University of Portsmouth - Deimos Space UK Sediment Disturbance Project

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Report prepared for Sussex IFCA, July 2021

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1. Bait collection impacts summary

1.1 Digging

Bait digging involves manually turning over the sediment to extract target species and is usually carried out with a garden fork (Watson et al., 2007). Hand digging in sedimentary habitats can impact the habitat, target species, and non-target species.

Habitat impacts:

Topography

- A key impact is changes in sediment topography (dug holes/trenches and mounds of spoil). The persistence of sediment scarring can vary with hydrodynamic regime, sediment type, and storminess (e.g. Dernie et al., 2003a; Fearnley et al., 2013; Sypitkowski et al., 2010) and whether holes are back-filled (e.g. Coates, 1983). At a low energy site in the Solent, for example, experimental 1m^2 digging scars were observable on foot for 83 ± 30 days SD (Watson et al., 2017b).

- Dernie et al. (2003a) found that depth of water that remained in disturbed pits decreased over time and the rate of infill correlated with the rate of recovery in numbers of individuals. The authors suggested infilling rate could potentially be used to predict community recovery.

Sediment characteristics

- Statistically significant changes (Anderson and Meyer, 1986; Carvalho et al., 2013) and indications (McLusky et al., 1983; Edwards et al., 1992; Watson et al. 2017b) of sediment coarsening have been identified previously in relation to digging. Though others have not identified statistically significant changes in sediment grain size (Sherman and Coull, 1980; Dernie et al., 2003b).

- Reduced organic content of sediments has been observed (Anderson and Meyer, 1986; significant difference identified by Watson et al. 2017b), although other studies did not identify statistically significant changes in organic content in relation to digging disturbance (Sherman and Coull, 1980; Dernie et al., 2003a,b; Carvalho et al., 2013). McLusky et al. (1983) identified higher organic content in pits, which can trap organic debris, and lower organic content in mounds of spoil subject to erosion.

- Increase in metal concentration (lead at the sediment surface) and bioavailability (cadmium in porewater) has also been linked to bait digging (Howell, 1985).

Target species impacts:

Arenicola marina

- Evidence of overexploitation leading to population crash (Olive 1993). Following initial reductions in numbers across three experiments, McLusky et al. (1983) identified faster repopulation of dug basins (recovery by 15, 24, and 51 days) and infilled trenches (recovery by 22 days) than recovery in mounds (50% recovery by 80 days or more).

Alitta virens

- Higher densities, but lower average weight have been observed for king ragworm *Alitta virens* at dug sites compared to undug sites, with no difference in percentage maturity (Watson et al., 2007).

Non-target impacts:

Macrofauna

- Reduced number of taxa (e.g. Brown and Herbert Wilson Jr., 1997; Carvalho et al., 2013) and changes in assemblage heterogeneity (e.g. Carvalho et al., 2013; Watson et al., 2017b) have been identified in relation to digging.

- There is evidence for negative impacts of digging on invertebrate bird prey species (e.g. Shepherd and Boates, 1999), including commercially targeted *Cerastoderma edule* (e.g. Jackson and James 1979; Watson et al., 2007).

Birds

- Inconsistent findings for effects on bird feeding have been identified, with no significant differences identified for curlew foraging in areas that had been bait dug (Liley et al., 2012), but with a reduced foraging efficiency by 68.5% for semipalmated sandpipers, potentially related to reduced prey by bait harvesting and interference with prey cues caused by the disturbed sediments (Shepherd and Boates, 1999).

1.2 Accessing/crossing shore (including trampling)

Further to the impacts of digging, accessing and crossing the shore and trampling associated with bait digging can also impact the sedimentary habitat, target, and non-target species.

Habitat impacts:

Topography

- Trampling of soft sediments can result in changes in topography. Rossi et al. (2007) observed a higher average (not significant) % depressions in a trampled mudflat site than controls at ~18 days following trampling, but not at 40 days. The authors highlighted the potential for standing pools and sediment compaction to influence biogeochemical processes.

Sediment characteristics

- Trampling effects on microalgae, as determined from assessments of chlorophyll, have been identified, including a decrease in chlorophyll in intensely trampled plots (Wynberg and Branch, 1997) and a negative correlation in microalgal biomass with percentage of depressions in trampled plots, but not in controlled plots (Rossi et al 2007).

Target species impacts:

Arenicola marina

- At a location impacted by trampling, larger variability in the number of *Arenicola* burrows among impacted sites was identified compared to control sites (Rossi et al., 2007).

Non-target impacts:

Macrofauna

- Trampling-induced changes in total macrofaunal numbers (Wynberg and Branch, 1997) and measures of community composition have been identified (Chandrasekara and Frid, 1996; Rossi et al., 2007).

- Negative effects of trampling have been observed on adult numbers of *Cerastoderma edule* and *Macoma balthica* (now *Limecola balthica*), likely resulting from direct damage or burial (Rossi et al., 2007). Decreases in polychaetes *Scoloplos armiger* and *Capitella capitata* have also been identified as a result of trampling (Chandrasekara and Frid, 1996). Each of these species are bird prey, with *C. edule* representing a commercially valuable species.

- Winter community structure was found to revert and *Capitella* abundance increased in the absence of summer trampling (Chandrasekara and Frid, 1996).

Birds

- The presence of bait harvesters on the shore can cause disturbance to birds (Townshend and O'Connor, 1993; Morrison, 2006; Ravenscroft et al., 2007; Cox and Ravenscroft, 2009; Liley et al., 2012; Fearnley et al., 2013). A significant negative correlation between number of waders and number of bait collectors has been identified (Watson et al., 2017b) as well as significant effects of harvester presence on curlew foraging activity (% of birds foraging), but not on other curlew foraging variables (Navedo and Masero, 2007).

Seals

- Disturbance caused by bait collectors and noise near seal haul-outs may increase seal alertness and cause them to swim away (Gaspari, 1994).

2. Total Ecosystem Management of the Intertidal Habitat (TEMITH)

Funded by the European Space Agency, TEMITH was an inter-disciplinary collaboration between Deimos Space UK and the University of Portsmouth, combining expertise in Earth Observation (EO) and Deep Learning for feature extraction and ecology, respectively. With a statutory duty to protect and conserve intertidal habitats, Natural England and the Southern Inshore Fisheries and Conservation Authority were key partners associated with the project and provided valuable input on data needs and user requirements. The TEMITH project aimed to design and prototype a solution to monitor pressures in the intertidal habitat in the Solent region using EO data in addition to existing sources of information. From a proposed four pressures (algal mats, litter, sediment disturbance, wastewater plumes), two became the primary focus for model development as the project progressed (sediment disturbance and algal mats).

2.1 Data sources

Sediment scarring resulting from different activities can be readily observed using aerial imagery. For TEMITH, the detection of intertidal sediment disturbance resulting from digging, shellfish dredging, and boat scars was prioritised (Figure 1), including detection from both drone imagery/aerial photography and satellite imagery. The priority data type for the development of the deep learning models used in TEMITH were mapped polygons. Priority datasets for digging were acquired for the Solent (Watson et al. 2013; White et al. 2019), Poole Harbour (Fearnley et al., 2013), and Wales (Perrins et al., 2020). One dredging dataset was acquired from Poole Harbour (Clarke et al., 2019), however classifications were not in a polygon format and the associated drone imagery was used for testing only. Additional labelling of available drone imagery, Channel Coastal Observatory (CCO) aerial photography, and high resolution satellite imagery was performed to produce more training data for digging, shellfish dredging, and boat scars. For digging, this was based on previous experience and methods (White et al., 2019). Dredging scars identified on foot during a 2018 University of Portsmouth (UoP) survey of bait collection that were visible in the corresponding drone imagery provided a basis for identifying the morphology of dredging scars. Examination of CCO aerial photography in relation to the distribution of fishing activities in the Solent and correspondence with relevant organisations, including Southern and Sussex IFCAs, further fed into a familiarisation with scarring types and confidence assessments for dredging scars. The Southern IFCA European Marine Site Habitats Regulations Assessments, which described gear types and included fishing sightings maps were also useful resources to inform labelling. Boat scars were also labelled using existing high resolution imagery. This included 'mooring' scars, often with a circular scarring feature, broader 'berth' scars at associated structures, and 'independent' scars that were consistent with boat scars, but independent of any mooring or structure or scars in areas with likely boat traffic that were not readily distinguishable as a specific boat scar type. Linear keel drags were distinguished from linear dredging scars using a confidence assessment. Key considerations in labelling were the morphology and context of the scarring. Table 1 depicts the high confidence descriptions for digging, dredging, and keel drags as employed for labelling. While the listed characteristics supported decisions on labelling, expert judgement was also used, including discussions between Research Associate and PI and seeking advice externally (IFCAs).

Table 1. High confidence descriptions for digging, shellfish dredging, and keel drags as employed for TEMITH labelling of high resolution imagery. Digging description from White et al., (2019).

Digging	Dredging	Keel drag
Mottled patterning: -Pits/mounds distinguishable -Patchy/irregular distribution on shore -Anoxic or gravelly sediments may be evident at surface -Features may be less distinct than above, but continuous with dug area and appearance and features are distinct from natural. Individual pits: Pit is near confidently dug AND consistent with dug area appearance AND is distinct from other manmade (e.g. boat marks) or natural features. May have pit/mound.	-Linear scarring in known fishing area -Width of clear individual tracks ~0.82-1.5m -No tight turns -Regular, overlapping of the same type -Features less distinct than above, but continuous with/among confident dredging and consistent in appearance, with no context to suggest keel drag or natural scar	-Linear scarring ruled out as dredging due to morphology (as below) and context (likely from boat traffic near mooring, marina, channel, pontoon or potentially a tidal/drainage channel) -Linear scar distinguishable from natural tidal/drainage channels -No known fishing at site -Clear scars <82cm width -Scar may reflect a tight turn -Linear scarring is clearly distinguishable (readily visible through colour contrasts) or less distinguishable but continuous with/adjacent to clearly distinguishable scarring and consistent in appearance

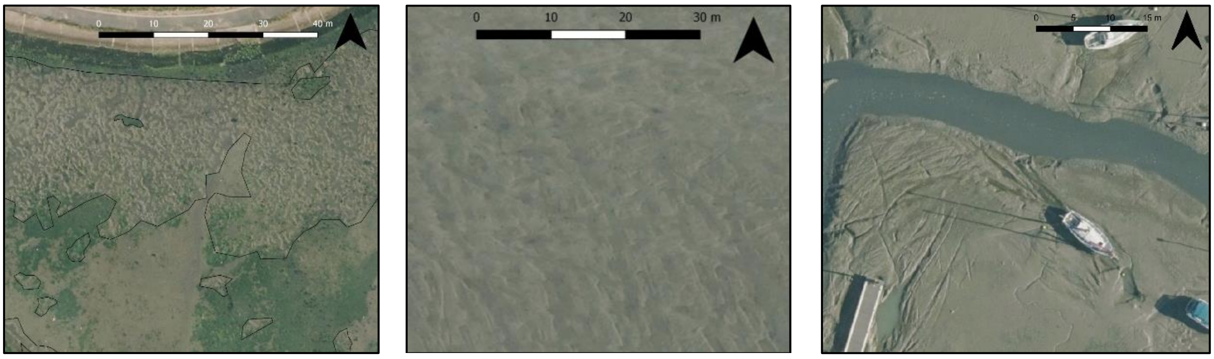


Figure 1. Sediment scarring from digging disturbance, shellfish dredging, and boats (left to right). Images: Copyright New Forest District Council. Image courtesy of the Channel Coastal Observatory.

Existing datasets and direct labelling of satellite imagery were used to train models for detection from satellite imagery. The existing datasets were linked to satellite imagery as close as possible to the collection date, however a maximum of 4 weeks away was deemed appropriate in the context of previous findings for the persistence of digging scars at a low energy site in the Solent (Watson et al., 2017b). The existing disturbance polygon datasets applied to corresponding satellite imagery were adjusted or polygons removed according to visibility in the imagery. Direct manual labelling of clips from additional satellite images was performed for images prioritised according to tidal exposure, site familiarity (with known sediment disturbance activity), and availability of high-resolution imagery and, in some cases, existing polygon datasets to help ground-truth the labelling process. With respect to the high-resolution imagery availability, this was imagery (e.g. drone or CCO aerial photography) within a year of the satellite image.

2.2 Model training

Feature extraction from the EO data was undertaken using Convolutional Neural Networks (CNNs), which is a technique that belongs to the field of Deep Learning, and Deep Learning is a specific field of machine learning. With 'deep' referring to networks of potentially many hidden layers. The approach selected has allowed for classification at the pixel level, providing detailed outputs for the extent of features of interest. Where confidence was indicated, high confidence polygons were selected for model training. Details of the datasets used in model training are presented in Table 2 for drone/aerial photography models and in Table 3 for satellite models. Six CNN models were trained to achieve detections of the three disturbance activities (bait digging, shellfish dredging, and boating) from drone imagery/aerial photography and from high resolution satellite imagery.

Table 2. Datasets used to train models for sediment disturbance (digging, shellfish dredging, boat scars) detection from drone imagery/aerial photography (resolution indicated 'res'). Number of sites/locations indicated may not have been used for each of the scarring types.

Imagery source	Labels source	Date	Type (res)	# Sites	Used in training
White et al. (2019)	**Digging** (White et al., 2019); **dredging and boats** (TEMITH manual labelling)	26-29/06/18	Drone ~2-3cm	3 (Solent harbours)	Yes
Copyright New Forest District Council. Image courtesy of the Channel Coastal Observatory. https://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/.	**Digging** (White et al. 2019; TEMITH manual labelling); **dredging and boats** (TEMITH manual labelling)	18/08 and 23-24/08/16	Aerial photo 10cm	4 (Solent harbours; Southampton Water)	Yes
Perrins et al. (2020)	**Digging** (Perrins et al. 2020); **boats** (TEMITH manual labelling)	09/19-11/19	Drone ~3cm	10 (Wales)	Yes
Fearnley, et al. (2013).	**Digging** (Fearnley et al. 2013)	11/12-02/13	Drone ~6cm	1 (Poole Harbour)	Yes
Clarke et al. (2019)	**Dredging -** not in a polygon format	23/11/15	Drone ~3.5cm	1 (Poole Harbour)	No (used in test)
Contains, or is based on, information supplied by Natural England. Terms of use: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/775365/NE-terms-ofuse.pdf	**Boats** (TEMITH manual labelling)	03/10/18	Drone ~3cm	1 (Langstone Harbour)	Yes

Table 3. Datasets used to train models for detection of sediment disturbance from satellite imagery. The satellite (Sat.) imagery resolution (res) is pan-sharpened and collected from WorldView-2 (WV2), WorldView-3 (WV3), GeoEye-1 (GE1), and QuickBird2 (QB2). Locations (loc.) are harbours (Langstone/LH, Chichester/CH, Portsmouth/PH) and Southampton Water/SW.

Imagery source	Labels source/ scarring type	Loc.	Date	Sat. (res)	Sat. date
Aerial Photography - Copyright New Forest District Council. Image courtesy of the Channel Coastal Observatory (CCO). https://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/.	Digging - White et al. (2019)	LH	18/08 and 23/08/16	WV3 (31cm)	23/08/16
		CH	23/08/16	GE1 (46cm)	23/09/16
N/A	Digging – Watson et al. (2013)	CH	14/09/11	QB2 (61cm)	19/08/11
Aerial Photography - CCO (row 1 for full reference)	Digging - TEMITH manual labelling	LH	18/08 and 23/08/16	WV3 (31cm)	23/08/16
N/A	Digging - TEMITH manual labelling - satellite	LH	N/A	WV2 (46cm)	27/06/16
		LH	N/A	WV2 (46cm)	09/08/19

		PH	N/A	GE1 (46cm)	14/09/17
N/A	Dredging - TEMITH Manual labelling - satellite	SW	N/A	GE1 (46cm)	14/09/17
		SW	N/A	WV2 (46cm)	06/06/14
Aerial Photography - CCO (row 1 for full reference)	Boats - TEMITH manual labelling	CH	23/08/16	GE1 (46cm)	23/09/16
		LH	18/08 and 23/08/16	WV3 (31cm)	23/08/16
Drone imagery - Contains, or is based on, information supplied by Natural England. Terms of use: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/775365/NE-terms-of-use.pdf		CH	03/09/19	WV3 (31cm)	04/09/19
Aerial Photography - CCO (row 1 for full reference)		SW	23-24/08/16	GE1 (46cm)	23/09/16
N/A	Boats - TEMITH manual labelling - satellite	LH	N/A	WV2 (46cm)	27/06/16
		SW	N/A	GE1 (46cm)	14/09/17

2.3 Evaluation

Model detections (vector outputs and raster probabilities for correct pixel classification) in validation clips and test images were considered in relation to the training labels or known areas of disturbance. Validation clips are subsamples from the training dataset that are unused in model training, therefore model detections in these clips reflect model performance, as for test areas that are not used in training. The ability of the models to detect broad areas of continuous disturbance and discrete scarring features, different scarring morphologies and confidence levels, and to distinguish from other scarring types and non-disturbance features was considered and is summarised in Table 4.

A virtual evaluation workshop with prospective end users was also held for evaluation of the outputs, their utility, and requirements for the development of the TEMITH service. Example global maps were shared, showing classifications for areas used in training (indicating the location of validation clips where applicable) and served to demonstrate the site-level classifications feasible from the TEMITH service. The validation clips were also shared for the sediment disturbance models to demonstrate model detection capabilities in different images and locations. Training data inputs were shared in addition to the modelled outputs.

Table 4. Summary of the internal evaluation of TEMITH sediment disturbance model capabilities determined from validation clips (subsampled labelled clips from training data sites and not used in training) and test imagery.

Model	Capabilities	Limitations
Digging – drone/aerial	Detects: -broad, continuous areas -discrete patches -within areas with algal cover -general (imperfect) distinction from mooring scars and dredging	-incomplete detections -false detections (other features and scarring types)
Dredging – drone/aerial	Detects: -separate dredge tracks -broader areas of disturbance -partial detection of spiral dredging	-incomplete detections -limited detection of visible lower confidence features
Boats – drone/aerial	Detects scars at moorings: -with/without boats present -at different style moorings -partially submerged adjacent to the water's edge Detects: -continuous and discrete disturbance -distinction from digging achieved	-incomplete detections -detections on land -limited detection for other mooring style unknown to model

	-range of boat scar morphologies	
Digging – satellite	Detects: -high confidence digging (broad areas and smaller patches)	-incomplete detections -limited detection of lower confidence digging
Dredging – satellite	Detects: -individual dredging scars -potential dredge scars underwater -incomplete detection of heavily disturbed areas with overlapping scarring	-incomplete detections -false detections of other linear features (e.g. natural channels) and saltmarsh areas
Boats – satellite	Detects scars at moorings: -empty moorings with full scarring feature (with/without boat present) -empty mooring with standing pool only -able to distinguish natural channels within scarring feature in some cases	-inconsistent detection of keel drags -potential detection of boat context versus scarring (e.g. detections around boats on land), however not all boats detected

Successful detection of a range of scarring morphologies linked to key activities contributing to disturbance of intertidal sedimentary habitats was achieved by the models. To improve detection of disturbance in different scenarios (expand applicability) and to refine the models' abilities to distinguish from other scarring types and non-disturbance classes, the evaluation indicated that more training data were required representing additional scarring morphologies and a greater range of contexts.

3. Post-TEMITH digging model revision

The TEMITH model for detection of bait digging disturbance from drone imagery/aerial photography was taken forward for further development in 2021. The model underwent three rounds of retraining with additional training data clips/labels produced using CCO imagery to reduce false positive and increase true positive detections (Table 5).

Table 5. Actions taken for post-TEMITH model revision.

Step	Action	Description
1	TEMITH model test	Full harbour classifications of 2013 and 2016 CCO imagery.
2	Round 1 labelling	New background clips and digging clips/labels produced based on model performance in TEMITH test images, TEMITH global maps for Dell Quay, and whole harbour classifications from Step 1.
3	Round 1 retraining	Existing efficientnetb4-UNet model (final model output of TEMITH project) fine-tuned with all training data collected and generated during the project, plus data from round 1 labelling
4	Model test	Full harbour classifications of 2016 and 2020 CCO imagery.
5	Round 2 labelling	New background clips and digging clips/labels produced based on model performance in step 4.
6	Round 2 retraining	Model from round 1 training fine-tuned with all training data collected and generated during the project, plus data from round 1 and 2 labelling.
7	Model tests	Four model versions - full harbour classifications of 2013, 2016 and 2020 CCO imagery. One model version – priority location classifications of 2013, 2016 and 2020 CCO imagery.
8	Round 3 labelling	New background clips and digging clips/labels produced based on performance of multiple models in step 7.
9	Round 3 retraining	New model trained from scratch, with the objective to eliminate unbalance in the data towards UAV data collected during TEMITH project. Same model architecture as before using only CCO training data collected and generated during the project, plus data from round 1, 2 and 3 labelling. Refined image

		augmentation technique to simulate more diversified data from available training set.
10	Model tests	Four model versions – priority location classifications of 2013, 2016 and 2020 CCO imagery.
11	Model selection	Selection of best model from step 10 in terms of digging coverage balanced against minimising false detections. The selected model was then compared against earlier model versions and a combination of two models, one from step 9 and one from step 6, was considered the most appropriate for representing digging coverage while limiting the overall false detections compared to other models.

In reviewing whole-harbour model detections of digging, some areas and specific sites were considered relative to a map previously shared by Sussex IFCA and Chichester Harbour Conservancy data presented in a Maritime Archaeology Trust report (Maritime Archaeology Trust, 2015) for bait collection distribution. Also, detections in Dell Quay and northeast Langstone Harbour were considered, as these areas were previously surveyed and assessed by the University of Portsmouth. Detections outside of known areas of disturbance fed into a harbour-wide consideration of the level of false positive detections by different model versions.

Round 1 and 2 digging clips were prioritised by location and temporal coverage to improve the model's ability to generalise, using areas with high confidence digging and a range of image conditions across years of CCO imagery. The aim was to have 2005, 2008, 2013, 2016, and 2020 imagery represented in the training dataset for Dell Quay (within the AOI), at least one site outside of Chichester Harbour previously surveyed by UoP for digging disturbance (two high confidence/known sites), and at least one other disturbed site outside of Chichester Harbour. Scarring consistent with digging at the latter sites was corroborated by G. Watson and sites mentioned for bait digging in online materials (e.g. reports/articles by nature groups/stakeholder partnerships, on fishing forums, or in news articles). Round 3 digging clips/labels were prioritised to improve the balance in representation of 2013 and 2020 CCO imagery against 2016 already represented by full site assessments/labels produced by White et al. (2019) and for TEMITH. Clips were derived from the surveyed sites (and nearby) represented in the White et al. (2019) dataset, and another Solent site with large swathes of digging disturbance.

Background clips were produced to address false positive detections and included representation of features such as non-digging disturbance scars, features with roughened texture (e.g. saltmarsh features, tidal channel edges, fields, breaking of the water surface), and other natural patterning. Background clips were primarily produced for TEMITH test images and Chichester Harbour 2013, 2016, and 2020 CCO imagery to directly address issues, with some additional representation of detected features in other non-test CCO imagery from the Solent. The spatio-temporal coverage of the clips produced is summarised in Table 6.

Table 6. Spatio-temporal distribution of new training clips produced using Channel Coastal Observatory aerial photography to improve model detections of digging and to reduce false detections of background.

Year	Chichester Harbour digging	Solent digging	Chichester Harbour background	Solent background
2020	1	16	6	2
2016	0	3	8	4
2013	2	12	3	7
2008	1	2	0	0
2005	0	1	0	1

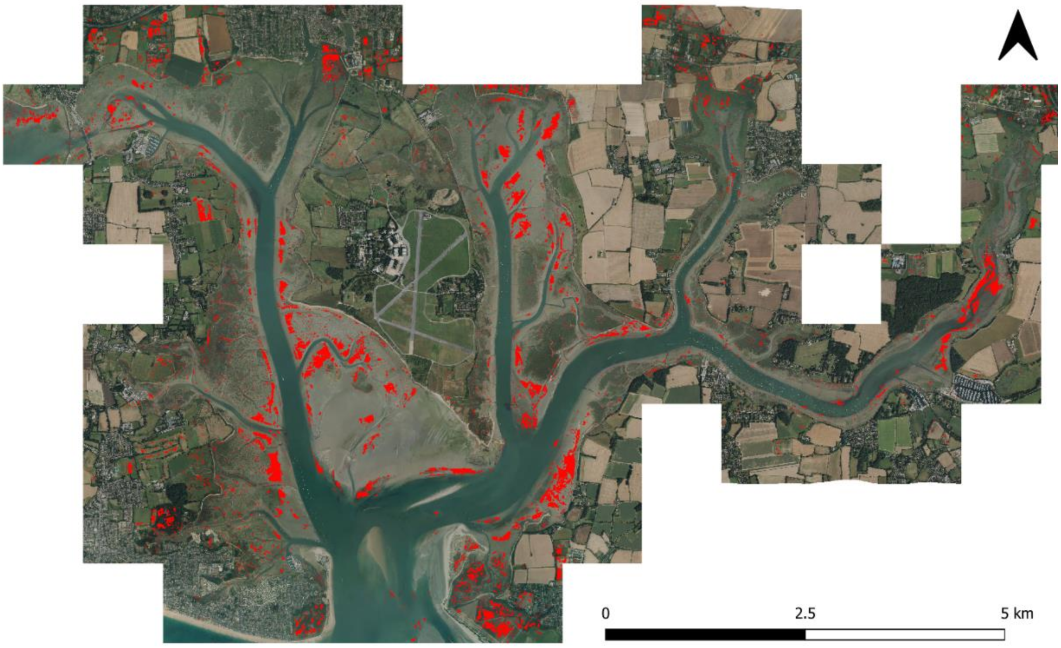
4. Selected model performance

The two models selected for full harbour digging assessment were derived from two different training datasets. Model A (from Table 5; Step 6) was derived from the digging datasets used for TEMITH (Table 2) plus the clips produced in the first two rounds of labelling here. Model B (from Table 5; Step 9) was trained using just CCO imagery labels. While substantial improvements in the model have been made

(Figure 2), review of the outputs in key locations indicated that not all digging is being detected and false positives still occur.

2016 imagery courtesy of Channel Coastal Observatory. Copyright New Forest District Council.

Outputs from University of Portsmouth - Deimos Space UK sediment disturbance project.



2016 imagery courtesy of Channel Coastal Observatory. Copyright New Forest District Council.

Outputs from University of Portsmouth - Deimos Space UK sediment disturbance project.

Figure 2. Revision to the TEMITH model has substantially reduced false positive detections. Above) Model A (orange) and B (red). Below) Test of starting TEMITH model on full harbour.

Different lighting conditions and different sensors can contribute to differences in the performance of the model for the detection of digging. The detection of digging represents a difficult modelling problem, in that there are different digging morphologies and the task for the model is to learn to detect differences in texture rather than a readily visible object that can be easily distinguished from the background (e.g. a house). Digging can represent a small feature of few pixels relative to the whole image, adding to this challenge. The presence of background features within labelled digging polygons can also present a challenge to the precision of the model. Example outputs for Model A and Model B combined across three CCO imagery years demonstrate variability in lighting, digging morphology, and tidal height, which can contribute to variability in model performance and comparability among years (Figure 3). The 2016 imagery had a much greater representation in the training dataset, although additional clips for the other years had been produced to help balance this. Despite the limitations at this stage, there is still more that can be done to improve the model, including increasing training data quality and quantity. On the modelling side, there are many more things that can be tried, but this requires trial and error and training Convolutional Neural Networks is a lengthy process.

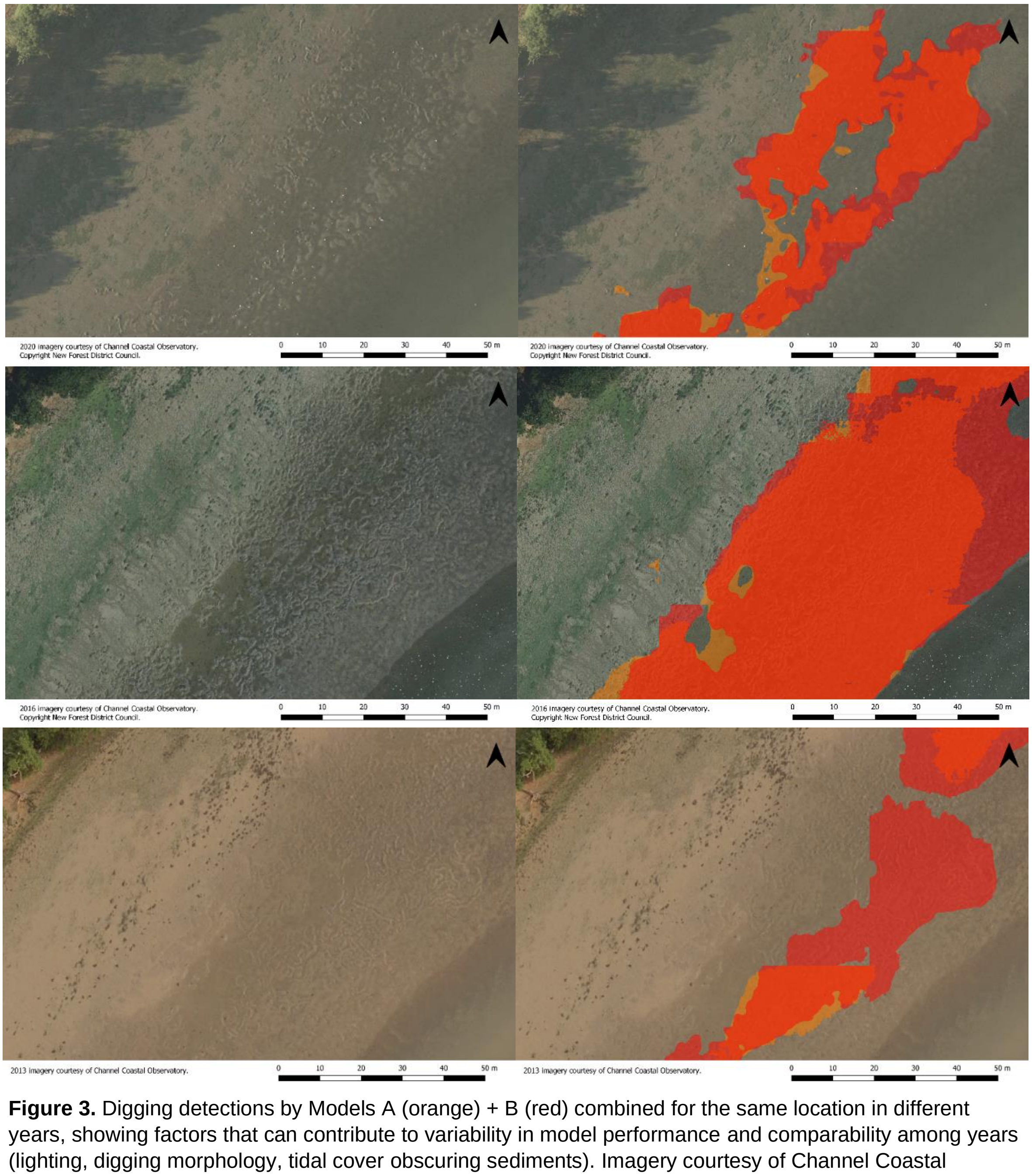


Figure 3. Digging detections by Models A (orange) + B (red) combined for the same location in different years, showing factors that can contribute to variability in model performance and comparability among years (lighting, digging morphology, tidal cover obscuring sediments). Imagery courtesy of Channel Coastal Observatory.

5. Temporal assessment of digging disturbance – Dell Quay

5.1 Introduction

Dell Quay, Chichester Harbour, is selected for a case study to examine digging disturbance over time using Convolutional Neural Network (CNN) models. Bait digging is known to have occurred over time here, with several assessments of digging at this site made since the early 2000s by the University of Portsmouth (Watson et al., 2007; Watson et al. 2015; Watson et al., 2017a,b; White et al., 2019).

To assess the temporal patterns in digging at Dell Quay, an evaluation of the CNN model outputs was first performed using expert judgment to identify detections consistent with digging. This was appropriate due to observed limitations in the accuracy of the CNNs (Section 4). Temporal comparisons of coverage and the location of digging disturbance were then made based on the confirmed model detections.

5.2 Methods

To confirm or reject each feature detected by the combined Model A and Model B CNN outputs (Section 4), model classifications were first converted from raster to vector format and combined for the two models. All spatial procedures and analyses were performed in QGIS using the British National Grid coordinate system. Model A and Model B classification raster files for each image tile (74 across the harbour) were converted to shapefiles and merged for each year-model combination (years 2013, 2016, 2020). The shapefiles were checked for valid vector geometry and geometries were fixed using the QGIS processing toolbox. The 'Union' and 'Dissolve' geoprocessing tools were used to combine the two model outputs for a given year and to remove internal boundaries within polygons representing model detections. The geometry tool 'Multipart to Singleparts' was used to separate out each polygon as an individual feature to which attributes could be assigned, as these were merged as one feature during the 'Dissolve' procedure. The field calculator geometry tool '$area' was used to calculate area covered by each polygon.

To evaluate the model outputs at Dell Quay (corresponding with CCO image tile SU8302), detections <1m^2 were first filtered out for practical reasons. Assessments were then made of the merged Model A+B output polygons overlaying the image tile for the respective year by scrolling at a scale of 1:300 and assigning one of the categories in Table 7. Each 'Yes' and 'Mixed' polygon was revisited for confirmation following the initial scroll. A final 1:600 scale scroll was performed to visualise and confirm all assignments.

Table 7. Assigned categories for model outputs at Dell Quay.

Assessment	Description
Yes	Confidently consistent with digging; majority looks like digging
Mixed	Contains consistent with digging, but also contains a large amount ($\geq$~25%) of 'uncertain'
Uncertain	Does not contain high confidence consistent with digging, but disturbance/patterning observable in sediments
No	Confidently not digging

To help identify locations impacted by bait digging over time at Dell Quay, the 'Intersection' geoprocessing tool was used to compare overlap in the 'Yes'/'Mixed' polygons between pairs of years. The 'Mixed' polygon areas were taken at face value for comparisons (area was not scaled down based on coverage by digging vs. 'uncertain').

5.3 Results and discussion

Merged Model A+B detections (including <1m^2) and their assessment as digging ($\geq$1m^2) are depicted for Dell Quay in 2020 (Figure 4), 2016 (Figure 5), and 2013 (Figure 6). The 'Yes' and 'Mixed' polygons, containing high confidence digging in full (Yes) or in part (Mixed) represented the majority of the area detected by the models for each of the years (2020 – 93.7% Yes, 3.01% Mixed; 2016 – 63.5% Yes, 26.8% Mixed; 2013 – 50.0% Yes, 37.6% Mixed), demonstrating the ability of the CNN models to detect these areas.

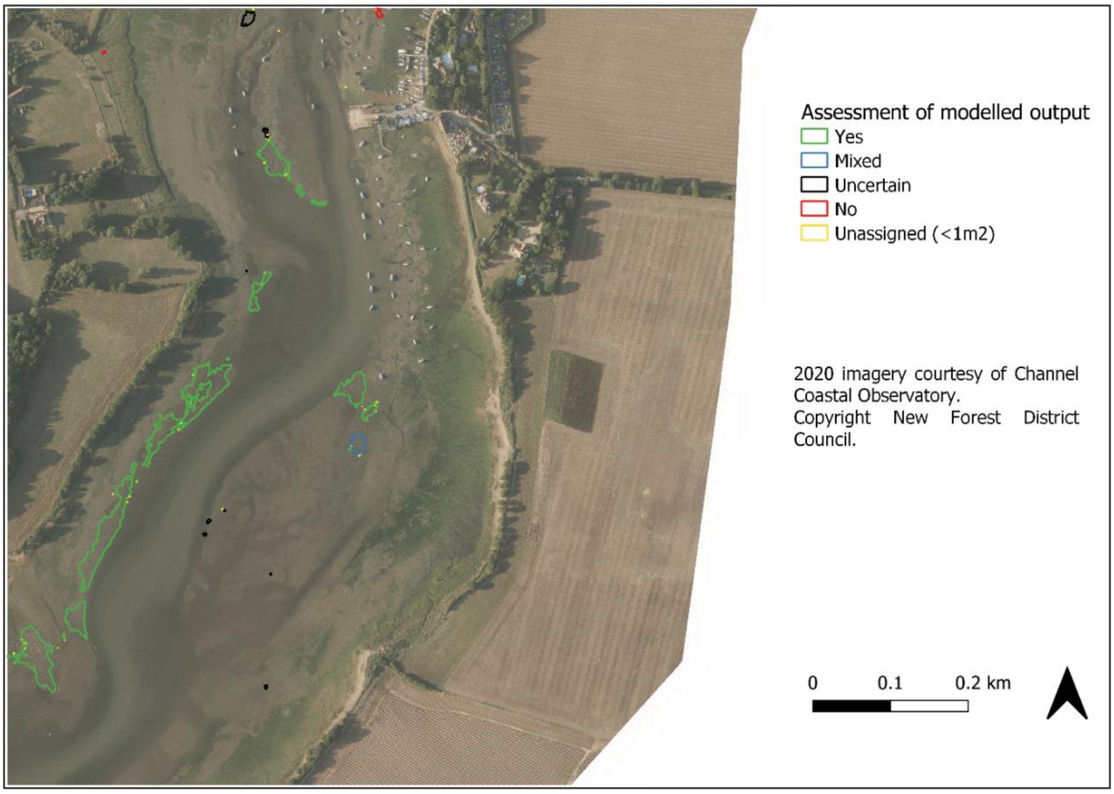


Figure 4. Assessment of Model A+B classifications of the August 20, 2020, imagery at Dell Quay.

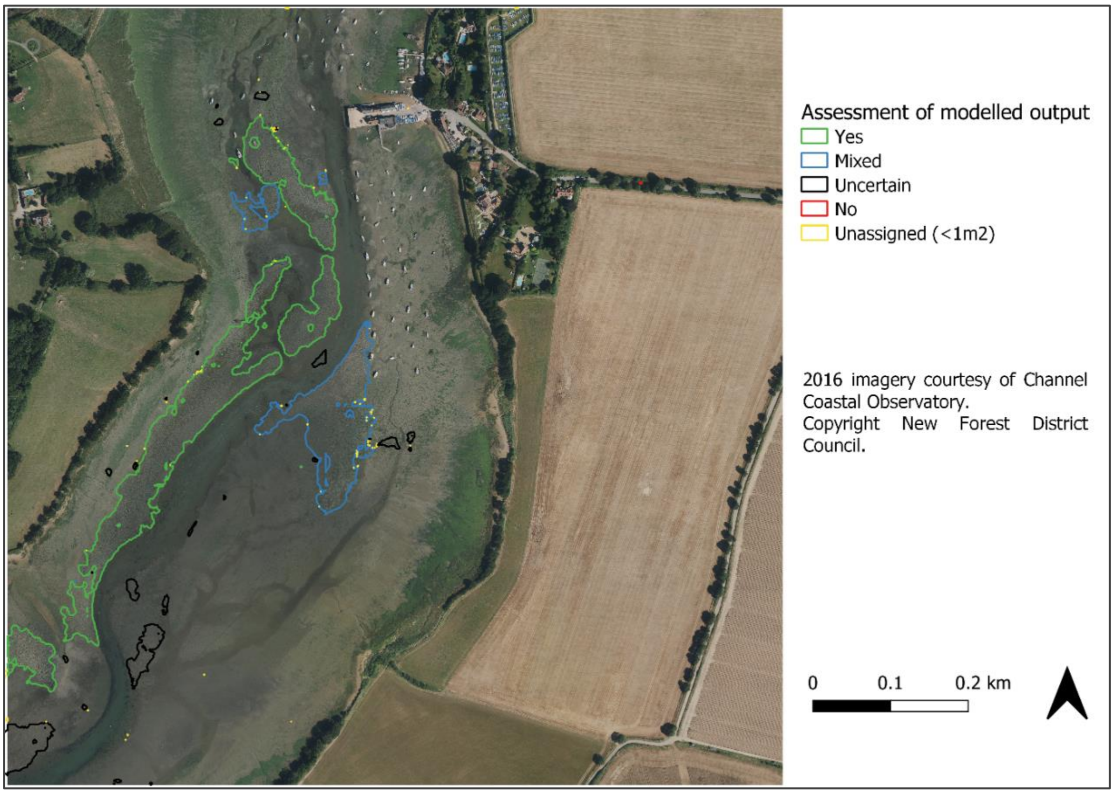


Figure 5. Assessment of Model A+B classifications of the August 23, 2016, imagery at Dell Quay.

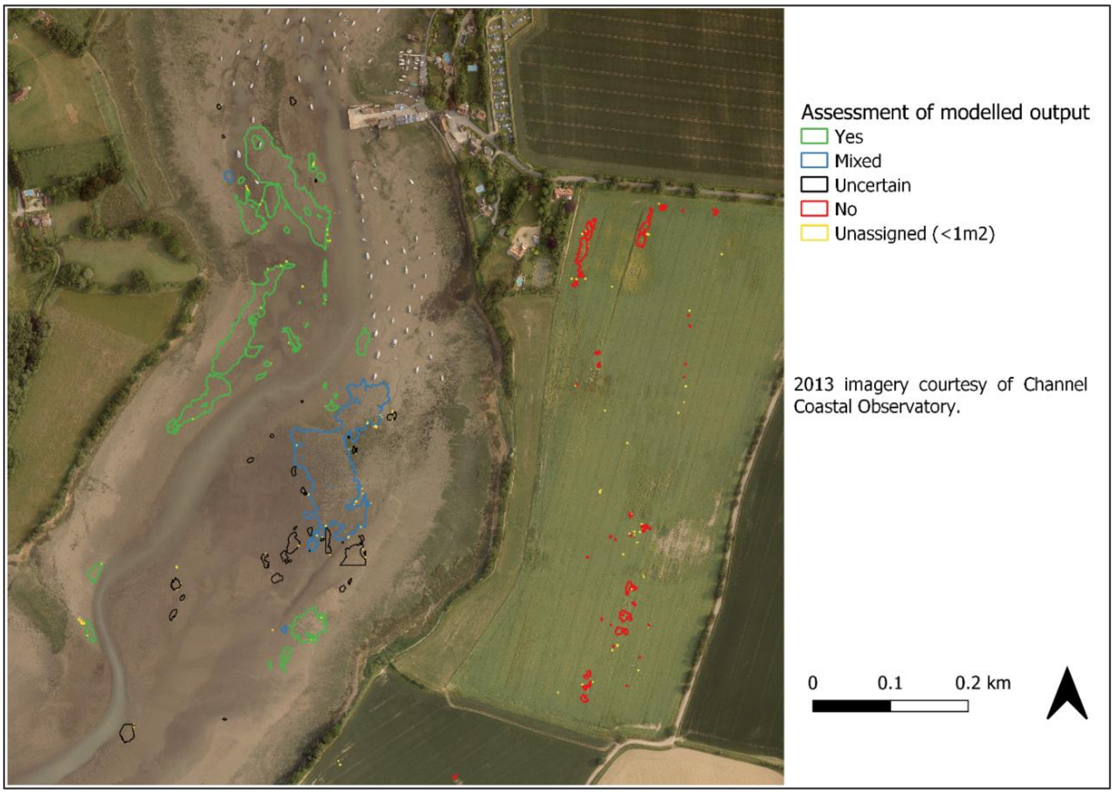


Figure 6. Assessment of Model A+B classifications of the June 26, 2013, imagery at Dell Quay.

The total area represented by each assessed category in Figures 4-6 is summarised in Figure 7. Absolute values for coverage by digging should be interpreted and compared with caution, as these may be affected by model performance (not all visible digging is being detected), differences in model performance between years, differences in shore height in the imagery between years, and the 'Mixed' polygons include coverage of potential non-digging areas.

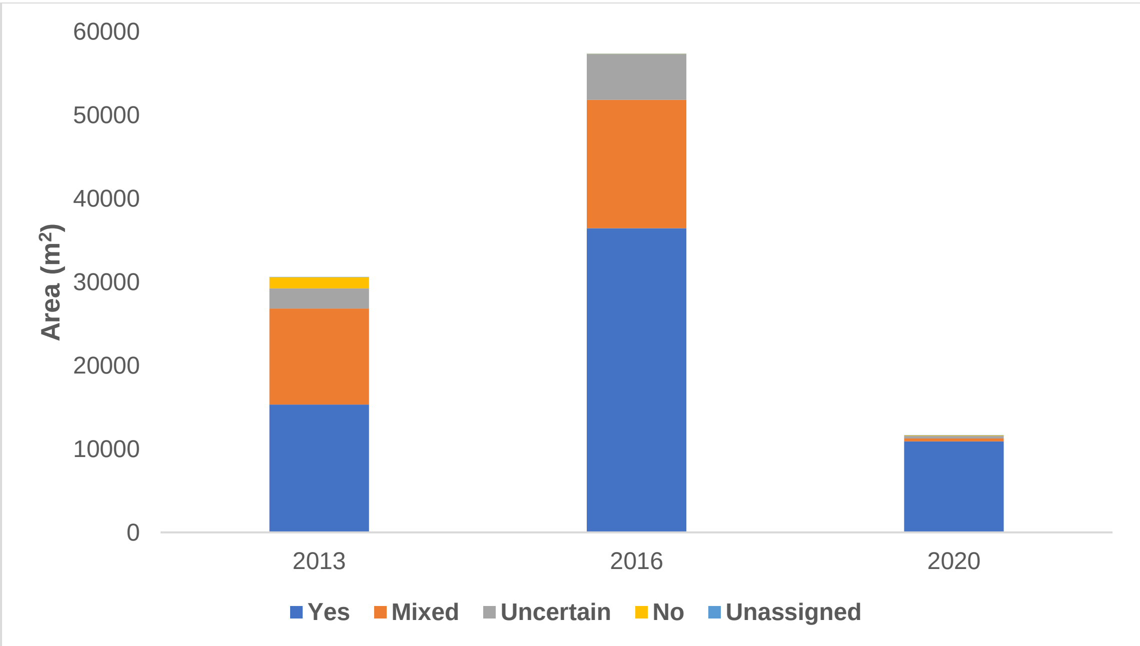


Figure 7. Area of coverage for each assessed category (Table 7) of the Model A+B classifications by year.

Notably, the model detections for 2020 had the lowest area of coverage, however the 2020 imagery had the lowest exposure of the intertidal area for assessment. The greatest amount of Yes/Mixed digging was detected in the 2016 imagery, for which the shore was more exposed than 2020. It is important to note, however, that the 2016 imagery and labels for this whole site (and other whole sites) were used in model training. Therefore, the model is likely to perform better than for the 2013 and 2020 Dell Quay imagery. With respect to the latter, the coverage detected for 2013 was lower in area than for 2016, although both image years had good exposure of the intertidal sediments. Large areas detected in 2016 (and some also in 2020) along the western side of the channel are not reflected in the 2013 detections, although disturbance is visible in the 2013 imagery. This is possibly due to the differences in lighting and morphology of the disturbance, affecting model performance and therefore overall coverage for 2013. Key contributors to the 'Uncertain' detections in 2016 and 2013 are areas of broad mottled patterning within or near the channel that could represent natural patterning or potentially washed out disturbance.

The 2013 and 2016 detections included large 'Mixed' areas, compared to 2020, with a large area detected on the eastern side of the channel contributing to this. Digging detections also occur in this area in the 2020 imagery, however, the extent of coverage (both detected by the model and visible in the imagery) is reduced compared to 2013 and 2016. This is particularly the case for the large southern/western portion of the 2013-2016 intersection (red patterning; Figure 8) on the east side of the channel, compared to 2020. The same area of the shore is exposed for each year here, indicating a potential change in digging distribution over time. A portion of the 2013 'Mixed' polygon here extends further southwest on the shore than in 2016 and may further support a retraction of the extent of the digging here over time (Figure 9). Most of the remaining areas detected as digging in 2013 and 2016, but not in 2020, occur in areas submerged or partially submerged in 2020, which would affect model detections. The intersection of 2020 with 2016 (black patterning; Figure 8) represents 92.5% of the total Yes/Mixed areas detected in 2020. This indicates that most of the digging detected in 2020 occurred in places that were dug previously. In contrast, the intersecting area between 2013 and 2020 (green patterning; Figure 8) only represents 29.9% of the Yes/Mixed areas detected in 2020, likely due to the missed detections along the western side of the channel in the 2013 imagery, as mentioned previously. Based on features in the 2013 imagery, other areas represented in 2020 and 2016, but not in the 2013 Yes/Mixed detections also appear to be missed or 'uncertain' detections. Therefore, the 2016-2020 intersection should not be interpreted as the distribution of digging activity into new areas since 2013. The 2013-2020 intersection (green patterning; Figure 8) occurs in areas also represented in 2016. These findings further affirm that certain areas within the site have been impacted by digging over time.

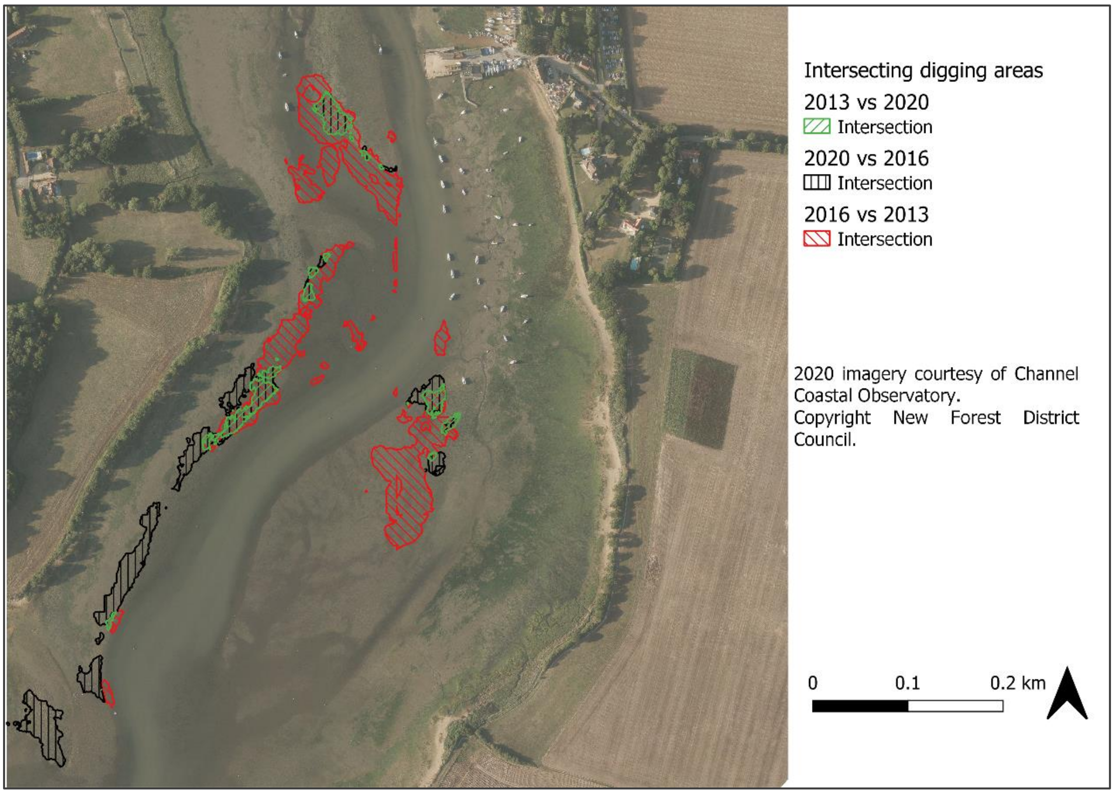


Figure 8. Pairwise areas of intersection for digging detections (assessed as 'Yes' or 'Mixed') over time for the years 2020, 2016, and 2013. Outputs demonstrate that digging occurs in historically dug areas, with some areas (with all three patterns overlapping or in proximity) common to all years, although this does not account for missed detections particularly evident in the 2013 outputs.

One area unique to 2013 with a large patch of digging was identified in the southeast of the image tile (Figure 9). Only small 'uncertain' features were visible in the other years of imagery for this area (only one clear disturbance feature detected by the model in 2020, but labelled 'uncertain' [Figure 4]). This could indicate a reduction of the extent of activity at this location within the site. With the exception of this unique larger area of digging in 2013, areas of coverage that are unique to a given year appear to be adjacent to or continuous with the areas detected in other years (Figure 9).

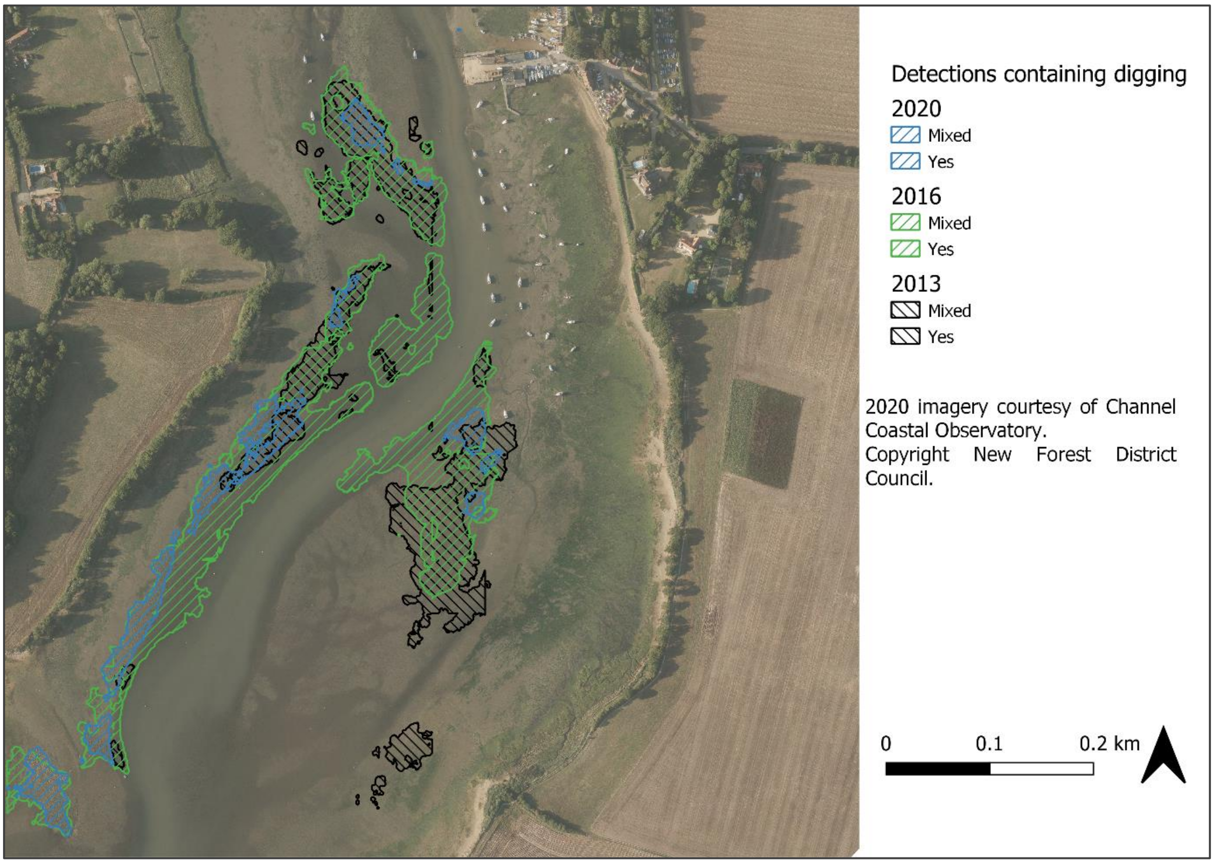


Figure 9. Distribution of Model A+B detections (for the three years) assessed as 'Mixed' and 'Yes' for containing features consistent with digging.

5.4 Summary

Although interpretations of coverage and changes in these need to be made in the context of the limitations in model performance and differences in shore height among years, the modelled outputs have revealed areas impacted by digging over time within the site. Additionally, potential changes in the distribution of digging were noted on the eastern side of the channel. A retraction from 2013 to 2020 in the southwest extent of an area south of the moorings was identified. A large area of disturbance detected only in 2013 and not in the other years indicated a reduction in digging extent for this area.

6. Maps of Chichester Harbour digging disturbance

6.1 Introduction

Visualising the distribution and extent of digging disturbance over broad geographic scales can help to characterise the potential impacts of the associated activities, particularly in relation to protected features of conservation concern. Maps for single timepoints provide a snapshot of activity, however there remain questions of the representativeness of that timepoint. Here, the harbour-wide distribution of digging disturbance was mapped for two years to build an understanding of its spatio-temporal extent. First, an evaluation of the CNN model outputs was performed using expert judgment to identify detections consistent with digging across the full harbour. This was appropriate due to observed limitations in the accuracy of the CNNs (Section 4). Maps of the evaluated model outputs were produced and temporal comparisons of digging location and coverage were made.

6.2 Methods

To enable mapping and temporal comparisons using just the model detected features of highest confidence and likelihood as digging (to exclude the false positives and lower confidence features), the combined Model A+B outputs (as described in section 5) were evaluated for the whole harbour by year

(2020 and 2016), using expert judgement. First, any features <1m^2 and/or outside of the Ordnance Survey SU_TidalWater shapefile boundary (OS Open Map – Local; Ordnance Survey data © Crown copyright and database right 2019) were filtered from the dataset and subsequently labelled 'Unassigned'. The remaining intertidal detections were evaluated at a scale of 1:300 (and broader for context) and assigned one of the categories in Table 8. These differ from the Table 7 assignments for Dell Quay by combining the 'Yes' and 'Mixed' categories, to flag detections containing digging irrespective of coverage, and by teasing out features that appear potentially consistent with digging from the 'Uncertain' category. The objective was to flag those detections most like digging in appearance for consideration, and therefore no distinction was made here between 'No' and other lower confidence 'Uncertain' patterning.

Table 8. Assigned categories for full harbour model outputs.

Assessment	Description
Yes	Contains feature(s) consistent in appearance with digging; highest confidence that it is likely digging
Potential	-Contains feature(s) that look like the appearance of digging (as standalone), but is not near other high confidence digging and there is uncertainty -Discrete feature near confident digging and consistent in appearance with the digging, but there is uncertainty -Excludes features that look potentially consistent with digging but are considered to be natural patterning based on surrounding context
X	-Other sediment scarring: washed out features not identifiable as digging as standalone; natural patterning; other confidently non-digging anthropogenic disturbance -Non-disturbance features

With respect to natural patterning, regularity and consistency in patterning on the mudflats across broad extents and in association with natural features (e.g. saltmarsh, channels) helped to differentiate likely natural patterning from potential digging in the evaluation. In some areas, the regularity of the wider patterning could not be determined and therefore features potentially consistent with digging against this backdrop were assigned 'Potential', but may reflect natural patterning. Other features in this category included likely digging but with a lower confidence, features that could represent either digging or potentially other scars (e.g. boat scars) or other features on the shore with an appearance that could not be ruled out as digging. Therefore, the 'Potential' category is likely to include a mix of digging and non-digging features and should be interpreted in this context. Coverage by the 'Yes' and 'Potential' polygons was derived from the QGIS field calculator geometry tool '$area'.

6.3 Results and discussion

All detected features for 2020 with their assessments are presented in the Figure 10 map, with just the 'Yes' and 'Potential' detections presented in Figure 11. These are presented for 2016 in Figures 12 and 13, respectively. Callout boxes are used to highlight the locations within Chichester Harbour with 'Yes' detections identified in 2020 (Figure 11) and 'Yes' locations detected in the 2016 imagery (Figure 13). Several of these areas were in common, indicating digging disturbance at these locations over time. Outputs for the northeast of Langstone Harbour are also presented in the maps, but this location was included to facilitate assessments of model outputs in a known location with a high level of digging disturbance.

For both years, the greatest extent of digging disturbance within Chichester Harbour was identified in the easternmost channel (Figure 14), with 21,239.78m^2 'Yes' in 2020 and 68,665.84m^2 'Yes' in 2016. The distribution of the digging through the channel appears generally similar between the two years, with some additional patches detected at the entrance to the channel and a greater extent of coverage within the same locations identified for 2016 (particularly for Dell Quay; section 5). However, at Copperas Point the extent of 2020 coverage appears narrower with the detection of mainly fresher digging patches, but the visible disturbance covers a wider area than this within the 2016 detected area (although much of this more washed out in appearance). 'Yes' digging detections were identified for both years near Cobnor Point, where more disturbance is visible for each year than detected (2020 'Yes' – 277.31m^2; 2016 'Yes' 493.59m^2; Figure 14). It must be noted for all comparisons that the areas are not absolute, as full coverage of all visible digging disturbance was not achieved by the model. 'Yes' detections were identified at the south of Bosham Channel and across from West Itchenor, but in 2016 only. For the latter ('Yes' – 204.03m^2), this may not represent a true change in distribution, as features potentially consistent with digging are visible in the 2020 imagery within the extent of the larger 2016 patch in this area, although the model did not detect this. For the relatively larger patch at the south of Bosham Channel ('Yes' – 1,320m^2; Figure 14), some potential digging is identified in this area for 2020, but the area is characterised by challenging irregular patterning that could potentially be natural, whereas in 2016 the digging is quite distinctive.

A greater extent of digging was detected near Bosham Quay in 2020 ('Yes' – 2,911.41m^2) compared to 2016 ('Yes' – 749.78m^2), however the water level at this location was lower in 2020 than for the 2016 imagery, which would contribute to differences (Figure 15). South of the main concentration of digging, a smaller patch of confident digging in 2020 also overlapped a 'Potential' digging area detected in 2016. 'Yes' digging was detected in the same location at the top of Thorney Channel (Figure 15), with a greater extent detected in 2016 ('Yes' – 625.03m^2) than in 2020 ('Yes' – 389.39m^2), however not all disturbance that appears consistent with digging in the 2020 imagery was detected and so the difference in extent must be interpreted with caution.

Southwest of Thorney Island in the 2016 imagery, one of several fresh discrete patches appearing consistent with digging was detected ('Yes' – 1.86m^2) and a nearby patch of broader mottled patterning, potentially consistent with digging was detected ('Potential' – 126.07m^2; includes area for another nearby 'potential' feature of lesser confidence) (Figure 16). Similar features were not readily evident in the 2020 imagery in these patches, except for the lower confidence 2016 'Potential' location, where the features have an appearance consistent with digging, but are not readily distinguishable from the surrounding natural patterning. 'Yes' digging (170.11m^2) was identified near Langstone Bridge in 2016 only, with additional patches of 'Potential' digging with a high likelihood of representing digging (though some uncertainty) also detected nearby. For the 'Yes' location and nearest 'Potential' locations, potential digging disturbance is also visible in the 2020 imagery, but was only detected by the model in one area near a mooring (Figure 16). Therefore, the absence 'Yes' digging here should not be interpreted as a decrease in extent.

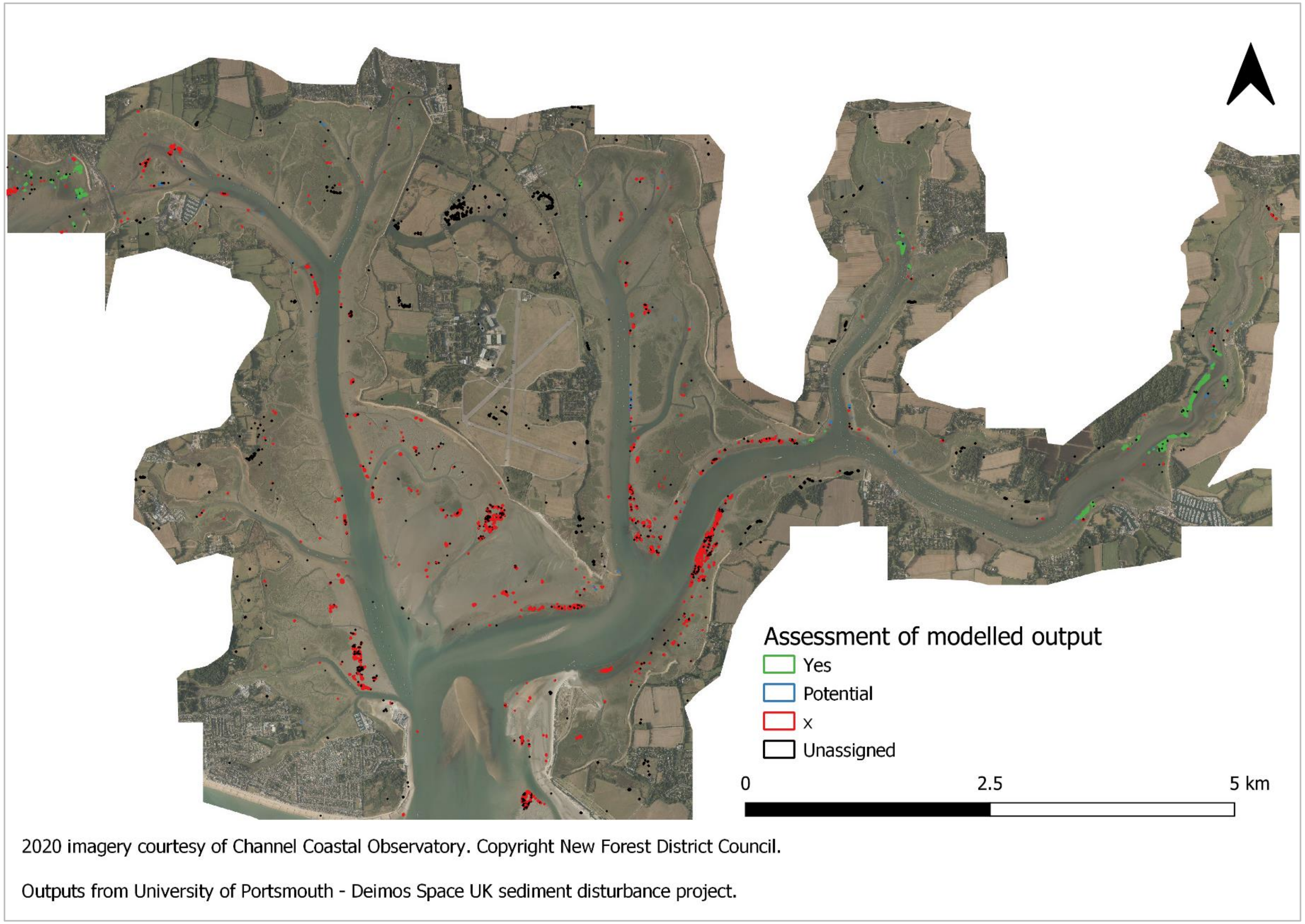


Figure 10. Assessment of Model A+B classifications for Chichester Harbour in 2020.

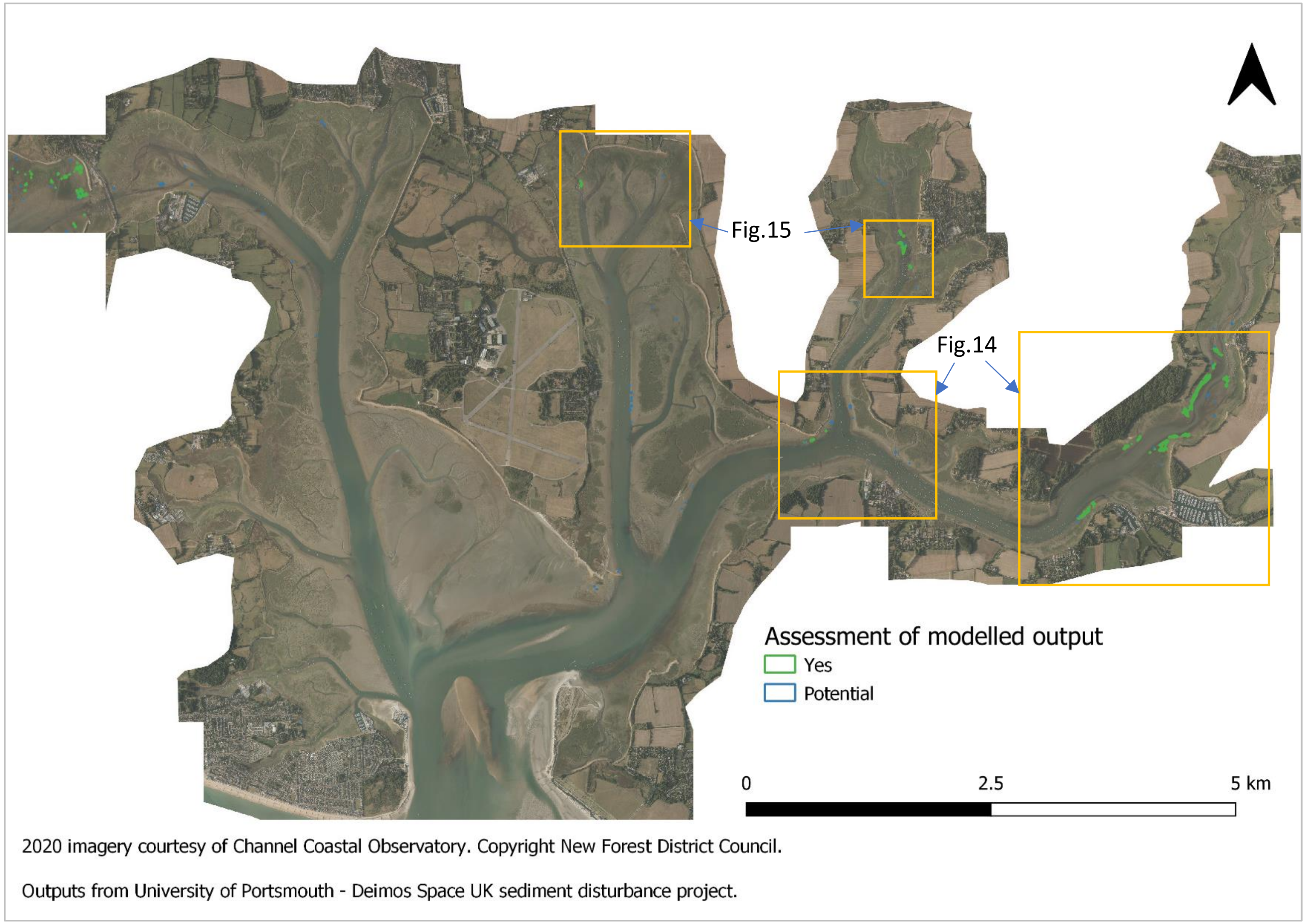
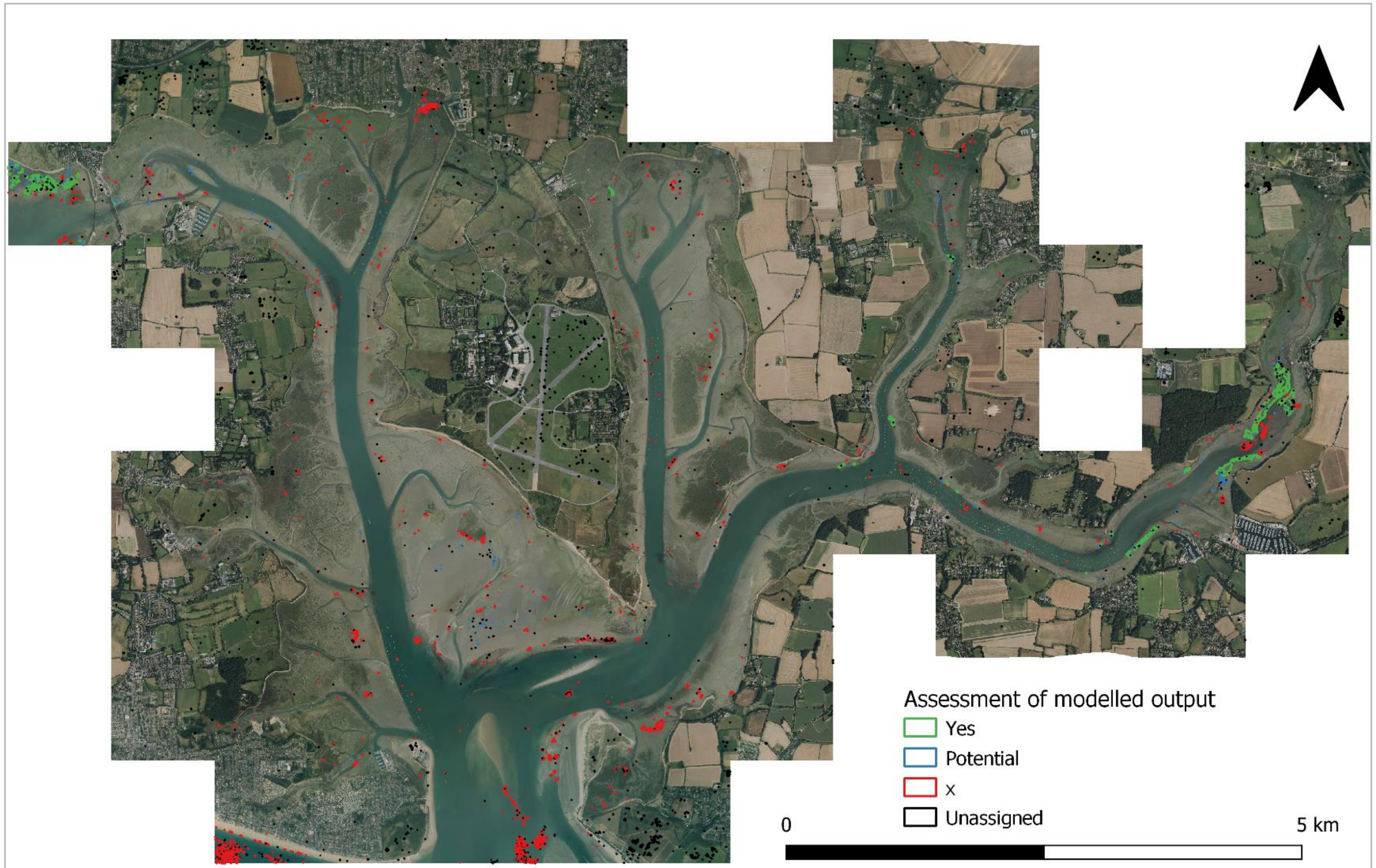


Figure 11. Assessment of Model A+B classifications for Chichester Harbour in 2020 for the detections of highest confidence as consistent with digging disturbance (Yes) and those that are potentially consistent with digging appearance (Potential), but with uncertainty. The yellow boxes flag the areas with 'Yes' detections and correspond with locations presented in Figures 14 and 15.



2016 imagery courtesy of Channel Coastal Observatory. Copyright New Forest District Council.

Outputs from University of Portsmouth - Deimos Space UK sediment disturbance project.

Figure 12. Assessment of Model A+B classifications for Chichester Harbour in 2016.

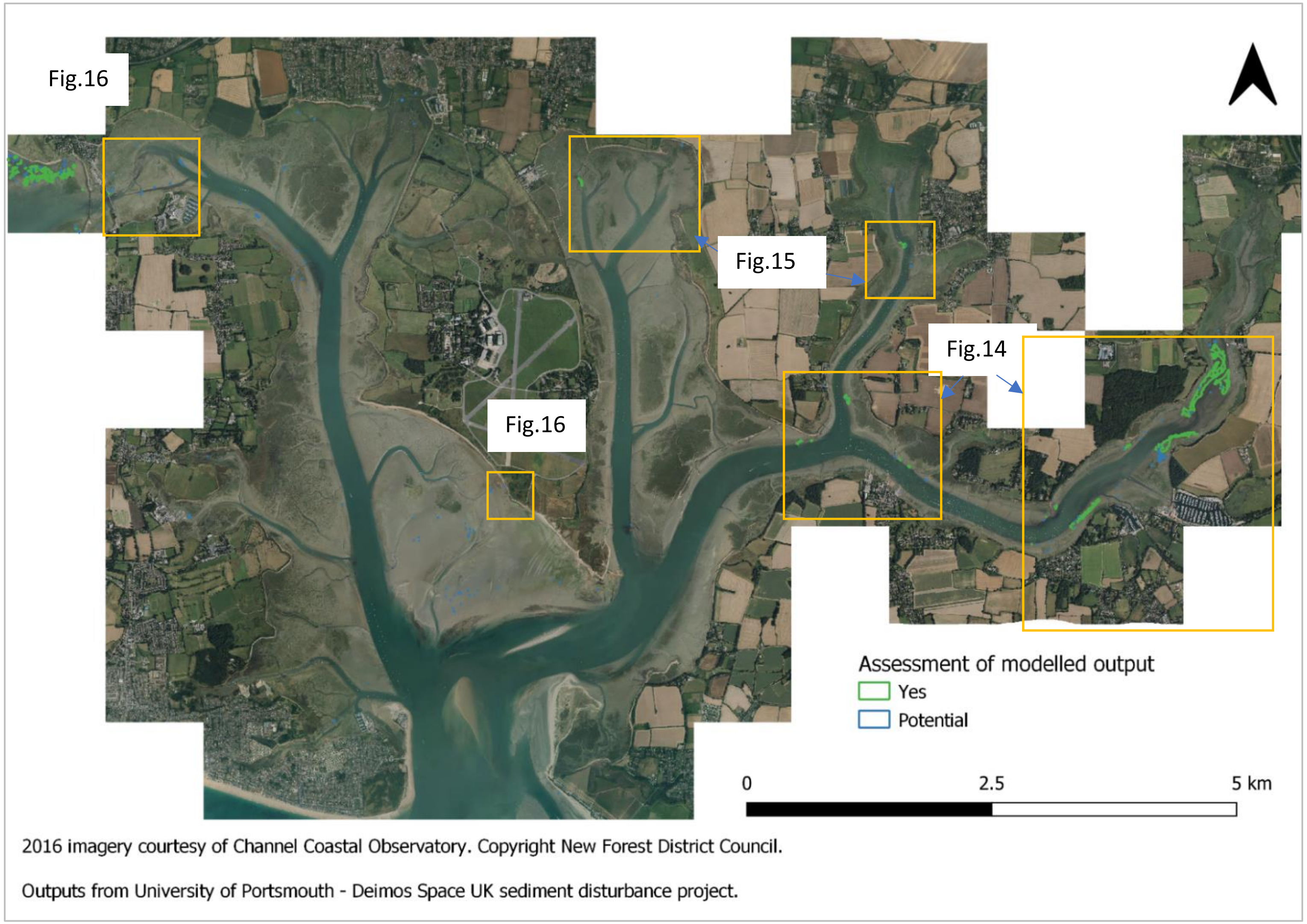


Figure 13. Assessment of Model A+B classifications for Chichester Harbour in 2016 for the detections of highest confidence as consistent with digging disturbance (Yes) and those that are potentially consistent with digging appearance (Potential), but with uncertainty. The yellow boxes flag the areas with 'Yes' detections and correspond with locations presented in Figures 14-16.

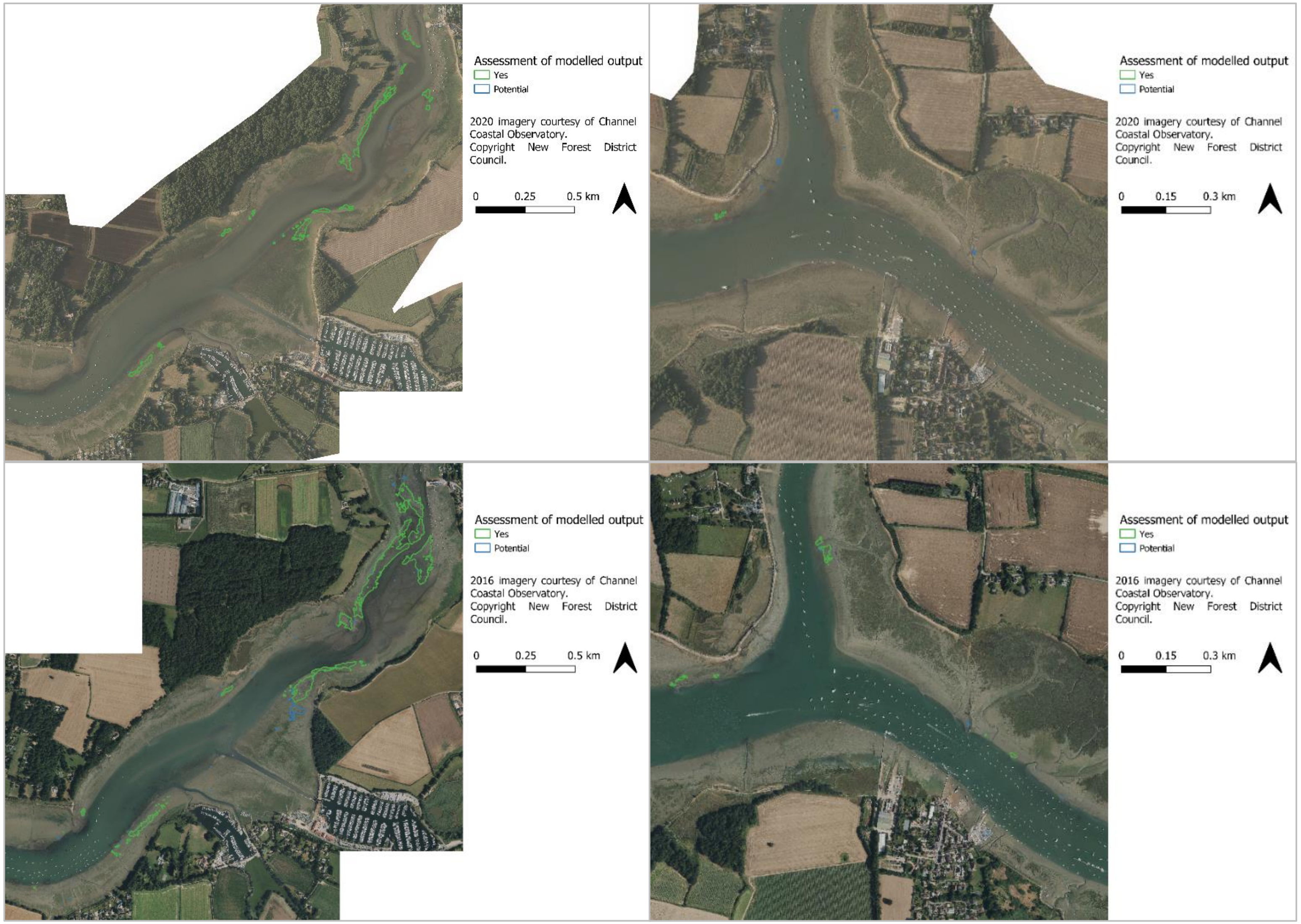


Figure 14. 'Yes' and 'Potential' digging identified for the easternmost channel in Chichester Harbour (left) and the area near Cobnor Point and West Itchenor (right) for 2020 (top) and 2016 (bottom).

Figure 15. 'Yes' and 'Potential' digging identified for the top of Thorney Channel (left) and near Bosham Quay (right) for 2020 (top) and 2016 (bottom).

Figure 16. 'Yes' and 'Potential' digging identified for the area adjacent to Langstone Bridge (left) and on the southwest side of Thorney Island (right) for 2020 (top) and 2016 (bottom). The yellow box indicates the 'Yes' digging at Thorney Island.

6.4 Summary

The highest confidence digging features occurred in similar locations between years, with differences in extent influenced by water level and limitations in model detections in some cases. This flags some key areas impacted by digging activity within the harbour over time. For the digging areas that appeared to be unique to 2016, evidence of potential digging was visible in the 2020 imagery near Langstone Bridge, across from West Itchenor, and at the entrance to the easternmost channel in areas not detected by the model in these locations. Seemingly unique to 2016 (potentially representing a real change in distribution) were the 'Yes' detections southwest of Thorney Island, at the south of Bosham Channel (though 'Potential' detected here in 2020 with high uncertainty), and differences in some of the locations of digging detected (2016) and visible (2020) at the entrance to the easternmost channel.

Large improvements from the TEMITH CNN model have been achieved here, facilitating assessments over broad scales. However, further development is required to achieve consistent and complete detections of the extent of digging features visible in the imagery and to reduce false positive detections. This can be achieved through the incorporation of additional training data with refined delineations around disturbance features and further trial and error with the modelling approach.

7. References

Anderson, F. E., & Meyer, L. M. (1986). The interaction of tidal currents on a disturbed intertidal bottom with a resulting change in particulate matter quantity, texture and food quality. *Estuarine, Coastal and Shelf Science,* 22, 19-29.

Brown, B., & Herbert Wilson Jr, W (1997). The role of commercial digging of mudflats as an agent for change of infaunal intertidal populations. *Journal of Experimental Marine Biology and Ecology*, *218*, 49-61.

Carvalho, S., Constantino, R., Cerqueira, M., Pereira, F., Subida, M. D., Drake, P., & Gaspar, M. B. (2013). Short-term impact of bait digging on intertidal macrobenthic assemblages of two south Iberian Atlantic systems. *Estuarine, Coastal and Shelf Science*, *132*, 65-76.

Chandrasekara, W. U., & Frid, C. L. J. (1996). Effects of human trampling on tidalflat infauna. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *6*, 299-311.

Clarke, L. J., Hill, R. A., Ford, A., Herbert, R. J., Esteves, L. S., & Stillman, R. A. (2019). Using remote sensing to quantify fishing effort and predict shorebird conflicts in an intertidal fishery. *Ecological Informatics, 50*, 136-148.

Coates, P. J. (1983). Fishing Bait Collection in the Menai Strait and its Relevance to the Potential Establishment of a Marine Nature Reserve with Observations on the Biology of the Main Prey Species, the Ragworm *Nereis Virens* (MSc and/or DIC dissertation, Centre for Environmental Technology, Imperial College, London).

Cox, J. & Ravenscroft, N. (2009). *Solent recreation and bird disturbance project: winter bird survey, first year report*, 53 pp.

Dernie, K. M., Kaiser, M. J., & Warwick, R. M. (2003a). Recovery rates of benthic communities following physical disturbance. *Journal of Animal Ecology*, *72*, 1043-1056.

Dernie, K. M., Kaiser, M. J., Richardson, E. A., & Warwick, R. M. (2003b). Recovery of soft sediment communities and habitats following physical disturbance. *Journal of Experimental Marine Biology and Ecology*, *285*, 415-434.

Edwards, A., Garwood, P., & Kendall, M. (1992). The Gann flat, Dale: thirty years on. *Field Studies*, *8*, 59-75.

Fearnley, H., Cruickshanks, K., Lake, S. & Liley, D. (2013). *The effect of bait harvesting on bird distribution and foraging behaviour in Poole Harbour SPA.* Unpublished report by Footprint Ecology for Natural England, 125 pp.

Gaspari, S. (1994). Haul-out behaviour, site fidelity and vigilance of common seals (*Phoca vitulina*) and grey seals (*Halichoerus grypus*) in the Tees Estuary, Durham theses, Durham University. Available at Durham E-Theses Online: http://etheses.dur.ac.uk/5824/

Howell, R. (1985). The effect of bait-digging on the bioavailability of heavy metals from surficial intertidal marine sediments. *Marine Pollution Bulletin*, *16*, 292-295.

Jackson, M. J., & James, R. (1979). The influence of bait digging on cockle, *Cerastoderma edule*, populations in North Norfolk. *Journal of Applied Ecology*, *16*, 671-679.

Liley D., Cruickshanks K., Fearnley H., & Lake S. (2012). *The effect of bait collection on waterfowl foraging in Holes Bay, Poole Harbour.* Report to Natural England. Footprint Ecology Ltd., Wareham, Dorset, 66 pp.

Maritime Archaeology Trust (2015). *Impact of Bait Digging on Archaeology: Chichester Harbour Pilot Project.* Prepared by The Maritime Archaeology Trust on behalf of Chichester Harbour Sustainable Development Fund & Interreg IVA Arch-Manche, 36 pp.

McLusky, D. S., Anderson, F. E., & Wolfe-Murphy, S. (1983). Distribution and population recovery of *Arenicola marina* and other benthic fauna after bait digging. *Marine Ecology Progress Series*, *11*, 173-179.

Morrison S.J. (2006). *Holes Bay Survey: Effects of bait digging on feeding behaviour of wildfowl and waders, Winter 2005/06*. Ecological Field Report No. 10, Produced by Ecological Field Research & Estate Management, Poole, for English Nature, 35 pp.

Navedo, J. G., & Masero, J. A. (2007). Measuring potential negative effects of traditional harvesting practices on waterbirds: a case study with migrating curlews. *Animal Conservation*, *10*, 88-94.

Olive, P.J.W. (1993). Management of the exploitation of the lugworm *Arenicola marina* and the ragworm *Nereis virens* (Polychaeta) in conservation areas. *Aquatic Conservation: Marine and Freshwater ecosystems*, *3*, 1-24.

Perrins, J., Lush, M., Taylor, T., Holt, R & Bunker, F. (2020). *Investigating the location and density of bait digging in Wales.* NRW Evidence Report Series Report No: 449, 170pp, NRW, Bangor.

Ravenscroft, N., Parker, B., Vonk, R., & Wright, M. (2007). *Disturbance to waterbirds wintering in the Stour-Orwell estuaries SPA.* A report from Wildside Ecology to the Suffolk Coast and Heaths Unit, 73 pp.

Rossi, F., Forster, R. M., Montserrat, F., Ponti, M., Terlizzi, A., Ysebaert, T., & Middelburg, J. J. (2007). Human trampling as short-term disturbance on intertidal mudflats: effects on macrofauna biodiversity and population dynamics of bivalves. *Marine Biology*, *151*, 2077-2090.

Shepherd, P.C.F. & Boates, J.S. (1999). Effects of a commercial baitworm harvest on semipalmated sandpipers and their prey in the Bay of Fundy Hemispheric Shorebird Reserve. *Conservation Biology, 13*, 347-356.

Sherman, K. M., & Coull, B. C. (1980). The response of meiofauna to sediment disturbance. *Journal of Experimental Marine Biology and Ecology*, *46*, 59-71.

Sypitkowski, E., Bohlen, C., & Ambrose Jr, W. G. (2010). Estimating the frequency and extent of bloodworm digging in Maine from aerial photography. *Fisheries Research*, *101*, 87-93.

Townshend, D. J., & O'Connor, D. A. (1993). Some effects of disturbance to waterfowl from bait-digging and wildfowling at Lindisfarne National Nature Reserve, north-east England. *Wader Study Group Bulletin*, *6*, 47-52.

Watson, G. J., Farrell, P., Stanton, S., & Skidmore, L. C. (2007). Effects of bait collection on *Nereis virens* populations and macrofaunal communities in the Solent, UK. *Journal of the Marine Biological Association of the United Kingdom*, *87*, 703-716.

Watson, G. J., Murray, J. M., Schaefer, M., & Bonner, A. (2015). Successful local marine conservation requires appropriate educational methods and adequate enforcement. *Marine Policy, 52*, 59-67.

Watson, G.J., Murray, J.M., Schaefer, M., Bonner, A., 2017a. Bait worms: A valuable and important fishery with implications for fisheries and conservation management. *Fish and Fisheries*, *18*, 374-388.

Watson, G. J., Murray, J. M., Schaefer, M., Bonner, A., & Gillingham, M. (2017b). Assessing the impacts of bait collection on inter-tidal sediment and the associated macrofaunal and bird communities: the importance of appropriate spatial scales. *Marine Environmental Research*, *130*, 122-133.

Watson, G., Murray, J.M., Schaefer, M., Bonner, A., & Gillingham, M. (2013) *Does local marine conservation work? Evaluating management strategies for bait collection in the Solent.* A report to Natural England with funding from the Crown Estate's Marine Stewardship fund, 168 pp.

White, S., Schaefer, M., Watson, G. (2019). *Cost benefit analysis of survey methods for assessing intertidal sediment disturbance: a bait collection case study.* Report by the University of Portsmouth for Natural England, 64 pp.

Wynberg, R. P., & Branch, G. M. (1997). Trampling associated with bait-collection for sandprawns *Callianassa kraussi* Stebbing: effects on the biota of an intertidal sandflat. *Environmental Conservation*, *24*, 139-148.