Report to Suffolk Marine Pioneer

Deben Estuary salt marsh status: extent, carbon stocks and Sea Bass nursery values, and the potential gain in these natural capital assets from successful restoration.

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October 2018

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Summary.

Three representative salt marshes in the Deben Estuary (**Melton**, **Loder's Cut and Kyson Point**, and **Waldringfield**) were investigated as part of a DEFRA Suffolk Marine Pioneer study to understand the natural capital context of these sites. Using publically-available national data, a methodology is described to determine salt marsh extent and condition (using vegetation cover as a proxy). The approach has been used to define the salt marsh as a carbon stock asset and to understand the potential gain from restoration of the asset. We estimate (based on a 2D model approach) that restoring fully the salt marshes at **Kyson Point** and **Loder's Cut** in the Deben estuary could increase the extent of salt marsh by **4.05 hectares,** for **Melton** an increase in extent of **1.07 ha** (restoring existing salt marsh), and if the whole site that was originally enclosed and has now reverted to mudflat, was restored, then increase of extent by **9.69 hectares.** For **Waldringfield** successful restoration has the potential to increase extent by up to **11.3 hectares.** Estimates of potential use of salt marshes by larval and juvenile Sea Bass (*Dicentrarchus labrax*) were calculated based on published data. Increasing the extent of existing salt marsh through restoration techniques at these three locations could provide additional habitat to allow for increases in Sea Bass daily use of between **35%** and **230 % (average 90.5%)**.

Using a 2D model approach showed that restoring fully the salt marshes at **Kyson Point** and **Loder's Cut** in the Deben estuary would increase the carbon stock by 82.5 tonnes, for **Melton** an increase of 21.9 tonnes (or 197 tonnes if the mudlfats were re-established as salt marsh), and for **Waldringfield** a increase in stock of 23.1 tonnes of carbon. A 3D modelling approach, utilising EA Lidar data to account for the differences in sediment bed heights of existing marshes and eroded sections, found that the potential carbon stock enhancement resulting from salt marsh restoration was estimated at **6,496** tonnes C at **Kyson / Loder's Cut**, **12,625** tonnes C at **Melton**, and **3,599** tonnes C at **Waldringfield**. Timescales for restoration or recovery of salt marsh are site specific and will depend on the management approach taken. Salt marsh vascular plants can establish on new sites within a 5-10 year timeframe, but achieving a natural capital value equivalent to a natural marsh may take 50-100 years. Restoration approaches may prevent further losses. Losses of salt marsh at Melton, based on comparison of GoogleEarth (2007) and EA Ortho (2016) images (based on 2D approach) indicate a loss of 5.5 tonnes of carbon and 2,723 m^2 (a 23 % reduction in extent) during that 10 year period. Losses of salt marsh at Waldringfield, indicate a loss of 3.2 tonnes of carbon and 1,587m^2 (a 4% loss) during that 10 year period).

The approaches described in this report use standardised published data on sediment carbon stocks and fish habitat utilisation, and can therefore be validly applied to other similar East Anglian salt marshes.

1. Determining from publically available data, the areal extent, degree of salt marsh fragmentation and marsh condition (vegetation cover) using three salt marshes in the Deben Estuary (1) Melton / Sutton Hoo, (2) Loder's Cut and Kyson Point, (3) Waldringfield marsh.

Shape files for the various locations were obtained from the Priority Habitat Inventory (Central) England (**https://naturalengland-defra.opendata.arcgis.com/datasets/priority-habitat-inventory-central-england**) (Figure 1).The area of each shape file of interest (m^2) was obtained from this data base (Table 1).

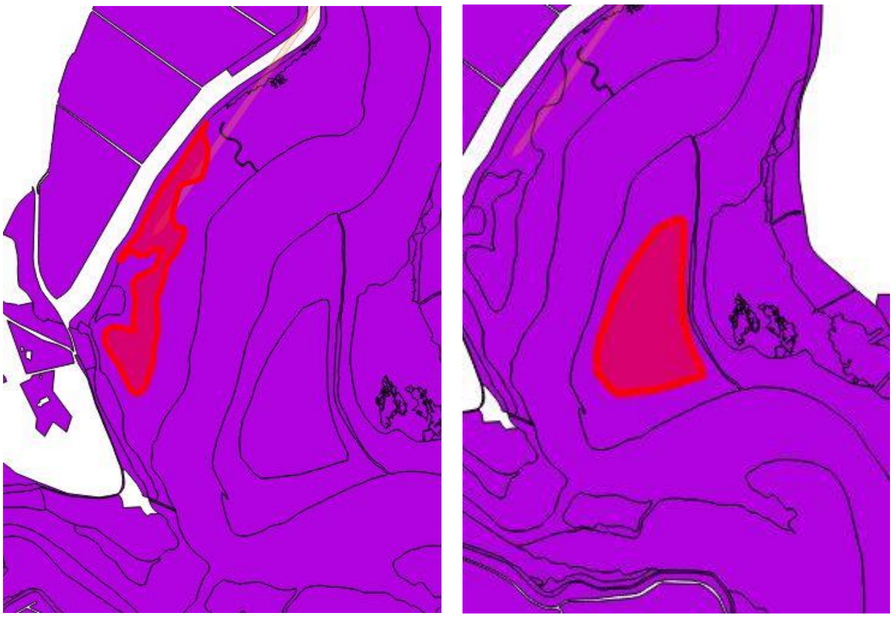
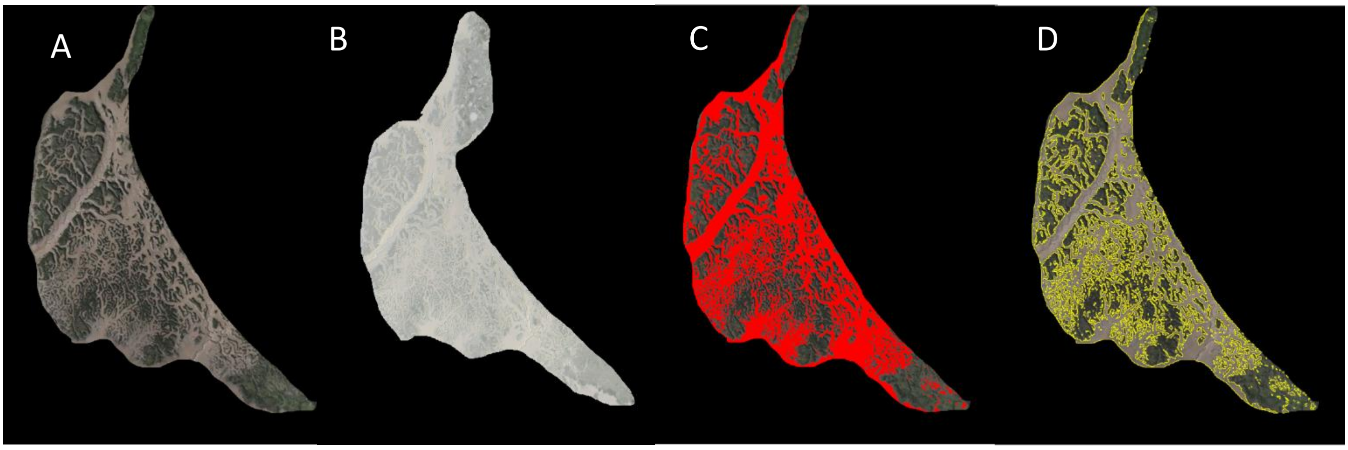


Figure 1. Example shape files for Kyson Point and Loder's Cut from the Priority Habitat Inventory (Natural England).

Vegetation cover was estimated using images from the Environment Agency 2016 aerial survey (as RBGN ortho files). Individual salt marshes were located within this data set, and the PNG images analysed using the freeware software *ImageJ* (ImageJ is an open source scientific image analysis programme from the US National Institute of Health, https://imagej.nih.gov/ij/). Using tools within ImageJ, the degree of vegetation cover in individual marshes was calculated (Figure 2), using an approach where image analysis tools permits the measurement of the total number of vegetated and non-vegetated pixels in an image. This method is taken from Green et al. 2009 and Green et al 2011. The % vegetation cover for each shape file is given in Table 1. The method is detailed in **Appendix 4**.

Figure 2. (A) GoogleEarth and (B, C, D) ortho RBGN images from EA 2016 data, and a



manipulated images (using *ImageJ*) of saltmarsh showing (C) non-vegetated (red) and (D) vegetated (green) areas.

The carbon stock of mudflat and for vegetated salt marsh has been calculated from published information (e.g. Thornton *et al.* 2002), and existing data sets from the NERC project CBESS and work recently completed for the NERC thematic project Shelf Sea Biogeochemistry (the latter in conjunction with CEFAS and University of East Anglia). This has provided a range of estimates. In this report, we use the average standing stock values for the top 10 cm depth of mudflats (1647 g C m^2, standard error ± 42.9) and salt marshes (3684 g C m^2, standard error ± 152) based on this work (Table 1).

With the areas of marsh identified from the shape files (column C), the corresponding % vegetation cover data (column G and H, shown as proportions), and the "standard stock values" for mudflat and salt marsh (column E and F), we have calculated the total current carbon stock within the top 10 cm of sediment for each shape file area (Column K) (Table 1). Healthy salt marsh in East Anglia possess natural internal creeks systems and open areas of sediment, which occupy approximately 12 ± 1.95 % of the marsh area (Green et al. 2009, 2012). Using these measures as a target value for full restoration, we have calculated the potential increased carbon stock in each of the areas at Kyson Point and Loder's Cut if the marsh was fully restored to a healthy vascular plant coverage (Columns L and M). This indicates a potential increase of carbon stock of 13,572 kg of carbon at Kyson Point, and 68,934 kg of C at Loder's Cut. These calculations are based on a 2D area basis only, and do not take into account potential sediment accumulation (3D) that may be needed to raise the sediment bed height to a position within the tidal frame where vascular salt marsh plant species could colonise (Cousins et al. 2017).

Using 2016 Environment Agency LIDAR height measurements (Cooper, G., pers. comm.) it was possible to estimate the vertical height of sediment needed in any marsh restoration schemes to result in a restored salt marsh being at the same height as existing marsh at each site (Table 2.). In making these calculations, we have assumed the same carbon values in existing mudflats (10 cm deep sections), and estimated there number of such sections required to underpin the surface marsh described in Table 1. Using these estimates, a fully restored set of marshes are Kyson Point and Loder's Cut would lock away 1,876.4 and 4,619.1 tonnes of carbon respectively (Table 2).

Similar calculations have been done for the extent of salt marsh at Melton / Sutton Hoo (Appendix 2) at the north end of the Estuary (Table 3). The Melton site has been considered in three main divisions: the existing marsh to the east-side and west-side of a track running across the centre of the site, and the large extent of mudflats within the line of a historic sea wall which enclosed the site, but is now breached in multiple places. In the Melton calculations, the shape files attributed/determined to be reed beds, located at the landward sides of the site have been excluded from the calculations.

Restoration of existing marsh at Melton could generated a further 10,768 m^2 of new salt marsh extent, and increase stocks by 21,938 kg of C. Recreation of new marsh on the current mudflat areas of Melton would create 86,191 m^2 of new marsh, and store an additional 175,597 kg of carbon. Estimates of losses of marsh and sediment carbon from this site, based on GoogleEarth and EAortho images from 2007 and 2016 respectively show a net loss of saltmarsh overall (Table 6) (note, all these are 2D estimates as discussed previously).

Estimates of carbon trapped using a 3D model and taking sediment accumulation into account, provides a much greater set of C stock estimates (Table 5) for Melton / Sutton Hoo: 2,237.1 tonnes within the current degraded marsh, and 10,387.5 tonnes on the extent of mudflats enclosed by the historic (breached) sea wall at the west end of the site.

At Waldringfield, restoration of the salt marsh to the north of the village (Appendix 3) has the potential to increase marsh areas by 11,346 m^2, and increase stocks by 23,114 kg of C (Table 6). Restoration of two further area of marsh to the north of this section could add a further 19,751 m^2, and increase stocks by 40,240 kg of C. Losses in this region between 2007 and 2016 are a net change of -1,581 m^2, and a decrease in C stocks of 3,221 kg (Table 8).

Estimates of carbon trapped using a 3D model and taking sediment accumulation into account, provides a much greater set of C stock estimates (Table 7) for Waldringfield: 429 tonnes within the current south and mid-section marsh, and 3,169.3 tonnes on the northern section of marsh.

2. Potential for extrapolation to other salt marsh locations within the region .

The approach described here can be extrapolated for other salt marshes within the Deben estuary, and for other clay-rich sites within East Anglia. The approach is using standardised values based on data form a wide range of east coast salt marsh. While individual marsh (and even areas within an individual marsh) will have some different characteristics, applying standard values provides a consistent approach across this type of habitat. East Anglian salt marshes conform to a characteristic floristic type, similar to those found in Kent and in Belgium and the Netherlands.

3. Challenges and cost-benefit assessment around creating finer resolution estimates of marsh carbon stocks.

Finer scale height differences, and a better profile of the organic carbon content of restoring and stabilised marshes could finesse these estimates for each location. However, fine scale height modelling would require significant additional data resolution (at a m^2 scale), and then modelling and computational power to do this on a spatial basis. This is all feasible but at a cost. Given the natural levels of spatial heterogeneity in salt marshes (which are already factored into the derivation of the estimated values), a more fine scale approach would probably not significantly change the broad estimates of existing and potential carbon stocks. For most marsh locations, data at this fine scale is not available, and a detailed study at any particular marsh, taking into account both horizontal and vertical scales of variability would be prohibitively expensive.

There is a shortage of relevant data on the organic carbon profiles of salt marsh sediments, and the temporal and diagenic changes that occur with depth, and further work funded by the Natural Environment Research Council is underway. In established salt marshes, there is a slightly lower organic carbon stock in deeper sediments (due to diagenic losses over time, but these can be offset by compaction of sediments increasing bulk density). Existing marshes often overlay a layer of peat, which has a high carbon content. However, peat is laid down primarily in freshwater environments, and the underlying peats of east Anglian salt marshes are a result of landward movements of salt marsh over previously fresh water marshes during progressive periods of sea level rise. Restoring salt marshes on existing sites would not restore these basal peat layers if they have been lost, though such restoration may protect existing underlying peat layers from further erosion, thus preventing further carbon losses.

4. Longer term potential for salt marshes to store carbon

Estimates of the carbon stocks locked into saltmarsh sediments have been calculated (See Tables 2, 4, and 7). Some of this carbon may already exist in the estuarine or near shore marine environment, associated with the sediment needed to accumulate on the sites. However, consolidating material within a location, and the associated microbial and vascular plant primary production associated with sediment accumulation and marsh growth, will retain both existing and new carbon in a less biologically- accessible stock, with lower rates of mineralisation. Salt marsh restoration approaches in the UK have been trialled over the last 20 years, and for longer time scales than this in the US. The rate(s) of recovery / regrowth depends on a range of factors, key to which are sediment bed height within the tidal frame, and the colonisation by pioneer and then a successional sequence of salt marsh vascular plant species (Mossman et al., 2012; Cousins et al., 2017). The trajectory of recovery is therefore site specific, but with 5-10 years, newly developing sites can have a level of vascular plant cover and of dominant species occurrence similar to established marshes, and possibly with similar (or equivalent) ecosystem functions (services). However, Mossman et al. (2012) did find that the time scales for new marshes to achieve levels of biodiversity and spatial heterogeneity (particular of higher marsh species) comparable to reference sites could be in excess of over 50 to 100 years. It is not clear if this level of biodiversity is key to delivering ecosystem functions and services, as there could be functional redundancy.

Longer term, east coast estuaries are under pressure from isostatic adjustment and rising sea levels. Future rates of sea level rise will partly depend on the rate of global greenhouse gas (GHG) emission. Using low and high future GHG emissions scenarios, Horton et al. (2018) predicted median sea level rises for Felixstowe of between 4.3 and 4.7 mm year (from 2010 to 2050) for a low emission scenario (representative concentration pathway RCP 2.6) and between 4.6 and 6.6 mm year (from 2010 to 2050) for a high emissions scenario (RCP 8.5), which will lead to a loss of salt marsh in the region (80% probability of marsh retreat by 2040 under RCP 8.5). Current monitoring work by the River Deben Association at Loder's Cut and Waldringfield may suggest that with active intervention, salt marsh could accrete sediment at these lower rates, and so it may be possibly to avoid "marsh drowning" with active intervention and a low future greenhouse emission scenario.

Relative sea level rise could also drive in morphological changes in the Deben. Recent modelling based on Regime Theory concepts by RoyalHaskoningDHV (2018) found that the mid and upper reaches of the Deben are in relative equilibrium with respect to morphology. They state that this conclusion is counter-intuitive with the measured rates of salt marsh loss in those part of the estuary. Breaches in existing seawall or managed realignment in the Deben would provide areas for new saltmarsh establishment, but it is not clear whether such changes would be a positive or negative impact on marsh locations where active restoration has occurred. Increasing sea levels, and/or changes to the morphological profile at the seaward end of the estuary (determined to be currently out of equilibrium, RoyalHaskoningDHV 2018) would also probably change conditions for salt marsh establishment and growth in the rest of the estuary.

Table 1. Shape file codes, extents, standing stocks, calculated vegetation cover, and estimates of carbon stocks, and potential increases in carbon stocks and new salt marsh extent for Kyson Point and Loder's Cut in the Deben Estuary, Suffolk.

A	B	C	D	E	F	G	H	I	J	K	L	M
Area	**shape file code**	**area (m2)**	**MF/ SM**	**SM (g C m-2)**	**MF (g C m-2)**	**% veg. cover**	**% non-veg cover**	**carbon stock veg (kg)**	**carbon stock mud (kg)**	**Total carbon stock (kg)**	**potential increase C stock (kg)**	**potential new salt marsh created (m2)**
Kyson point mudflat	425461	61,517	MF	3684.3	1647	0.00	1.00	-	101,318	101,318		
Kyson Point (small islet)	433037	1,273	SM	3684.3	1647	0.37	0.63	1,717	1,329	3,046		
restoration potential		1,273	SM	3684.3	1647	0.88	0.12	4,128	252	4,379	**1,333**	654
Kyson Point (main - saltmarsh)	433010	14,822	SM	3684.3	1647	0.47	0.53	25,923	12,824	38,746		
restoration potential		14,822	SM	3684.3	1647	0.88	0.12	48,056	2,929	50,985	**12,239**	6,007
sum											*13,572*	*6,662*
Loder's Cut "mid channel island"	433009	24,497	SM	3684.3	1647	0.26	0.74	23,854	29,683	53,537		
restoration potential		24,497		3684.3	1647	0.88	0.12	79,424	4,842	84,265	**30,728**	15,083
Loder's Cut east shore lower marsh	433038	28,005	SM	3684.3	1647	0.43	0.57	44,645	26,166	70,812		
restoration potential		28,006	SM	3684.3	1647	0.88	0.12	90,801	5,535	96,336	**25,524**	12,527
Loder's Cut east shore high marsh	489834	14,725	SM	3684.3	1647	0.67	0.33	36,370	7,993	44,364		
restoration potential		14,726	SM	3684.3	1647	0.88	0.12	47,744	2,910	50,655	**6,291**	3,086
Loder's Cut, east shore, southern en	489833	9,129	SM	3684.3	1647	0.54	0.46	18,041	6,970	25,011		
restoration potential		9,129	SM	3684.3	1647	0.88	0.12	29,597	1,804	31,401	**6,390**	3,137
sum											*68,934*	*33,832*

assuming healthy marsh is 12% non-veg - Ref. Colne Point, Green *et al.* 2012, 2009.

Table 2. Shape file codes, extents, standing stocks, calculated vegetation cover, and estimates of carbon stocks, and potential increases in carbon stocks and new salt marsh extent, assuming sediment infill to raise existing eroded salt marsh areas to the height of current salt marsh for Kyson Point and Loder's Cut in the Deben Estuary, Suffolk.

A	B	C	D	E	F		G	H	I	J	K	L	M
Area	**shape file code**	**area (m2)**	**MF/ SM**	**SM (g C m-2)**	**MF (g C m-2)**	**sediment required (depth m)**	**% veg. cover**	**% non-veg cover**	**carbon stock veg (kg)**	**carbon stock mud (kg)**	**Total carbon stock (kg)**	**potential increase C stock (kg)**	**potential new salt marsh created (m2)**
Kyson point mudflat	425461	61,517	MF	3684.3	1647		0.00	1.00	-	101,318	101,318		
Kyson Point (small islet)	433037	1,273	SM	3684.3	1647		0.37	0.63	1,717	1,329	3,046		
carbon stock of infill		1,273	MF	3684.3	1647	1.53		0.63		188,900			
restoration potential top 10 cm		1,273	SM	3684.3	1647		0.88	0.12	4,128	252	193,280	**190,233**	654.25
Kyson Point (main - saltmarsh)	433010	14,822	SM	3684.3	1647		0.47	0.53	25,923	12,824	38,746		
carbon stock of infill		14,822	MF	3684.3	1647	1.39		0.53		1,673,889			
restoration potential		14,822	SM	3684.3	1647		0.88	0.12	48,056	2,929	1,724,874	**1,686,128**	6,007
sum												*1,876,361*	*6,662*
Loder's Cut "mid channel island"	433009	24,497	SM	3684.3	1647		0.26	0.74	23,854	29,683	53,537		
carbon stock of infill		24,497	MF	3684.3	1647	0.73		0.74		1,869,760			
restoration potential		24,497		3684.3	1647		0.88	0.12	79,424	4,842	1,954,026	**1,900,489**	15,083
Loder's Cut east shore lower marsh	433038	28,006	SM	3684.3	1647		0.43	0.57	44,647	26,167	70,814		
carbon stock of infill		28,006	MF	3684.3	1647	0.75		0.57		1,710,059			
restoration potential		28,006	SM	3684.3	1647		0.88	0.12	90,801	5,535	1,806,395	**1,735,581**	12,527
Loder's Cut east shore high marsh	489834	14,725	SM	3684.3	1647		0.67	0.33	36,370	7,993	44,364		
carbon stock of infill		14,725	MF	3684.3	1647	0.75		0.33		520,540			
restoration potential		14,726	SM	3684.3	1647		0.88	0.12	47,744	2,910	571,195	**526,832**	3,086
Loder's Cut, east shore, southern end	489833	9,129	SM	3684.3	1647		0.54	0.46	18,041	6,970	25,011		
carbon stock of infill		9,129	MF	3684.3	1647	0.75		0.46		449,849			
restoration potential		9,129	SM	3684.3	1647		0.88	0.12	29,597	1,804	481,250	**456,239**	3,137
sum												*4,619,140*	*33,833*
assuming healthy marsh is 12% non-veg - Ref. Colne Point, Green *et al.* 2012, 2009.													

Table 3. Shape file codes, extents, standing stocks, calculated vegetation cover, and estimates of carbon stocks, and potential increases in carbon stocks and new salt marsh extent for Melton / Sutton Hoo in the Deben Estuary, Suffolk.

Calculations for carbon stocks, top 10 cm sediment

A	B	C	D	E	F	G	H	I	J	K	L	M
Area	shape file code	area (m2)	MF/ SM	SM (g C m-2)	MF (g C m-2)	% veg. cover	% non-veg cover	carbon stock veg (kg)	carbon stock mud (kg)	Total carbon stock (kg)	potential increase C stock (kg)	potential new salt marsh created (m2)
Melton marsh W. of centre track	489988	26,737	SM	3684.3	1647	0.70	0.30	69,339	13,039	82,378		
restoration potential		26,737	SM	3684.3	1647	0.88	0.12	86,686	5,284	91,971	**9,592**	4,708
Melton marsh W. eroded N section	452511	1,228	SM/MF	3684.3	1647	0.44	0.56	2,009	1,124	3,133		
		1,228	SM	3684.3	1647	0.88	0.12	3,980	243	4,223	**1,090**	535
Melton marsh W. eroded W section	452510	4,722	SM/MF	3684.3	1647	0.41	0.59	7,129	4,590	11,719		
		4,722	SM	3684.3	1647	0.88	0.12	15,309	933	16,242	**4,523**	2,220
Melton marsh E. of centre track	489986+490050	8,826	SM	3684.3	1647	0.51	0.49	16,440	7,186	23,626		
restoration potential		8,826	SM	3684.3	1647	0.88	0.12	28,614	1,744	30,358	**6,732**	3,304
sum											*21,938*	*10,768*
Melton mudflats NW quarter	425253+452495	33,836	MF	3684.3	1647	0.00	1.00	-	55,727	55,727		
restoration potential		33,836		3684.3	1647	0.88	0.12	109,701	6,687	116,388	**60,661**	29,775
Melton mudflats SW quarter	425244	30,552	MF	3684.3	1647	0.00	1.00	-	50,319	50,319		
restoration potential		30,552	SM	3684.3	1647	0.88	0.12	99,055	6,038	105,093	**54,774**	26,886
Melton mudflats NE quarter	425250	22418.11	MF	3684.3	1647	0.00	1.00	-	36,923	36,923		
restoration potential		22418.11	SM	3684.3	1647	0.88	0.12	72,684	4,431	77,114	**40,192**	19,728
Melton mudflats SE quarter	425245	11,139	MF	3684.3	1647	0.00	1.00	-	18,346	18,346		
restoration potential		11,139	SM	3684.3	1647	0.88	0.12	36,115	2,202	38,317	**19,971**	9,802
sum											*175,597*	*86,191*

assuming healthy marsh is 12% non-veg - Ref. Colne Point, Green *et al.* 2012, 2009.

Table 4. Shape file codes, extents, standing stocks, calculated vegetation cover, and estimates of carbon stocks, and potential increases in carbon stocks and new salt marsh extent, assuming sediment infill to raise existing eroded salt marsh areas to the height of current salt marsh for Melton / Sutton Hoo in the Deben Estuary, Suffolk.

A	B	C	D	E	F		G	H	I	J	K	L	M
Area	shape file code	area (m2)	MF/ SM	SM (g C m-2)	MF (g C m-2)	sediment required (depth m)	% veg. cover	% non-veg cover	carbon stock veg (kg)	carbon stock mud (kg)	Total carbon stock (kg)	potential increase C stock (kg)	potential new salt marsh created
Melton marsh W. of centre track	489988	26,737	SM	3684.3	1647		0.70	0.30	69,339	13,039	82,378		
carbon stock of infill		26,737		3684.3	1647	1.00		0.30			1,193,371		
restoration potential		26,737	SM	3684.3	1647		0.88	0.12	86,686	5,284	1,285,342	**1,202,964**	4,708
Melton marsh W. eroded N section	452511	1,228	SM/MF	3684.3	1647		0.44	0.56	2,009	1,124	3,133		
carbon stock of infill		1,228		3684.3	1647	0.66		0.56			63,788		
restoration potential		1,228	SM	3684.3	1647		0.88	0.12	3,980	243	68,011	**64,878**	535
Melton marsh W. eroded W section	452510	4,722	SM/MF	3684.3	1647		0.41	0.59	7,129	4,590	11,719		
carbon stock of infill		4,722		3684.3	1647	0.91		0.59			371,646		
restoration potential		4,722	SM	3684.3	1647		0.88	0.12	15,309	933	387,887	**376,169**	2,220
Melton marsh E. of centre track	489986+490050	8,826	SM	3684.3	1647		0.51	0.49	16,440	7,186	23,626		
carbon stock of infill		8,826		3684.3	1647	0.92		0.49			586,414		
restoration potential		8,826	SM	3684.3	1647		0.88	0.12	28,614	1,744	616,773	**593,146**	3,304
sum												*2,237,157*	*10,768*
Melton mudflats NW quarter	425253+452495	33,836	MF	3684.3	1647		0.00	1.00	-	55,727	55,727		
carbon stock of infill		33,836		3684.3	1647	0.76		1.00			3,650,126		
restoration potential		33,836		3684.3	1647		0.88	0.12	109,701	6,687	116,388	**3,356,542**	29,775
Melton mudflats SW quarter	425244	30,552	MF	3684.3	1647		0.00	1.00	-	50,319	50,319		
carbon stock of infill		30,552		3684.3	1647	0.76		1.00			3,295,881		
restoration potential		30,552	SM	3684.3	1647		0.88	0.12	99,055	6,038	105,093	**3,350,655**	26,886
Melton mudflats NE quarter	425250	22,418	MF	3684.3	1647		0.00	1.00	-	36,923	36,923		
carbon stock of infill		22,418		3684.3	1647	0.76		1.00			2,418,432		
restoration potential		22,418	SM	3684.3	1647		0.88	0.12	72,684	4,431	77,114	**2,458,624**	19,728
Melton mudflats SE quarter	425245	11,139	MF	3684.3	1647		0.00	1.00	-	18,346	18,346		
carbon stock of infill		11,139		3684.3	1647	0.76		1.00			1,201,675		
restoration potential		11,139	SM	3684.3	1647		0.88	0.12	36,115	2,202	38,317	**1,221,645**	9,802
sum												*10,387,467*	*86,191*

assuming healthy marsh is 12% non-veg - Ref. Colne Point, Green *et al.* 2012, 2009.

Table 5. Shape file codes, extents, standing stocks, calculated vegetation cover, and estimates of changes in carbon stocks for existing salt marsh at Melton / Sutton Hoo in the Deben Estuary, Suffolk over a 10 year period, based on GoogleEarth 2007 and EAortho 2016 images.

Calculations for carbon losses top 10 cm sediment 2007 to 2016														
A		B	C	D	E	F	G	H	I	J	K	L	M	N
Area		shape file code	area (m2)	MF/ SM	SM (g C m-2)	MF (g C m-2)	% veg. cover	% non-veg cover	carbon stock veg (kg)	carbon stock mud (kg)	Total carbon stock (kg)	change in C stock (kg)	change in salt marsh (m2)	% change salt marsh extent
Melton marsh W. of centre track	Google Earth 2007	489988	26,737	SM	3684.3	1647	0.68	0.32	66,620	14,254	80,875			
	Ortho2016		26,737	SM	3684.3	1647	0.70	0.30	69,339	13,039	82,378	**1,503**	738	4.08
Melton marsh W. eroded N section	Google Earth 2007	452511	1,228	SM/MF	3684.3	1647	0.66	0.34	2,993	684	3,677			
	Ortho2016		1,228	SM	3684.3	1647	0.44	0.56	1,995	1,130	3,125	**-552**	-271	-33.36
Melton marsh W. eroded W section	GoogleEarth 2007	452510	4,722	SM/MF	3684.3	1647	0.57	0.43	9,831	3,382	13,213			
	Ortho2016		4,722	SM	3684.3	1647	0.41	0.59	7,129	4,590	11,719	**-1,494**	-733	-27.48
Melton marsh E. of centre track	GoogleEarth 2007	489986+490050	8,826	SM	3684.3	1647	0.78	0.22	25,489	3,141	28,630			
	Ortho2016		8,826	SM	3684.3	1647	0.51	0.49	16,440	7,186	23,626	**-5,004**	-2,456	-35.50
	sum											*-5,547*	*-2,723*	

Table 6. Shape file codes, extents, standing stocks, calculated vegetation cover, and estimates of carbon stocks, and potential increases in carbon stocks and new salt marsh extent for Waldringfield in the Deben Estuary, Suffolk.

Calculations for carbon stocks, top 10 cm sediment

A	B	C	D	E	F	G	H	I	J	K	L	M
Area	**shape file code**	**area (m2)**	**MF/ SM**	**SM (g C m-2)**	**MF (g C m-2)**	**% veg. cover**	**% non-veg cover**	**carbon stock veg (kg)**	**carbon stock mud (kg)**	**Total carbon stock (kg)**	**potential increase C stock (kg)**	**potential new salt marsh created (m2)**
Waldringfield S section	499611	6,326	SM	3684.3	1647	0.57	0.43	13,248	4,497	17,745		
restoration potential		6,326	SM	3684.3	1647	0.88	0.12	20,511	1,250	21,761	**4,016**	1,971
Waldringfield eroded mid section	489822	12,508	SM/MF	3684.3	1647	0.67	0.33	30,755	6,852	37,606		
	(plus....)	12,508	SM	3684.3	1647	0.88	0.12	40,552	2,472	43,024	**5,417**	2,659
Waldringfield mid section mud	part of 425411	7,631	SM/MF	3684.3	1647	0.00	1.00	-	12,568	12,568		
		7,631	SM	3684.3	1647	0.88	0.12	24,741	1,508	26,249	**13,681**	6,715
sum											*23,114*	*11,346*
Waldringfield N. end SM	489824	14,754	MF	3684.3	1647	0.73	0.27	39,615	6,590	46,205		
restoration potential	inc 489825+....97)	14,754		3684.3	1647	0.88	0.12	47,834	2,916	50,750	**4,545**	2,231
Waldringfield top section	433028	46,922	MF	3684.3	1647	0.51	0.49	87,578	38,130	125,709		
restoration potential		46,922	SM	3684.3	1647	0.88	0.12	152,130	9,274	161,403	**35,695**	17,521
sum											*40,240*	*19,751*

assuming healthy marsh is 12% non-veg - Ref. Colne Point, Green *et al.* 2012, 2009.

Table 7. Shape file codes, extents, standing stocks, calculated vegetation cover, and estimates of carbon stocks, and potential increases in carbon stocks and new salt marsh extent, assuming sediment infill to raise existing eroded salt marsh areas to the height of current salt marsh for Waldringfield in the Deben Estuary, Suffolk.

A	B	C	D	E	F		G	H	I	J	K	L	M
Area	**shape file code**	**area (m2)**	**MF/ SM**	**SM (g C m-2)**	**MF (g C m-2)**		**% veg. cover**	**% non-veg cover**	**carbon stock veg (kg)**	**carbon stock mud (kg)**	**Total carbon stock (kg)**	**potential increase C stock (kg)**	**potential new salt marsh created (m2)**
Waldringfield S section	499611	6,326	SM	3684.3	1647		0.57	0.43	13,248	4,497	17,745		
carbon stock of infill		6,326		3684.3	1647	0.32		0.43			97,074		
restoration potential		6,326	SM	3684.3	1647		0.88	0.12	20,511	1,250	118,836	**101,090**	1,971
Waldringfield eroded mid section	489822	12,508	SM/MF	3684.3	1647		0.67	0.33	30,755	6,852	37,606		
carbon stock of infill	(plus)	12,508		3684.3	1647	0.32		0.43			191,922		
restoration potential		12,508	SM	3684.3	1647		0.88	0.12	40,552	2,472	234,946	**197,339**	2,659
Waldringfield mid section mud	part of 425411	7,631	SM/MF	3684.3	1647		0.00	1.00	-	12,568	12,568		
carbon stock of infill		7,631		3684.3	1647	0.32		0.43			117,094		
restoration potential		7,631	SM	3684.3	1647		0.88	0.12	24,741	1,508	143,344	**130,775**	6,715
sum												*429,205*	*11,346*
Waldringfield N. end SM	489824	14,754	MF	3684.3	1647		0.73	0.27	39,615	6,590	46,205		
carbon stock of infill		14,754		3684.3	1647	0.64		0.27			352,097		
restoration potential	inc 489825+....97)	14,754		3684.3	1647		0.88	0.12	47,834	2,916	402,848	**356,642**	2,231
Waldringfield top section	433028	46,922	MF	3684.3	1647		0.51	0.49	87,578	38,130	125,709		
carbon stock of infill		46,922		3684.3	1647	0.83		0.49			2,776,947		
restoration potential		46,922	SM	3684.3	1647		0.88	0.12	152,130	9,274	2,938,351	**2,812,642**	17,521
sum												*3,169,284*	*19,751*

assuming healthy marsh is 12% non-veg - Ref. Colne Point, Green *et al.* 2012, 2009.

Table 8. Shape file codes, extents, standing stocks, calculated vegetation cover, and estimates of changes in carbon stocks for existing salt marsh at Waldringfield in the Deben Estuary, Suffolk over a 10 year period, based on GoogleEarth 2007 and EAortho 2016 images.

Calculations for carbon losses top 10 cm sediment 2007 to 2016													
A	B	C	D	E	F	G	H	I	J	K	L	M	N
Area	shape file code	area (m2)	MF/ SM	SM (g C m-2)	MF (g C m-2)	% veg. cover	% non-veg cover	carbon stock veg (kg)	carbon stock mud (kg)	Total carbon stock (kg)	change in C stock (kg)	change in salt marsh (m2)	% change salt marsh extent
Waldringfield S section Google Earth 2007	489988	6,326	SM	3684.3	1647	0.54	0.46	12,572	4,799	17,372			
Ortho2016		6,326	SM	3684.3	1647	0.57	0.43	13,248	4,497	17,745	**374**	183	5.38
Waldringfield eroded mid section Google Earth 2007	489822	12,508	SM/MF	3684.3	1647	0.71	0.29	32,810	5,933	38,743			
Ortho2016	(plus...)	12,508	SM	3684.3	1647	0.67	0.33	30,755	6,852	37,606	**-1,136**	-558	-6.26
Waldringfield N. end SM GoogleEarth 2007	489824	14,754	SM/MF	3684.3	1647	0.79	0.21	42,806	5,164	47,970			
Ortho2016	inc 489825+....97)	14,754	SM	3684.3	1647	0.73	0.27	39,615	6,590	46,205	**-1,764**	-866	-7.45
Waldringfield top section GoogleEarth 2007	433028	46,922	SM	3684.3	1647	0.54	0.46	94,078	35,224	129,303			
Ortho2016		46,922	SM	3684.3	1647	0.51	0.49	87,578	38,130	125,709	**-3,594**	-1,764	-6.91
sum												*-3,221*	*-1,581*

5. Estimating the potential of Deben estuary salt marsh sites as nursery grounds for Sea Bass larvae and juveniles.

Sea Bass (*Dicentrarchus labrax*) are an important species of commercial and recreational interest. Sea Bass use salt marsh as seasonal feeding grounds, especially larval and juvenile stages (Colclough et al 2005, Green et al. 2009, Fonseca et al. 2011; Green et al 2012, Colclough 2017a). Green et al. (2009) conducted a comprehensive study of the distribution of fish in five east Anglian marshes (Fig. 3). Using flume net-fish traps placed across creeks, fish numbers were measured on ebbing tides, and standardised as numbers of larval and juvenile fish per tide per 100 m^2 extent of salt marsh creeks.

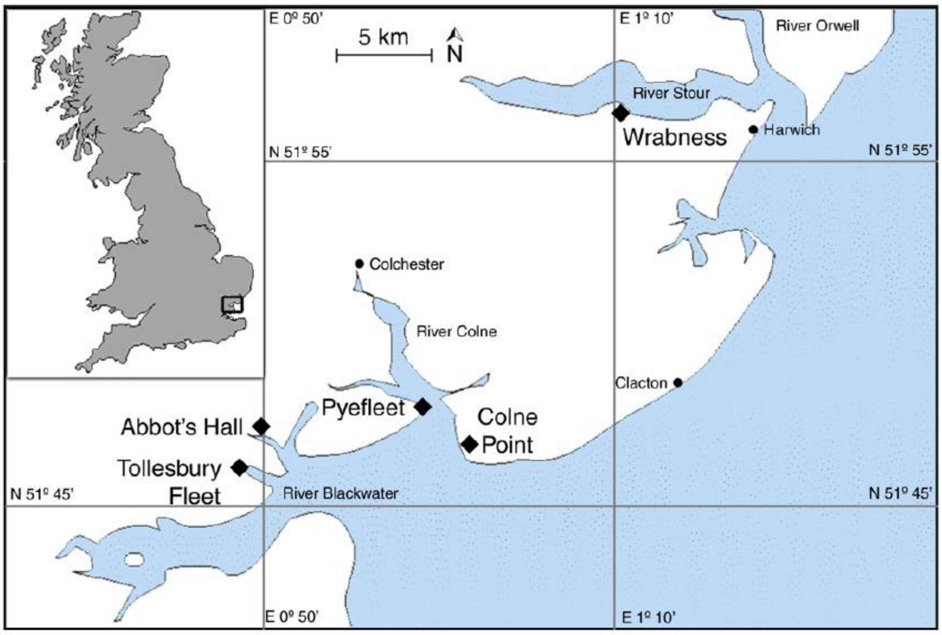


Figure 3. Five saltmarshes investigated for seasonal fish use by Green et al. (2009).

From Green et al. (2009), we have taken an average numbers of larval and juvenile (year 1+) sea bass using a set extent of saltmarsh per tide, during the relevant seasons on the year (Table 9). Using this, we have estimated the daily fish use of the current marsh extents in the Deben, and calculated the potential daily fish use if restoration occurred (using the assumption that healthy salt marsh comprises 88% vegetated surface and 12% are of creeks (form Green et al. 2009).

Table 9. Average numbers of sea bass (Dicentrarchus labrax) captured in

		Average density of Sea Bass (from Green et al. 2009)			
	season	per 100 m^2 creek (indiv. $tide^{-1}$)	standard error	per 100 m^2 salt marsh (indiv. $tide^{-1}$)	standard error
Larvae	June to Sept	5.62	1.43	0.67	0.17
Juveniles	May to Nov	1.47	0.52	0.18	0.06

Using these factors, and grouping the individual salt marsh shape files (Appendix 1, 2 & 3) into coherent ecological units, we can estimate the current and future potential increase in sea bass use of the three marsh locations (Table 10). These are broad estimates: fish use can be locally variable (Green et al. 2012), with seasonal variation (Green et al. 2009, Colclough 2017a), and also relies on a spawning population of adults to provide a source of larvae and juvenile fish to the estuary. Colclough (2017b) reported sea bass using the Waldringfield marshes in October 2016, with a total of 23 fish caught in three sampling locations, in a size range of 60-102 mm. It is not possible to directly compare these values to the "per area values" given in Table 9, but both the orders of magnitude and size ranges reported by Colclough (2017b), and also in a similar study in Hazlewood marsh in the Alde estuary (Colclough, 2017a), concur with the values reported in Green et al. (2009) and Green et al. (2012).

Table 10. Estimated sea bass (*Dicentrarchus labrax*) daily use of three different salt marsh extents in the Deben estuary (per total extent of marsh, based on values for larvae and juvenile fish, and seasonal occurrence given in Table 9). The potential increased capacity, and total resulting daily use, if salt marsh restoration was successful is given.

		Sea Bass usage:- numbers (individuals) per tide during season			
		Larvae (average tide^{-1})	S.E.	Juveniles (year 1+) (average tide^{-1})	S.E.
Melton / Sutton Hoo					
marsh west of track	current	163	*41*	41	*15*
	potential	57	*15*	15	*5*
	total	**220**	***56***	**56**	***21***
marsh east of track	current	34	*9*	9	*3*
	potential	25	*6*	7	*2*
		59	***15***	**16**	***6***
mudflats within old seawall	current	0	*0*	0	*0*
	potential	660	*168*	168	*61*
		660	***168***	**168**	***61***
Kyson and Loder's Cut					
Kyson Point	current	57	*14.6*	15	*5.3*
	potential	51	*12.9*	13	*4.7*
	total	**109**	***28***	**28**	***10***
Loder's Cut Island	current	50	*12.6*	12.6	*4.6*
	potential	116	*29.3*	29.3	*10.8*
	total	**165**	***42***	**42**	***15***
Loder's cut - East Side	current	206	*52.3*	54	*19.2*
	potential	144	*36.4*	37	*13.4*
	total	**350**	***89***	**91**	***33***
marsh N. of Waldringfield					
saltmarsh	current	174	*44.1*	44	*16.2*
	potential	104	*26.4*	27	*9.7*
	total	**278**	***71***	**71**	***26***
saltmarsh north of point	current	182	*46.2*	47.5	*17.0*
	potential	134	*34.1*	35.0	*12.5*
		316	***80***	**83**	***29***

6. References

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Colclough, S. R. (2017a) Hazlewood Marshes, Alde Estuary, A survey of fish populations associated with the marshes Draft Report February 2017. SC^2 Reference: SuffolkWT/001 Colclough & Coates - SC^2 Ltd, Chatham, Kent, ME5 9JQ

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Fonseca, L., Colclough, S., Hughes, R.G., (2011) "Variations in the feeding of 0-group bass Dicentrarchus labrax (L.) in managed realignment areas and saltmarshes in SE England." Hydrobiologia 672.1: 15-31.

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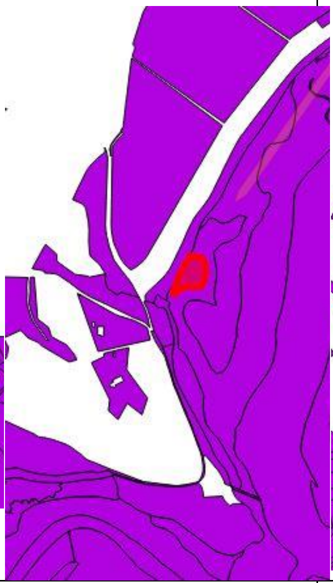
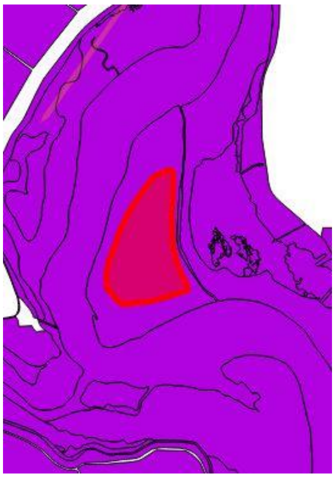
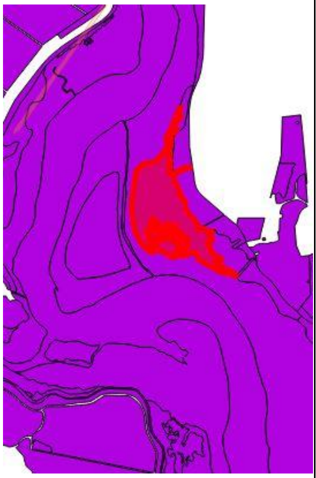
RoyalHaskoningDHV. (2018). Healthy Estuaries 2020: an assessment of estuary morphological equilibrium – Aldre-Ore, Deben and Hamford Water. Natural England Commissioned Reports, Number250.

Thornton D.C.O., Dong, L.F., Underwood, G.J.C. and Nedwell, D.B. (2002) Factors affecting microphytobenthic biomass, species composition and production in the Colne estuary (UK) *Aquatic Microbial Ecology*. 27: 285-300.

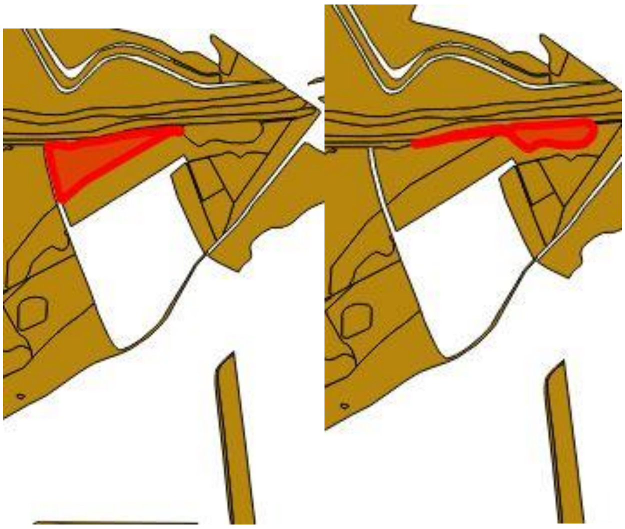
END

Appendix 1. Shape files codes and images for the areas described in Table 1.

425461 	**433037** 	**433010** 	
433009 	**433038** 	**489834** 	**489833** 

Appendix 2. Shape files codes and images for the areas described in Table 2 & 3 (Melton).

489986 + 490050

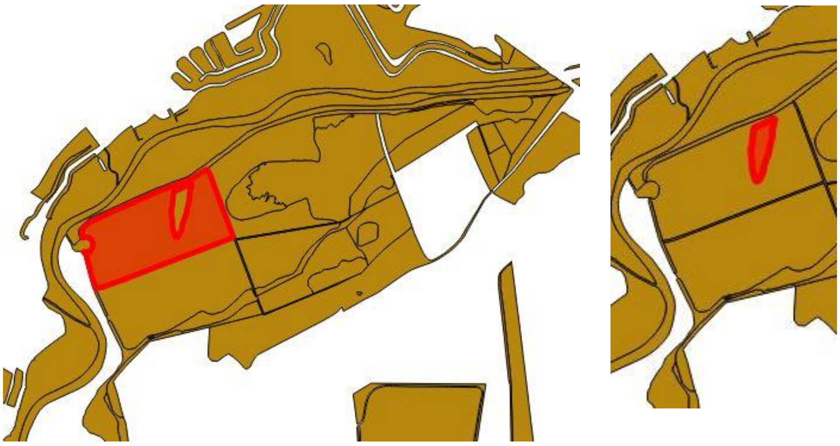


452510

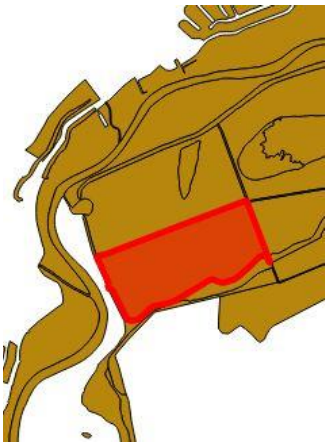
452511

489988

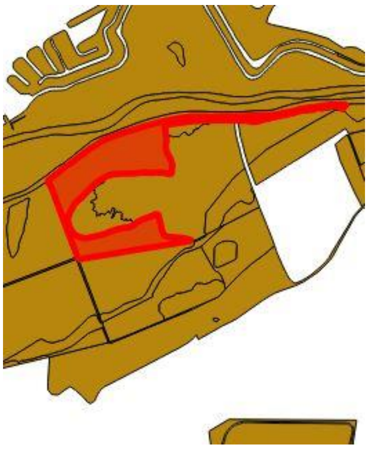
425253+452459



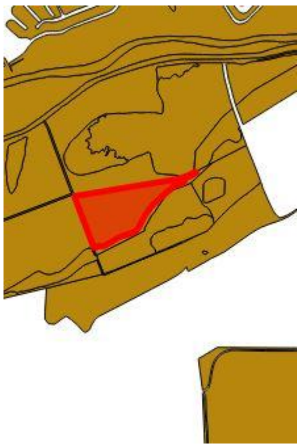
425244



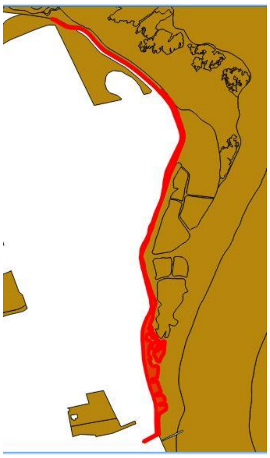
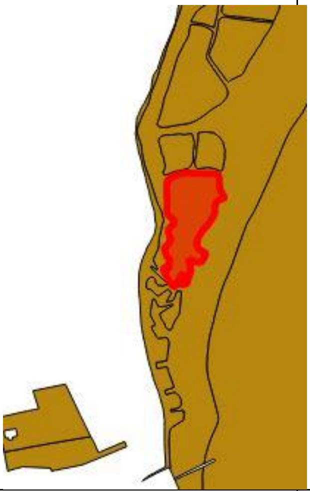
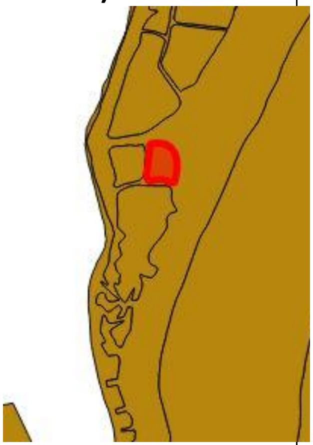
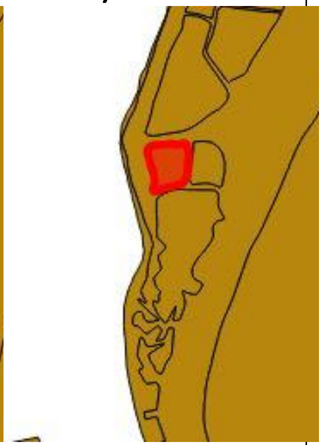
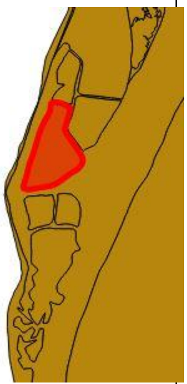
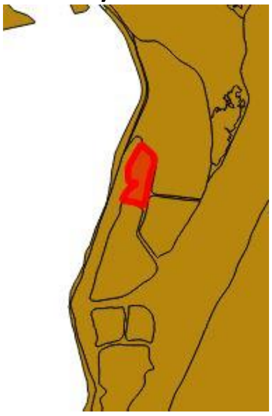
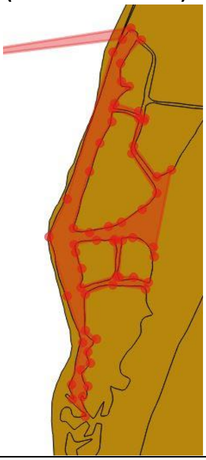
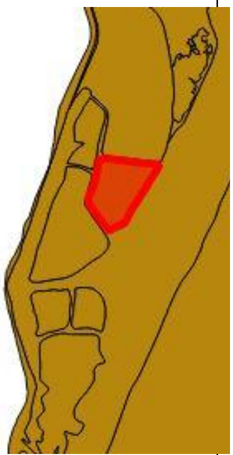
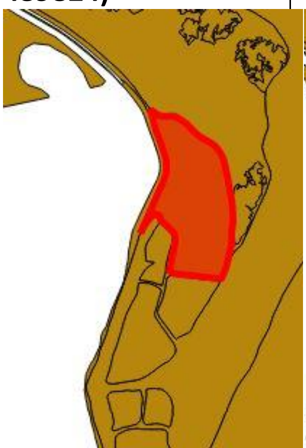
425250



425245



Appendix 3. Shape files codes and images for the areas described in Table 4 & 5 (Waldringfield).

499611 	**489822** 	**489895** (inc. with **489822)** 	**489894** (inc. with **489822)** 
489823 (inc. with **489822)** 	**489896** (inc. with **489822)** 	Part of **425411** (mudflat infill) 	**489824** 
489825 (with 489824) 	**489897 (with 489824)** 	**433028** 	

Appendix 4. Methodology for extracting relevant data from shape files.

IMAGE ANALYSIS USING IMAGE-J

Download the ImageJ bundle "Fiji" which includes pre-installed plugins:
https://imagej.net/Fiji/Downloads

Downloads are available for Windows 64-bit, Windows 32-bit, MacOS, Linux 64-bit, and Linux 32-bit

Your Download will appear as a Compressed (zipped) Folder. The folder will be called Fiji-win64 for example, if you are downloading the Windows 64-bit program.

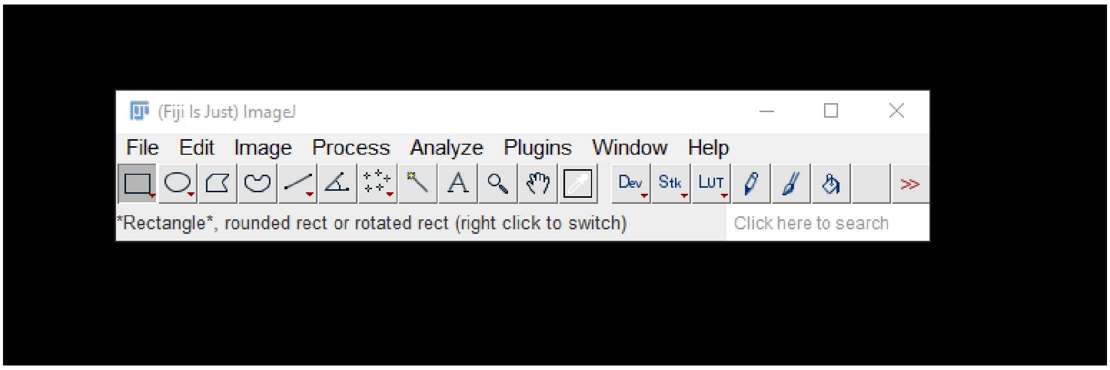
Once downloaded to your destination of choice, right click the zipped folder and select "Extract all"

Once extracted, double-click on the new folder which will have the same name as the zipped folder

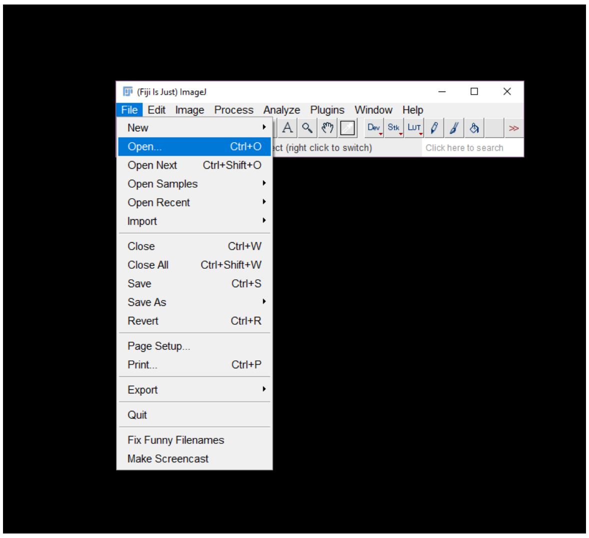
Once open, you will see a folder called "Fiji.app" Double-click this folder

You will see a lot of files and folders in Fiji.app, however, the only item you need is the file with the microscope icon in front of it. If you have installed Fiji for Windows-64, the file will be called ImageJ-Win64

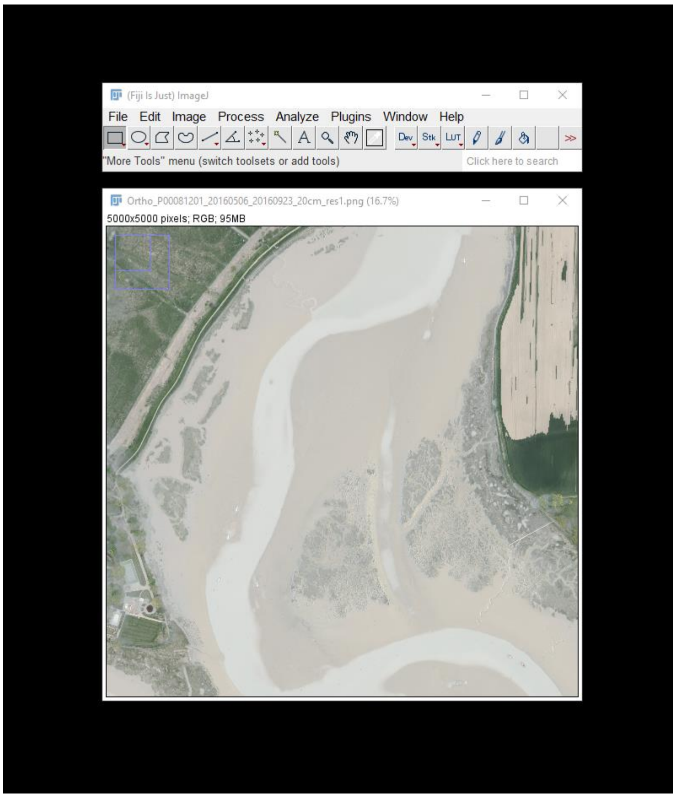
Double click the file, the Fiji logo will appear and the ImageJ window will open



The next step will be to add the image you want to analyse. To do this, click File → Open

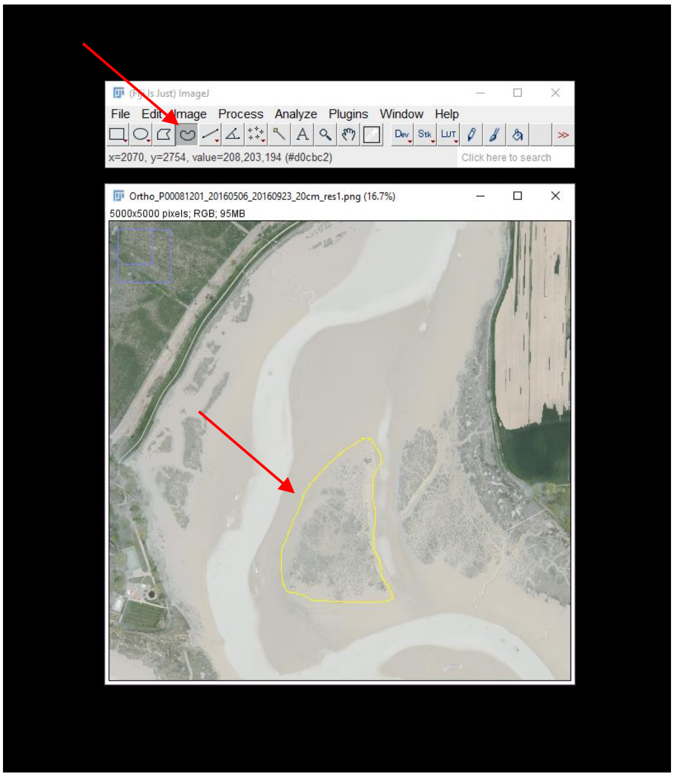


When you click "Open", a window will appear asking you to select the file you wish to open for analysis. The image can be any type of image file including jpeg, png, or tiff to name a few.



Once selected, the image will open in the Fiji/ImageJ window.

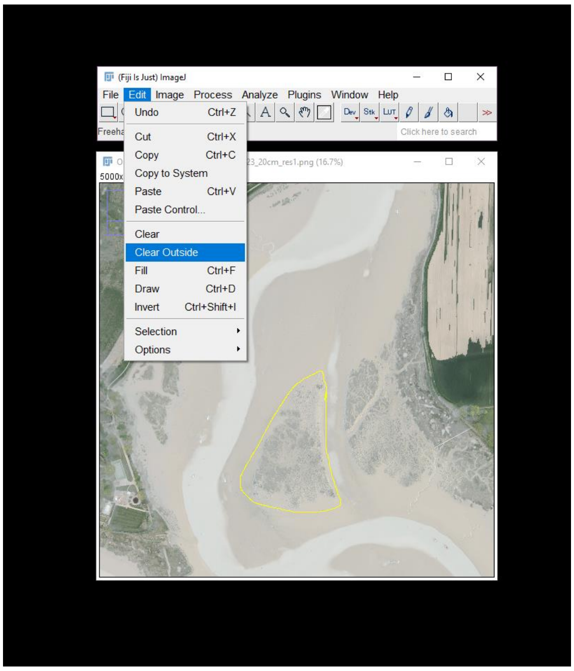
You can expand or reduce the size of the image box to your personal preference; it will not interfere with the analysis.

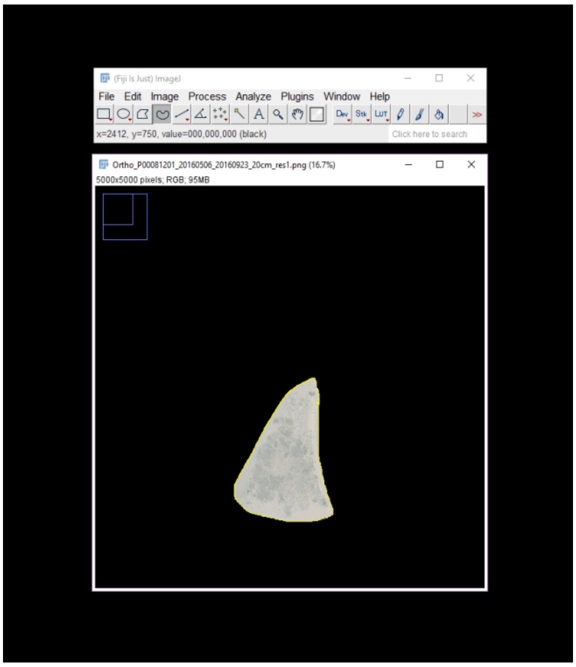


Next, click on the bean-shaped icon called Freehand Selection.

Hold down the left mouse button and trace around the shape you wish to analyse.

Note: If you make a mistake or need to redraw a section, you will have to re-click the icon and start drawing from the beginning.

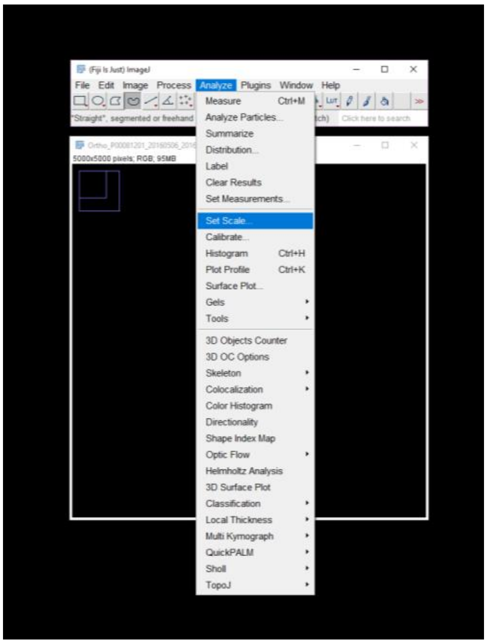


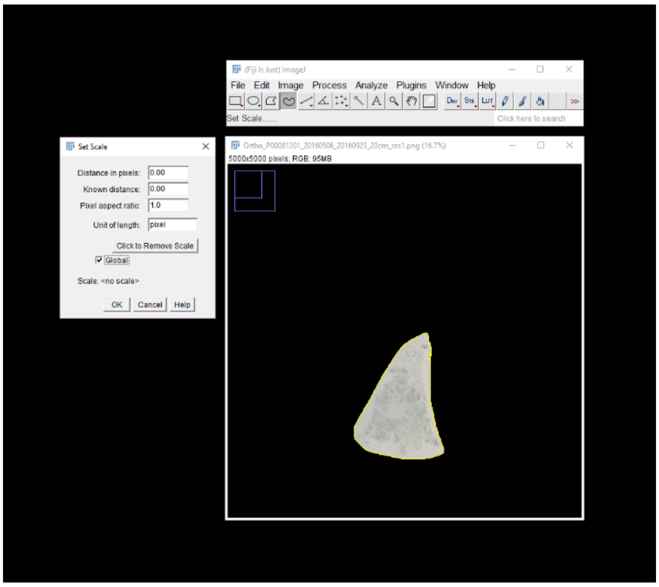


Once you have drawn/traced the area you wish to analyse go to Edit → Clear Outside.

This will blackout all parts of the image that are not of interest (second image above).

Alternatively, if you have a very large area to analyse you can trace the area you are not interested in and click Clear. This will clear the inside.

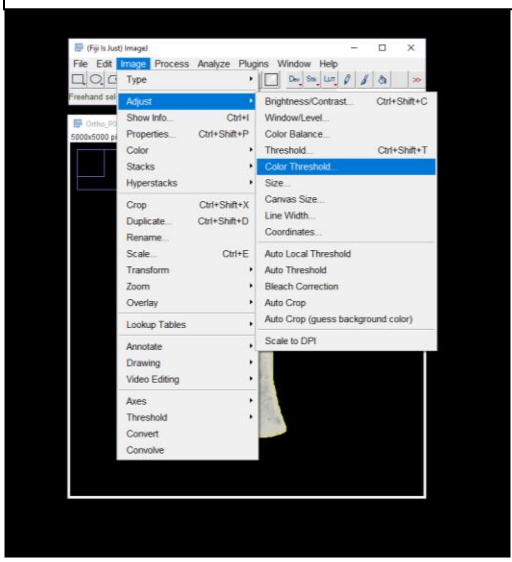


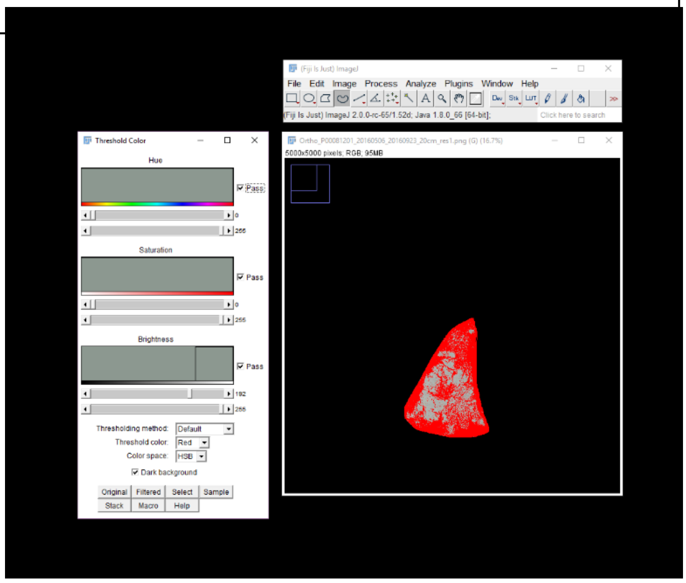


Now click Analyse → Set Scale.

Click on the button that says, "Click to Remove Scale"

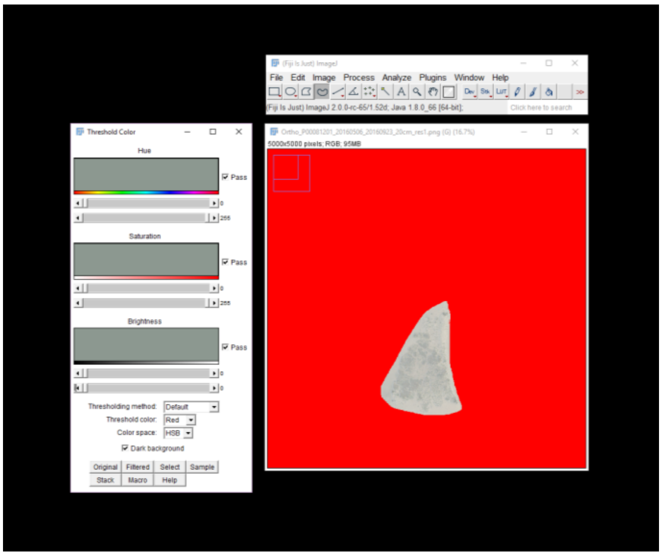
Then check the box that says Global and click Ok





Next, click Image → Adjust → Colour Threshold

A new window will appear and your image will change to red.



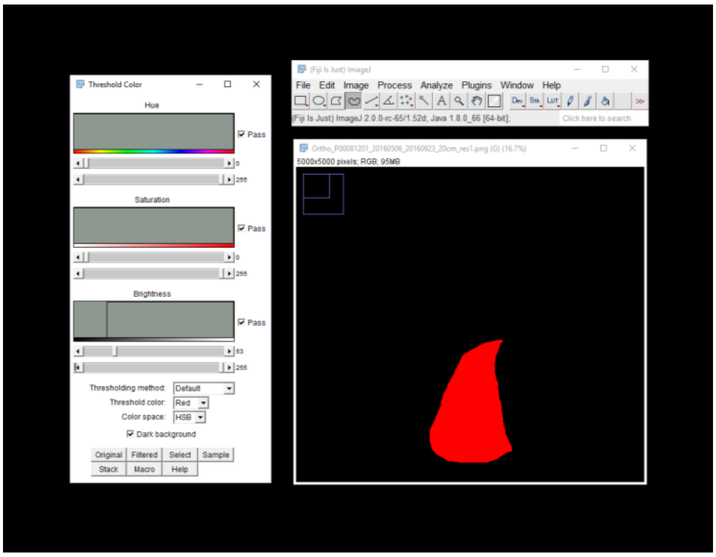
Under the heading Brightness, move both sliders all the way to the left.

Allow a minute for the software to update. Once updated, the area around your image will be red.

Next, move the bottom Brightness slider to the right until it is at about 50.

Then move (or use the arrows) the top slider so it is right above the bottom slider.

Now move the bottom slider back all the way to the right, where we started. Be sure to keep the top slider in place.

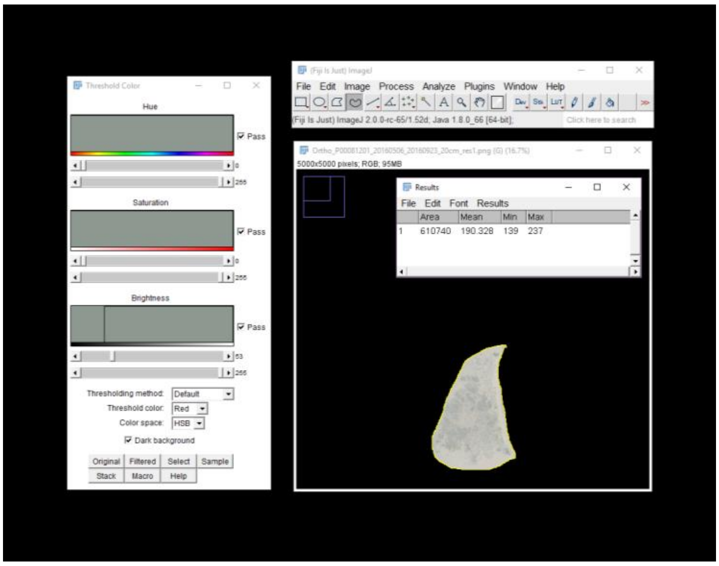


Your area should now be in red with a black background.

Once the two sliders are in place, click Select

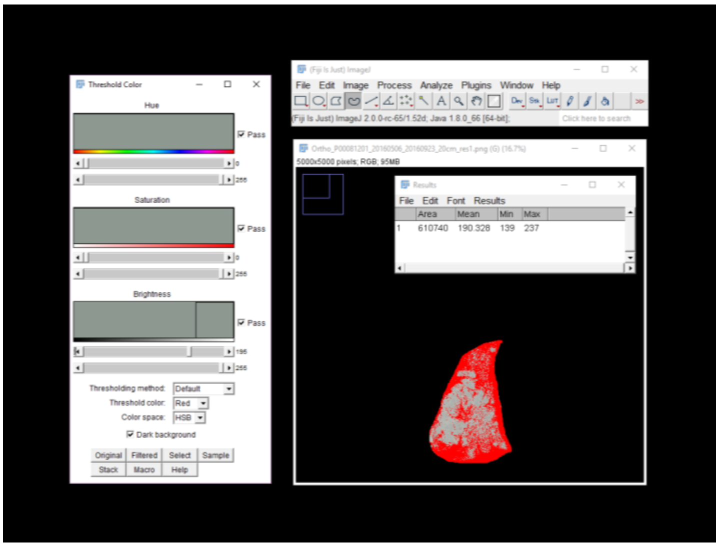
The image area will go back to normal.

Now go back up to the main menu and click Analyse → Measure



A new window will appear listing Area, Mean, Min, and Max. We are interested in the Area.

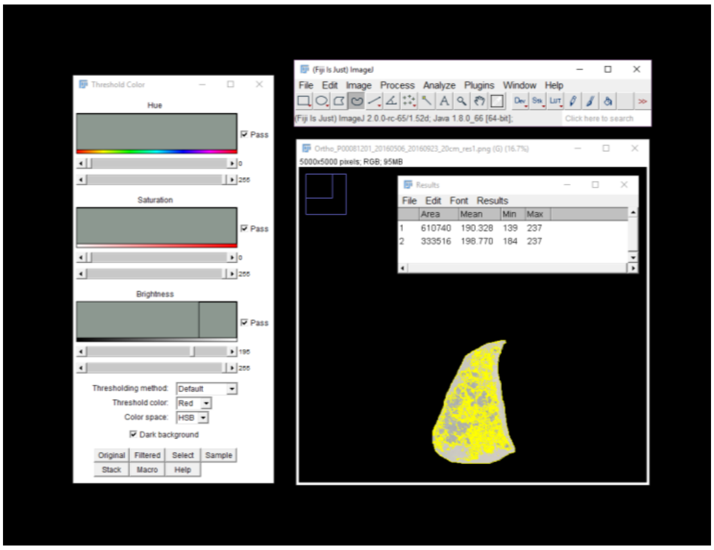
Make a note of this first measurement. This is the number of pixels.



Now move the top slider all the way to the right

Then slowly move it back to the left until you see red filling in the area of interest.

For this example, I keep moving the slider to the left until it appears all non-vegetation area is covered in red.



Note: It may be helpful to zoom in and out to ensure you are as accurate as possible when filling the area in red. You can also use the Original button (at the bottom) to see the image before and after shading. Move the slider left and right until you are happy with the shading.

Once you are happy with the area is covered click on Select.

When you click Select, the area will be outlined in Yellow.

Now click Analyse and Measure.

A second measurement will appear in your window. This is the pixels of the area selected.

Divide the smaller number by the larger and multiply that final value by 100. This will give you the percent of the area shaded (i.e. percentage non-vegetation).

In this example, the image is approximately 54.6% non-vegetation.

To obtain the percent vegetation, simply subtract the non-vegetation percentage from 100 (100-54.6 = 45.4%). In this image, there is approximately 45.4% vegetation.