Several nesting beaches used by sea turtles have already been assessed with regard to potential SLR impacts, with studies predicting significant losses of coastal habitat, under median SLR scenarios, ranging from 45 to 65% (Baker et al., 2006, Fish et al., 2005, Fish et al., 2008, Fuentes et al., 2010, Katselidis et al., 2014).

Concerns regarding the impacts of climate change associated SLR mandates the development of highly accurate modelling techniques that should be cost-effective to be broadly used. To estimate habitat loss due to SLR on marine turtle nesting beaches a range of methods have been employed to create beach DTMs: beach profiles can be measured at transect points across a beach using an Abney Level (e.g. Fish et al., 2005, Fish et al., 2008), which is a low-cost approach requiring only basic equipment. However the estimates obtained from these types of surveys, however, are usually limited to discrete beach transects (i.e. are not capable of delivering spatially-distributed data without considerable time and effort), and may be subject to systematic errors and low accuracy (Isaak et al., 1999). At the other methodological extreme, terrestrial and airborn LiDAR (Light Detection and Ranging) uses expensive and heavy equipment to pulse lasers across a surface to create highly accurate DTMs (e.g. Long et al., 2011, Yamamoto et al., 2015), but generally instrumentation and software costs exceed several tens of thousands of pounds per survey, and thus can be operationally prohibitive, even more so for repeat surveys.

The ability to obtain a robust DTM of the current nesting habitat, where possible impacts can be projected, is an essential baseline for use in combination with SLR predictions to make informed decisions, and prioritize conservation efforts to mitigate the consequences of SLR to sea turtle populations. What is now needed is a more cost-effective method than airborne and terrestrial LiDAR for scale-appropriate and spatially-distributed estimation of beach terrain.

Structure-from-motion (SfM) photogrammetry using aerial photos from drones (also referred to as unmanned aerial vehicle, UAV, or unmanned aerial system, UAS, in literature), has now emerged as a cost-effective tool to generate robust surface and terrain models in geoscience applications (Glendell et al.,2017, Westoby et al., 2012, Capolupo et al., 2015, Cunliffe et al., 2016). It uses multiple overlapping aerial photos and merges them into a 3D model using a computer vision technique known as bundle adjustment (Bolton, 2016). However, to achieve an accurate bare Earth DTM over a beach-type study system typically requires access to a differential GPS (dGPS), or a 'real time kinematic' (RTK) system, to record the locations of a series of deployed ground control points (GCPs) in the survey area which are used to both georeference the 3D model and improve its quality. The purchase of a high accuracy single RTK surveying unit is often high (e.g. in the UK, such a system would cost £5,000-15,000) which means that the costs are again prohibitive for many users. Here we describe a new workflow that was developed to circumvent the requirement for expensive equipment to produce fine-grained and high accuracy DTMs for coastal monitoring applications and how such a workflow can be achieved by combining the use of drones and SfM photogrammetry with an alternative ground-based RTK surveying solution. We used a key sea turtle rookery at Alagadi, northern Cyprus (Broderick et al., 2002), to demonstrate the application of our method and to estimate the future impacts of SLR on nesting beach habitat of two sympatric sea turtle species.

Methodology

Study site and nesting data

Alagadi (35.34º N, 33.49º E) is a major sea turtle nesting area in north Cyprus

(Broderick et al., 2002) and is composed of two beaches separated by a rocky point covering a total extension of ca. 1700 m, with Beach 1 to the west, extending for 1000 m, and Beach 2 to the east, extending for 700 m (Supplemental Fig. S1). Both beaches are generally made up of fine sand sediment and are micro-tidal, hosting two species of nesting sea turtles (green *Chelonia mydas*, and loggerhead *Caretta caretta*; Broderick et al., 2002). During the nesting season, night patrols assure near-perfect attribution of nests to known nesting females (for details in survey methods see Stokes et al., 2014). From 2012 to 2016, we recorded the location of all 767 green and 293 loggerhead clutches laid at both beaches using a handheld GPS Garmin eTrex 10 (horizontal accuracy of ± 3m). Hatched nests were excavated and we measured top clutch depth, i.e. from the surface to the first egg shell found as well as bottom clutch depth, i.e. from the surface to the last egg shell found.

Photogrammetry workflow

We used a custom made quadcopter drone equipped with a Canon S100 compact digital camera with 12 megapixel image sensor (Supplemental Fig. S2) to collect aerial photographs of the turtle nesting beaches. The drone was flown in automated survey mode, whereby it followed a GPS-waypointed path pre-programmed into the open-source Pixhawk autopilot software, to avoid human piloting error and to achieve a consistent forward and side overlap of ≥80% between the aerial images, which is required for an accurate DTM and orthophoto generation (Haala et al., 2013). The drone flew at 30 m altitude at a velocity of 4 $m.s^{-1}$ with the camera triggering a photo every two seconds. The aerial survey resulted in 773 photos for Beach 1 and 436 photos for Beach 2. The camera focus was set to automatic, aperture at f4.5, shutter speed 1/1200 and ISO 400. To improve the accuracy of the final model, following Tonkin et al., (2014), we distributed 30 GCPs, (25 x 25cm tiles) evenly along each beach, and selected 10 additional natural features on the ground to serve as control check points to assess the accuracy of the final model. We then proceeded to record their individual centroid coordinates in x,y,z using a novel RTK-GPS system, the Piksi (www.swiftnav.com/piksi-multi).

The Piksi is a low-cost, alternative carrier phase RTK GPS with centimetre level relative positioning accuracy consisting of two modules: the rover, which we used to survey the GCPs, and the base station, which we kept stationary in a GCP placed on the high tide mark. Both base and rover were connected to a survey grade Global Navigation Satellite System (GNSS) external antenna to enhance satellite signal. Each GCP was surveyed with the rover in a static position for approximately 1 min in order to assure an accurate measurement. Two field studies have assessed the accuracy of the Piksi, reporting 4.1 – 8.2 cm of horizontal accuracy, and 1.1 – 5.2 cm vertically (Fazeli et al., 2016, Zollo & Gohalwar, 2016).

After manually removing the photos that were captured during take-off and landing phases, and any that were blurred, the remaining images were imported into Agisoft PhotoScan Professional software v 1.3.1 (© Agisoft) which is a software that performs photogrammetric processing of digital images and generates spatially distributed data in 3D point cloud format. Following generation of a sparse point cloud, we manually identified the survey GCP centroids in the input photoset and assigned their real-world, RTK-GPS co-ordinates to simultaneously refine camera calibration parameters, georeference the model, and optimize the geometry of the output point cloud, before generating a dense point cloud using a multi-view stereo algorithm as detailed in previous studies (e.g. Westoby et al., 2012; Gonçalves & Henriques, 2015). The parameters used for SfM processing are shown in supplemental Table S1. The final result was a georeferenced orthophoto and a DTM. In our case we had unvegetated sandy beaches, so the digital surface model (DSM) produced by PhotoScan was treated as a DTM (bare Earth model) since there was no overlying vegetation to remove.

Characterization of nesting preferences

The resulting georeferenced orthophoto and DTM were imported in raster format into ESRI ArcGIS software (v10.4), along with GPS coordinates of all green and loggerhead sea turtle nests between 2012 and 2016. To quantify preferred nest sites by species and by nesting season, we applied a Kernel Density Estimation (KDE) interpolation (as described by Macleod, 2014), with an output cell size of 1 m side length and bandwidth (search radius) set to 30 m.

Nest elevation

To estimate the elevation of nests (i.e. their height above sea level, from which we could estimate inundation risk from SLR) we overlaid the GPS coordinates of sea turtle nests on the DTM and used the ArcMap 3D Analyst Toolset to extract the beach surface elevation at each nest. We then subtracted from this the depth from the beach surface elevation down to the deepest egg shell found for each nest estimate the nest elevation at the bottom of the clutch (available through a long-term monitoring study established at the site, which excavates and records the fate of all nests). We assume that nests became partly inundated when the bottom nest elevation estimate is below the predicted sea level, and used these data to estimate the proportion of green turtle and loggerhead clutches that would be affected under 0.1 m increments of SLR scenarios, assuming no changes in beach morphology (I.e. passive flooding). We believe this approach is more meaningful than estimating the available nesting area that would be inundated, as it considers the current optimal nest site areas of the two species of turtle.

Inundation scenarios

To show the visual impact of this method, we used the final SfM-derived orthophoto to simulate habitat loss under the three SLR scenarios (0.48 m, 0.63 m, and 1.2 m). The former two, were Representative Concentration Pathways (RCPs) in the Intergovernmental Panel for Climate Change (Collins et al., 2013); one intermediate (RCP6) and one high emissions scenario (RCP8.5). The latter, more extreme scenario was based on semi-empirical models (0.7 - 1.2 m SLR by 2100; Horton et al., 2014).

Results

DTM and orthophoto accuracy

From the comparison of the checkpoints coordinates measured with the Piksi against the final DTM we found a mean ± SD horizontal error of 6.8 ± 0.8 cm (range: 1.2 to 7.5 cm, n=10), and a mean ± SD vertical error of 9.4 ± 1.0 cm (range: 6.9 to 10.0 cm, n=10) for Beach 1 and 6.5 ± 1.8 cm (range: 1.8 to 7.9 cm, n=10), 9.3 ± 1.4 cm (range: 5.4 to 9.9 cm, n=10), respectively, for Beach 2.

Nesting site preferences

Core areas of green turtle nest distribution were generally centred in the eastern portion of both beaches (Fig. 1a), while the loggerhead core areas were more evenly distributed throughout each beach with a lesser preference for eastern areas (Fig.

1b).

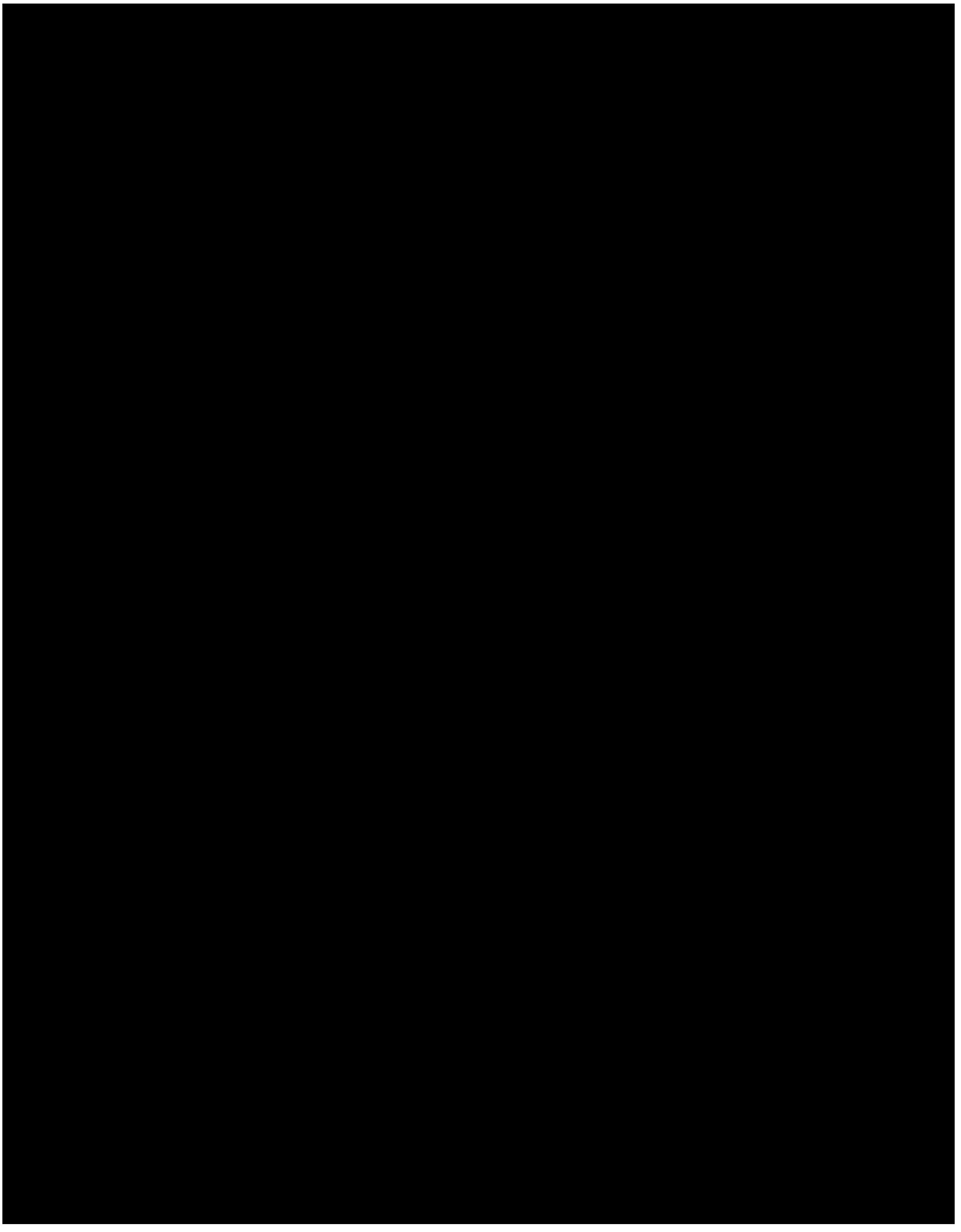

Fig 1: Orthophoto with kernel density estimation; shaded according to density of nests per area and showing density of nests of **a.** green turtles, and **b.** loggerhead turtles at Alagadi, northern Cyprus. Dots represent GPS location of 768 green turtle nests (green), and 294

loggerhead turtle nests (purple), surveyed from 2012 to 2016. Contour colours get darker as modelled nesting habitat utilisation distribution (UD) increases from yellow (peripheral) to dark brown (core).

The mean bottom elevation of green turtle clutches was approximately 0.76± 0.12 m below the sand surface (mean± SD, range: 0.36 to 1.20 m, n=720 nests or 94% of all green turtle nests laid), while the mean bottom elevation of loggerhead nests were 0.48± 0.07 m below the sand surface (mean, ± SD, range 0.27 to 0.82 m, n=251 or 86% of all nests laid by loggerhead turtles). For the remaining nests (which were not measured), we used the mean depth for each species calculated here.

Independent-sample Welch's t-tests indicated that there were significant differences in nest surface elevation above the highest tide line (not taking into account the clutch depth) for the five year period between species: Beach 1: $t_{428.85} = 7.2$, $P < 0.0001$, Beach 2: $t_{270.62} = 7.2$, $P < 0.0001$), and between beaches within the same species. Nest elevation was significantly lower in Beach 2 for green turtles (Fig. 2, Beach 1 = 2.2 ± 0.9 m SD, Beach 2 = 1.4 ± 1.1 m SD; $t_{746.54}=11.8$, $P < 0.0001$) and loggerheads (Beach 1 = 1.7 ± 0.8 m SD, Beach 2 = 0.5 ± 0.5 m SD; $t_{250.36} = 13.9$, $P < 0.0001$).

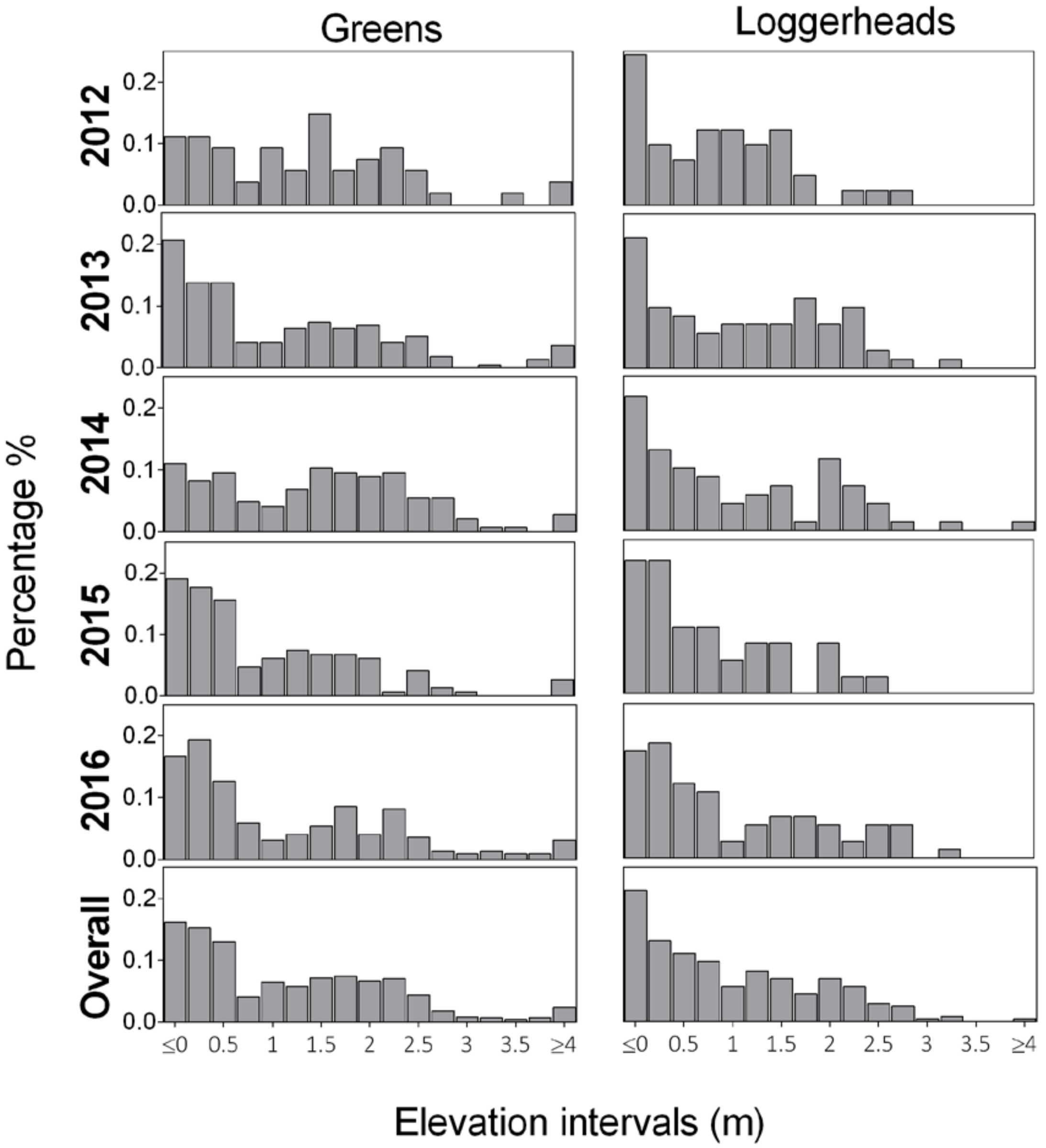

Figure 2. Clutch elevation distribution (i.e. elevation from surface to bottom of clutch) of green turtle and loggerhead turtle nests, from 2012 to 2016, and five-year mean per species, at Alagadi beach, Northern Cyprus.

Sea Level Rise

For green turtles we estimated that with a 0.48 m SLR scenario, inundation would affect 33.2% - 43.5% of the clutches (sea water reaching top and bottom of clutch, respectively), 42.3% - 47.0% with 0.63 m SLR and 57.1% - 59.1% with 1.2 m SLR (Fig. 3a). For loggerheads we project a loss of 36.5% - 44.1%; 43.3% - 49.4% and 62.1% - 67.4%, for 0.48 m, 0.63 m and 1.2 m SLR scenarios, respectively (Fig. 3b). Nesting beach inundation under each of the three SLR scenarios can be seen on figure 4.

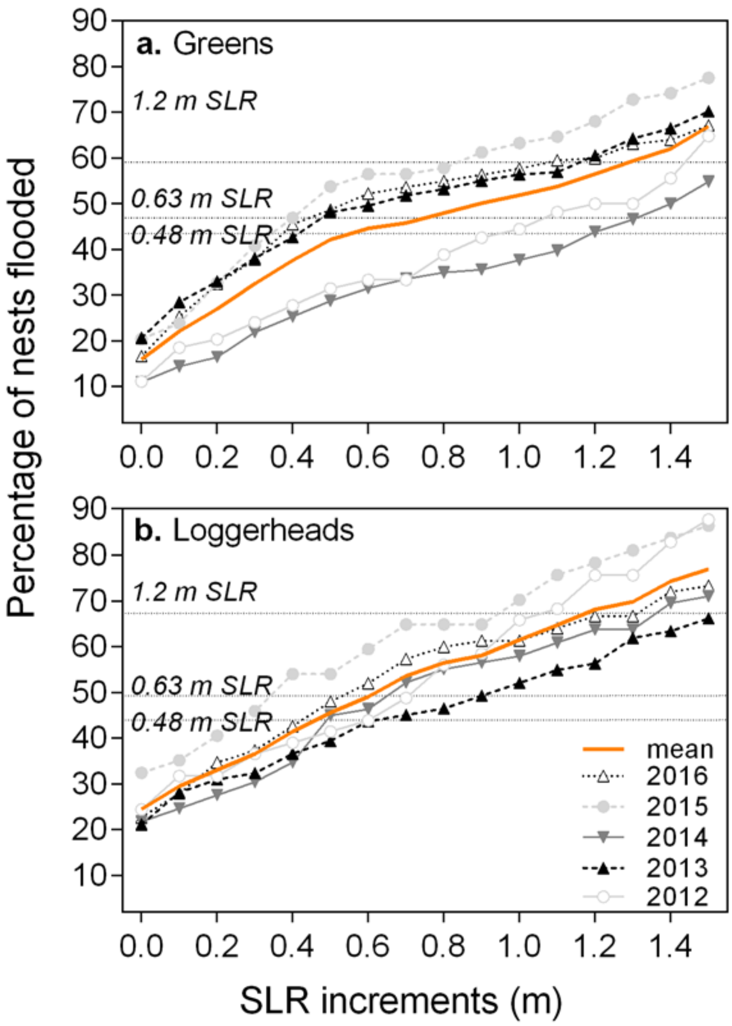

Figure 3. Percentage of green (**a**), and loggerhead (**b**) turtle clutches expected to be inundated under increments of 0.1 m of sea level rise (SLR) at Alagadi, Northern Cyprus, each year from 2012 to 2016, and five-year mean (orange line). Horizontal

dashed lines indicate percentage of affected clutches under each SLR scenario (0.48, 0.63, and 1.2 m).

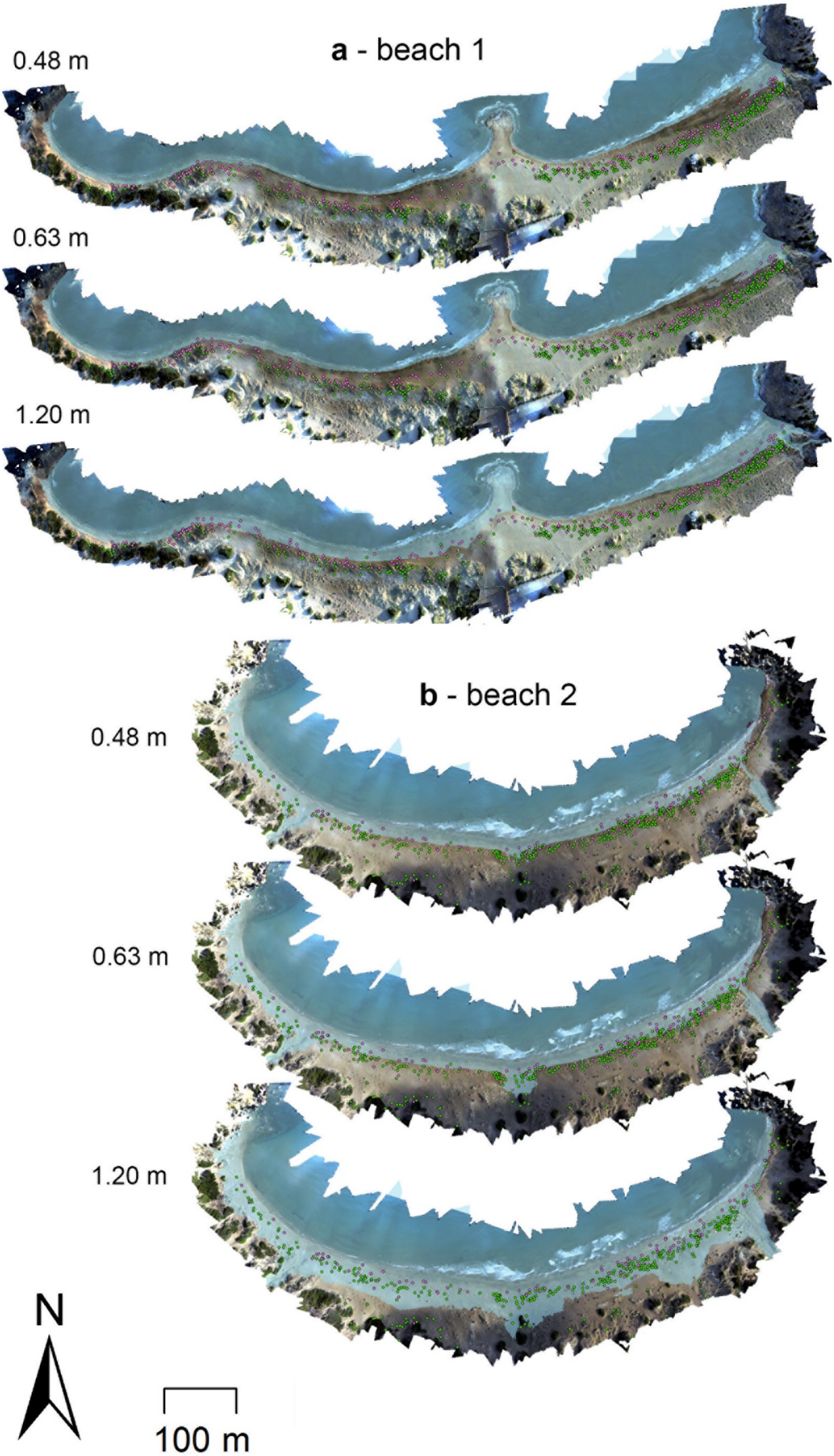

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Figure 4. Inundation scenarios of 0.48, 0.63 and 1.2 m of SLR projected on orthophoto of **a)** Beach 1 and **b)** Beach 2. Dots represent actual location of sea turtle nests for each species, surveyed from 2012 to 2016 (pink for loggerhead turtles and green for green turtles).

Discussion

Recent improvements in the resolution, affordability, and ease of acquisition of remotely sensed data, coupled with new tools for geospatial analysis, can assist with mapping putative anthropogenic threats, such as the predicted consequences of SLR (Fish et al., 2008). Existing methods for creating DTMs of sea turtle nesting habitats, result in models which are not visually realistic and may also be too expensive to implement or lack the accuracy to make robust inferences. Here we present a method to create high resolution and accurate DTMs and orthophoto imagery data of coastal areas, improving on all main aspects of those currently employed - visual impact, accuracy, cost and portability.

1. DTM visual impact, accuracy, cost and portability

Our workflow produced a high-resolution DTM and orthophoto mosaic combination and achieved an error under ± 10 cm which is a similar to high-end survey methods using LiDAR (Stockdon et al., 2017 ,Yamamoto et al., 2015) or photogrammetric methods incorportating dGPS or total station control (Westoby et al., 2012, Smith et al., 2016), but with a much lower cost and higher portability than either method (Table 1). Although digital photogrammetry is already widely used in other disciplines for creating DTMs, it typically requires a dGPS like a Leica Total Station or similar, weighing over 5kg and costing £5000-15,000 rendering it cost-prohibitive for most conservation projects. The total build cost of the Piksi RTK GPS system was £1500 (prices in April 2018).

The total cost of our drone survey system (drone, camera) was £850, excluding the licence for Agisoft PhotoScan (£385; educational licence, price April 2018), but there are free software alternatives available that perform the same task (e.g. http://opendronemap.org). Each Piksi module fits the palm of the hand and weighs 26 grams, making it also extremely portable and therefore ideal for deployment in remote locations.

Our final orthophotos (Fig. 5) are photo-realistic and are easier to visually interpret than data obtained through traditional survey methods, making it useful not only for scientific analysis but also as an effective visual aid for enabling science communication and knowledge transfer to the general public and decision makers, including planning professionals addressing other coastal development issues such as water-front tourism development. Similarly, the SfM-derived DTM can be used for virtual ‘fly-throughs’ to engender a sense of reality (as we shown in supplemental video in Rees et al., 2018) The accurate DTM and orthophoto allow the retrieval of valuable information concerning nest elevation and nest site preferences of each sea turtle population. Additionally, the use of DTM differencing methods, where successive DTMs are subtracted from one another to produce spatially distributed maps of topographic change, would enable the quantification of subtle shifts in beach morphology over time, and facilitate analysis of any impacts on sea turtle nesting activities.

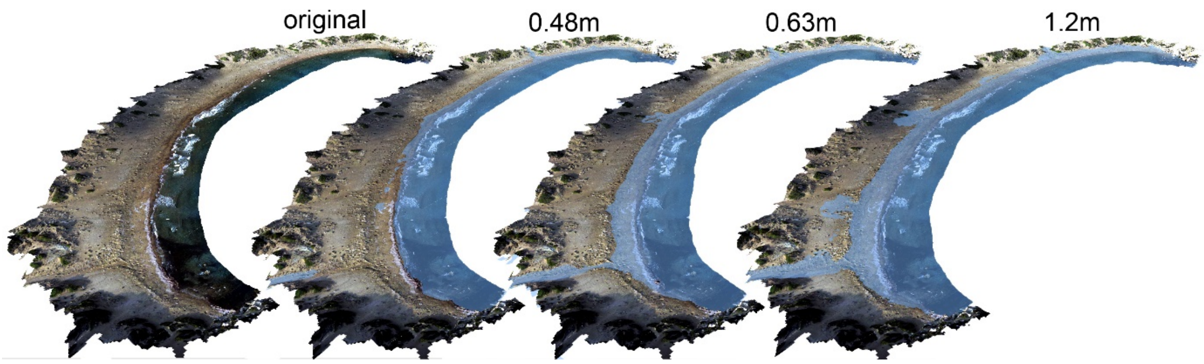

Figure 5. Realistic view of the 3D Model of Beach 2, Alagadi, Northern Cyprus, under three inundation scenarios (0.48, 0.63 and 1,2 m of SLR)

Looking to the future, it is clear that this method will likely become cheaper and easier as drones and RTK solutions flood the market at lower prices and with higher capabilities. In addition to the Piksi, there are other available RTK-GPS alternatives (e.g. Emlid Reach, https://emlid.com/reach Accessed: 2018-07-11.) and several others in development that can be used in conjunction with a similar SfM-based methodology and at comparatively low cost. New drone solutions are starting to integrate on-board RTK-GPS positioning, and in time will likely render the requiring for ground-based control obsolete, therefore simplifying the process of acquiring data. However, this is unlikely to be a viable surveying solution for most applications in the short term.

Table 1. DTM survey methods summary. Photogrammetry + PIKSI is the method presented in this study.

Surveying Methods	Accuracy in cm	Visual Impact	Equipment Cost in £	Portability of Equipment in kg
Abney Level	± 25	Low / 2D profile	± 25	1
Theodolite	< 1	Low/ 2D profile	> 1000	6
LiDAR	6 – 22	High/ 3D aerial	> 30000	>1000

Photogrammetry + dGPS	< 5	Very High/ 3D aerial + realistic view	> 7000	10
Photogrammetry + PIKSI	< 10	Very High/ 3D aerial + realistic view	± 2500	6

2. Nest site selection and SLR scenarios

Green turtles, on average, utilised the nesting habitat at higher elevations than the loggerheads. However, the risk of inundation under SLR scenarios was comparable for both species, since green turtles dig deeper nest chambers and thus their clutches are at similar elevations to those of loggerheads when compared to the mean sea level. This shows the importance of field measurements of clutch depth, particularly in sites where relocation of clutches laid at lower elevations is a common conservation practice.

Both species laid their nests at lower elevations on Beach 2. This might be because this beach is located within a more sheltered cove, so sand at lower altitudes is more stable as it is less influenced by wind and wind-driven waves action. The nest density shows the successful nesting areas but not necessarily the preferred areas. Both species emerge from the water in all available beach extension, but only manage to nest in different specific areas, showing that the conditions for successful nesting change between species within the same habitat.

Our results also show that while the two beaches in our study vary in their physical characteristics, they do not vary greatly in their susceptibility to the potential impacts of SLR. Except for the western section of Beach 1, which will most likely be inundated under a medium SLR scenario, the rest of the beach extent still offers room to migrate landward into areas which are currently dunes, despite modest development behind Beach 1. However it is important to make sure that the current area for beach migration is safeguarded from future coastal development and that planning accounts for the most extreme SLR scenario and increased storm activity. This is particularly important for the endangered green turtles as these two beaches are key areas for this population. Priority conservation areas where development should be specifically restricted include the highest nest density areas which are also at a higher risk of inundation.

3. Limitations

Our methodology highlights the potential area of beach under threat but it does not, however, offer a complete analysis of the potential shoreline response. The lack of data on long-term beach profile changes and knowledge about precise coastal processes, makes it challenging to forecast the response of each beach to sea-level rise. Beach sediments redistribution is dictated by numerous factors, such as substrate type, topographic relief and shelter from wave energy and wind (Wells, 1995), and accurate models to project coastal adjustments have proven difficult to produce so far. The most commonly used method has been the Bruun rule (Bruun, 1962), which predicts increased erosion and an upward and landward migration of beaches. However this very simple model has limited application, and its ability to provide reliable predictions has been questioned even under ideal conditions (Pilkey & Cooper, 2004). This field of study is however under significant progress and new, more accurate, models working with fine sediment movement may soon become available. Models such as XBeach have already been successfully tested on several study sites with gravel beaches (McCall et al., 2015, Christie et al., 2017, Mickey et al., 2017). Accurate DTMs will be needed to test such future models and our method could be useful here.

Field-work limitations such as wind gust conditions or small particles of airborne sand, which could possibly damage the drone engines should also be taken into account (for more details see Duffy et al., 2017). Additionally, restrictions regarding drone transport and local regulations governing the use of drones in specific countries or locales should be considered and require careful pre-survey planning. For sea turtle nesting beaches, however, one of main limitations is the amount of vegetation cover. While small bushes or sparse trees are acceptable, areas with dense vegetation will block the view of the ground from the air, therefore rendering the photos unsuitable for photogrammetric reconstruction of bare earth topography. To overcome this, the Piksi RTK can be used in rover mode to ground-survey what cannot be seen from an aerial perspective the air and combine these data with those acquired from aerial SfM.

Future work should include the Piksi (or a similar RTK-GPS based system) as the tool for measuring nest GPS coordinates, thereby reducing the error introduced by handheld GPS**.** Here we used five years of nests coordinates acquired using an eTrex 10 GPS with ± 3 m horizontal accuracy, but given the large sample size (1062 nests) our predictions overall should be robust. However, the vertical accuracy of the eTrex (± 10 m) is clearly unsuitable for the desired accuracy estimates of elevation and thus for this purpose we used estimates from the DTM (under 10 cm accuracy) instead.

4. Future and wider applications

The potential for our low-cost and accurate workflow to augment and improve understanding of climate change associated impacts for sea turtles is quite profound. With cheap, portable, accurate and visually appealing/easily understood results, we have demonstrated it to be a viable solution for assessing the likely damage to marine turtle nesting habitat, from which well-informed and effective management responses to coastal squeeze (Fish et al., 2008), can be made. This workflow can be used for other sea turtle species and populations - as we demonstrate in Patricio et al., (2018), but can also be broadly applied to any vulnerable species or coastal habitats, e.g. mangroves (Ellison, 2015, Spencer et al., 2016, Woodroffe, C. D., 2018), and shorebirds (Thorne et al., 2018, Galbraith et al., 2002, Kane et al., 2015) or forecasting likely extent of oil spill contamination (Lauritsen et al 2017), which require a realistic model for SLR projections. Finally, our surveying solution can also be deployed by researchers in other disciplines where SfM is routinely used for topographic characterisation as it reduces costs while increasing portability when replacing the dGPS with an alternative RTK solution.

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References

Baker, J. D., Littnan, C. L., & Johnston, D. W. (2006). Potential effects of sea level rise on the terrestrial habitats of endangered and endemic megafauna in the Northwestern Hawaiian Islands. Endangered Species Research, 2, 21-30.

Bellard, C., Bertelsmeier, C., Leadley, P., Thuiller, W., & Courchamp, F. (2012). Impacts of climate change on the future of biodiversity. Ecology letters, 15(4), 365-377.

Broderick, A. C., Glen, F., Godley, B. J., & Hays, G. C. (2002). Estimating the number of green and loggerhead turtles nesting annually in the Mediterranean. Oryx, 36(3), 227-235.

Capolupo, A., Pindozzi, S., Okello, C., Fiorentino, N., & Boccia, L. (2015). Photogrammetry for environmental monitoring: The use of drones and hydrological models for detection of soil contaminated by copper. Science of the Total Environment, 514, 298-306.

Chown, S. L., & Duffy, G. A. (2017). The veiled ecological danger of rising sea levels. Nature ecology & evolution, 1(9), 1219.

Christie, E. K., Spencer, T., Owen, D., McIvor, A. L., Möller, I., & Viavattene, C. (2017). Regional coastal flood risk assessment for a tidally dominant, natural coastal setting: North Norfolk, southern North Sea. Coastal Engineering.

Collins, M., Knutti, R., Arblaster, J., Dufresne, J. L., Fichefet, T., Friedlingstein, P., ... & Shongwe, M. (2013). Long-term climate change: projections, commitments and irreversibility.

Cunliffe, A. M., Brazier, R. E., & Anderson, K. (2016). Ultra-fine grain landscape-scale quantification of dryland vegetation structure with drone-acquired structure-from-motion photogrammetry. Remote Sensing of Environment, 183, 129-143.

DeConto, R. M., & Pollard, D. (2016). Contribution of Antarctica to past and future sea-level rise. Nature, 531(7596), 591.

Duffy, J.P., Cunliffe, A.M., DeBell, L., Sandbrook, C., Wich, S.A., Shutler, J.D., Myers-Smith, I.H., Varela, M.R. and Anderson, K. (2018). Location, location, location: considerations when using lightweight drones in challenging environments. Remote Sensing in Ecology and Conservation, 4(1), 7-19.

Ellison, J. C. (2015). Vulnerability assessment of mangroves to climate change and sea-level rise impacts. Wetlands Ecology and Management, 23(2), 115-137.

Fairbanks, R. G. (1989). A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation.

Nature, 342(6250), 637.

Fazeli, H., Samadzadegan, F., & Dadrasjavan, F. (2016). Evaluating the potential of RTK-UAV for automatic point cloud generation in 3D rapid mapping. The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 41, 221.

Fish, M. R., Cote, I. M., Gill, J. A., Jones, A. P., Renshoff, S., & Watkinson, A. R. (2005). Predicting the impact of sea-level rise on Caribbean Sea turtle nesting habitat. Conservation biology, 19(2), 482-491.

Fish, M. R., Cote, I. M., Horrocks, J. A., Mulligan, B., Watkinson, A. R., & Jones, A. P. (2008). Construction setback regulations and sea-level rise: mitigating sea turtle nesting beach loss. Ocean & Coastal Management, 51(4), 330-341.

Fuentes, M. M. P. B., Limpus, C. J., Hamann, M., & Dawson, J. (2010). Potential impacts of projected sea-level rise on sea turtle rookeries. Aquatic conservation: marine and freshwater ecosystems, 20(2), 132-139.

Galbraith, H., Jones, R., Park, R., Clough, J., Herrod-Julius, S., Harrington, B., & Page, G. (2002). Global climate change and sea level rise: potential losses of intertidal habitat for shorebirds. Waterbirds, 25(2), 173-183.

Glendell, M., McShane, G., Farrow, L., James, M. R., Quinton, J., Anderson, K., ... & Jones, L. (2017). Testing the utility of structure-from-motion photogrammetry reconstructions using small unmanned aerial vehicles and ground photography to estimate the extent of upland soil erosion. *Earth Surface Processes and Landforms*, *42*(12), 1860-1871.

Gonçalves, J. A., & Henriques, R. (2015). UAV photogrammetry for topographic monitoring of coastal areas. ISPRS Journal of Photogrammetry and Remote Sensing, 104, 101-111.

Grinsted, A., Moore, J. C., & Jevrejeva, S. (2010). Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD. Climate Dynamics, 34(4), 461-472.

Haala, N., Cramer, M., & Rothermel, M. (2013). Quality of 3D point clouds from highly overlapping UAV imagery. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci, 4-6.

Hoegh-Guldberg, O., & Bruno, J. F. (2010). The impact of climate change on the world's marine ecosystems. Science, 328(5985), 1523-1528.

Horton, B. P., Rahmstorf, S., Engelhart, S. E., & Kemp, A. C. (2014). Expert assessment of sea-level rise by AD 2100 and AD 2300. Quaternary Science Reviews, 84, 1-6.

Hawkes, L. A., Broderick, A. C., Godfrey, M. H., & Godley, B. J. (2007). Investigating the potential impacts of climate change on a marine turtle population. Global Change Biology, 13(5), 923-932.

Hawkes, L. A., Broderick, A. C., Godfrey, M. H., & Godley, B. J. (2009). Climate change and marine turtles. Endangered Species Research, 7(2), 137-154.

Isaak, D. J., Hubert, W. A., & Krueger, K. L. (1999). Accuracy and precision of stream reach water surface slopes estimated in the field and from maps. *North American Journal of Fisheries Management*, *19*(1), 141-148.

Jezkova, T., & Wiens, J. J. (2016). Rates of change in climatic niches in plant and animal populations are much slower than projected climate change. Proc. R. Soc. B, 283(1843), 20162104.

Kane, H. H., Fletcher, C. H., Frazer, L. N., & Barbee, M. M. (2015). Critical elevation levels for flooding due to sea-level rise in Hawai ‘i. Regional environmental change, 15(8), 1679-1687.

Katselidis, K. A., Schofield, G., Stamou, G., Dimopoulos, P., & Pantis, J. D. (2014). Employing sea-level rise scenarios to strategically select sea turtle nesting habitat important for long-term management at a temperate breeding area. Journal of experimental marine biology and ecology, 450, 47-54.

Lauritsen, A. M., Dixon, P. M., Cacela, D., Brost, B., Hardy, R., MacPherson, S. L., & Witherington, B. (2017). Impact of the Deepwater Horizon oil spill on loggerhead turtle Caretta caretta nest densities in northwest Florida. *Endangered Species Research*, *33*, 83-93.

Long, T. M., Angelo, J., & Weishampel, J. F. (2011). LiDAR-derived measures of hurricane-and restoration-generated beach morphodynamics in relation to sea turtle nesting behaviour. International journal of remote sensing, 32(1), 231-241.

Meylan, A. B., Bowen, B. W., & Avise, J. C. (1990). A genetic test of the natal homing versus social facilitation models for green turtle migration. Science, 248(4956), 724-727.

Mickey, R. C., Long, J. W., Plant, N. G., Thompson, D. M., & Dalyander, P. S. (2017). A methodology for modeling barrier island storm-impact scenarios (No. 2017-1009). US Geological Survey.

MacLeod, C. D. (2014). An introduction to using GIS in marine biology. Supplementary workbook four. Investigating home ranges of individual animals.

Nicholls, R. J., & Cazenave, A. (2010). Sea-level rise and its impact on coastal zones. science, 328(5985), 1517-1520.

Nicholls, R. J., Marinova, N., Lowe, J. A., Brown, S., Vellinga, P., De Gusmao, D., ... & Tol, R. S. (2011). Sea-level rise and its possible impacts given a ‘beyond 4 C world’in the twenty-first century. Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, 369(1934), 161-181.

Pachauri, R. K., Allen, M. R., Barros, V. R., Broome, J., Cramer, W., Christ, R., ... & Dubash, N. K. (2014). Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change (p. 151). IPCC.

Patrício, A. R., Varela, M. R., Barbosa, C., Broderick, A. C., Airaud, M. B. F., Godley, B. J., ... & Catry, P. (2018). Nest site selection repeatability of green turtles, Chelonia mydas, and consequences for offspring. Animal Behaviour, 139, 91-102.

Poloczanska, E. S., Limpus, C. J., & Hays, G. C. (2009). Vulnerability of marine turtles to climate change. Advances in marine biology, 56, 151-211.

Rees, A. F., Avens, L., Ballorain, K., Bevan, E., Broderick, A. C., Carthy, R. R., ... & Mangel, J. C. (2018). The potential of unmanned aerial systems for sea turtle research and conservation: a review and future directions. Endangered Species Research, 35, 81-100.

Smith, M. W., Carrivick, J. L., & Quincey, D. J. (2016). Structure from motion photogrammetry in physical geography. Progress in Physical Geography, 40(2), 247-275.

Spencer, T., Schuerch, M., Nicholls, R. J., Hinkel, J., Lincke, D., Vafeidis, A. T., ... & Brown, S. (2016). Global coastal wetland change under sea-level rise and related stresses: The DIVA Wetland Change Model. Global and Planetary Change, 139, 15-30.

Stockdon, H. F., Doran, K. S., & Sallenger Jr, A. H. (2009). Extraction of lidar-based dune-crest elevations for use in examining the vulnerability of beaches to inundation during hurricanes. Journal of Coastal Research, 59-65.

Stokes, K. L., Fuller, W. J., Glen, F., Godley, B. J., Hodgson, D. J., Rhodes, K. A., ... & Broderick, A. C. (2014). Detecting green shoots of recovery: the importance of long-term individual-based monitoring of marine turtles. Animal conservation, 17(6), 593-602.

Thomas, C. D., Cameron, A., Green, R. E., Bakkenes, M., Beaumont, L. J., Collingham, Y. C., ... & Hughes, L. (2004). Extinction risk from climate change. Nature, 427(6970), 145.

Thorne, K., MacDonald, G., Guntenspergen, G., Ambrose, R., Buffington, K., Dugger, B., ... & Holmquist, J. (2018). US Pacific coastal wetland resilience and vulnerability to sea-level rise. Science Advances, 4(2), eaao3270.

Tonkin, T. N., Midgley, N. G., Graham, D. J., & Labadz, J. C. (2014). The potential of small unmanned aircraft systems and structure-from-motion for topographic surveys: A test of emerging integrated approaches at Cwm Idwal, North Wales. Geomorphology, 226, 35-43.

Vousdoukas, M. I., Mentaschi, L., Voukouvalas, E., Verlaan, M., Jevrejeva, S., Jackson, L. P., & Feyen, L. (2018). Global probabilistic projections of extreme sea levels show intensification of coastal flood hazard. Nature Communications, 9: 2360.

Westoby, M. J., Brasington, J., Glasser, N. F., Hambrey, M. J., & Reynolds, J. M. (2012). 'Structure-from-Motion'photogrammetry: A low-cost, effective tool for geoscience applications. Geomorphology, 179, 300-314.

Woodroffe, C. D. (2018). Mangrove response to sea level rise: palaeoecological insights from macrotidal systems in northern Australia. Marine and Freshwater Research, 69(6), 917-932.

Yamamoto, K. H., Anderson, S. J., & Sutton, P. C. (2015). Measuring the effects of morphological changes to sea turtle nesting beaches over time with LiDAR data. Journal of Sea Research, 104, 9-15.

Zollo, D., and Gohalwar, R., 2016. Piksi ™ for UAV aerial surveying: RTK direct georeferencing with Swift Navigation's Piksi GPS receiver [White Paper]. Retreived June 28, 2018, from SwiftNav: https://www.swiftnav.com/whitepaper/uav-survey-whitepaper