EUROSAM - TASK 6

FINAL REPORT

ANALYSIS OF THE NUTRIENT CONTROL OF THE ORGANIC CARBON CYCLE IN A SALT MARSH (ANCOSM) AND THE MODELLING OF THE NITROGEN CYCLE (NITROMOD)

L.A.Boorman, J. Hazelden and M.S. Boorman
L A B Coastal
The Maylands
Holywell
St Ives
CAMBS PE27 4TQ

June 2000

EUROSAM - TASK 6 FINAL REPORT

ANALYSIS OF THE NUTRIENT CONTROL OF THE ORGANIC CARBON CYCLE IN A SALT MARSH (ANCOSM) AND THE MODELLING OF THE NITROGEN CYCLE (NITROMOD)

CONTENTS

PART B. MODELLING OF ORGANIC AND NITROGEN FLUXES

PART A. ORGANIC MATTER FLUXES AND EXCHANGES

1. INTRODUCTION

The modelling of salt marsh processes is crucial for the successful management of a vital coastal resource (Boorman, 1999). Of the various approaches tried in the past the treatment of the subject by considering the processes on the basis of individual small areas of marsh as component cells seemed to offer the best chances of success (Boorman *et al*., 1996). This cellular approach does, however, demand a very detailed knowledge of salt marsh structure and spatial characteristics. It also had the disadvantage that it was based on the assumption that the addition of sediment to the marsh surface is the sole contributor to the building up of the salt marsh. Recent calculations show that below-ground primary productivity can also make a significant contribution to this process (Boorman, 2000).

The alternative approach to the cellular concept is based on a study of the overall cycling of organic material in the salt marsh ecosystem. The fact that the incoming sediment has an organic component means that the study of organic carbon dynamics can include sediment fluxes whilst the alternative study of sediment dynamics precludes the detailed consideration of organic cycling. The cycling of organic carbon can best be studied by a broad system model such as ANCOSM which is described below. ANCOSM can be varied continuously to fit the recognisable salt marsh sub-divisions that exist between the extremes of pioneer marsh and high marsh. It does not have to be limited to any particular number of vegetation types, indeed, when fully developed, it could be used to test the validity of the structural/functional divisions made.

A problem that is common to all models is that two data sets are needed; one to build the model in the first instance and a second data set to validate its functionality. The ANCOSM model proposed will be built with existing data from two previous salt marsh studies supplemented by data from the literature where necessary. The innovative methods for field research that are set out below will ensure that the initial model will be validated by a second data set collected by a new and independent approach (the *in situ* mesocosm). This will ensure the independence of the two data sets and thus the validity of the final model. Because it is based on salt marsh functional units, units that can be defined and tested, it will be equally applicable to large or small salt marsh systems. It will serve to identify the environmental control of the major processes of salt marsh productivity, salt marsh fluxes and development. It will thus provide a vital tool in the understanding and management of salt marshes under a wide variety of situations.

The objective of these studies is to define the main parameters of the various organic carbon cycles in the salt marsh ecosystem and to identify the main environmental factors which control them. The approach proposed here (ANCOSM) is a new way of collecting data on salt marsh processes designed to facilitate the validation of models built up with existing data collected on established lines. The data collected by this new approach will be supplemented by selective tidal monitoring and flux data taken on the established lines. This study (Task 6a) concentrates on the modelling of the organic carbon cycle and is linked with a parallel study (Task 6b) concentrating on modelling the turnover and cycling of nitrogen.

These innovative proposals are based on the approach to salt marsh process studies proposed at the recent Linnean Society Meeting on Salt Marshes (Boorman, 2000) which identified the various routes and processes by which organic matter was transformed. The emphasis of the paper was on the processes through which salt marshes provided a link between land and sea. However, it also served to identify the breadth of the range of processes of production, mineralisation and transfers involved. In addition, fresh consideration was given to aspects of salt marsh growth. The vertical growth of the salt marsh is generally interpreted in terms of the accumulation of sediment on the surface. A careful examination of the data does, however, indicate that below-ground production can significantly supplement the direct addition of material to the marsh surface. The feasibility of building a predictive model along the lines proposed has been tested with a preliminary version which also allowed the feasibility of the experimental approach outlined below to be tested.

While the experimental approach based on ANCOSM formed the central core of these studies there were other studies which were considered necessary to support and enhance the interpretation of the ANCOSM results and to aid in the modelling of the cycling of organic matter in salt marsh systems. These studies relate both to the further elucidation of salt marsh processes in relation to the ANCOSM study site and to the interpretation of the data from that site with regard to its significance on a much wider basis.

It had become clear from the earlier studies at Tollesbury (Boorman *et al.,* 1996) that the vertical growth of the salt marsh surface is dependant on both the addition of sediment to the marsh surface (accretion) and on the addition of organic material below-ground as a result of primary production from roots and rhizomes of salt marsh plants. While both these processes contribute positively to the upward growth of the salt marsh the overall effect is reduced by the subsequent compaction of the mineral and organic sediment in the deeper layers of the marsh. Studies were therefore proposed to make an estimate of the net effect of the balance between the various soil processes involved in changes in the level of the salt marsh surface.

Many recent studies, particularly the precursors of the present project, have emphasised the importance of the contribution made by the intertidal to the productivity of adjacent coastal waters through the export of various forms of organic matter. The estimates of the magnitude of these contributions varies considerably from site to site but is commonly quoted as being between 20 and 40 %. The studies involved have been based largely on sites where tidal creeks have provided a channel along which the exchanges could be determined and monitored. However, with the discharge of the creeks into more or less open sea the subsequent movements of the organic material were largely untraceable.

Scottish sea lochs provide interesting parallels and contrasts. They each have varying areas of intertidal and these areas themselves have varying proportions of salt marsh. The individual lochs are relatively self-contained water bodies, often isolated by the presence of distinct sills. This enables the fate of the organic matter produced to be followed more closely. The different lochs also have varying inputs of fresh water in relation to the areas of the lochs themselves. This makes the variable conditions in the different lochs in some ways similar to differences between lowland estuaries with their varying degrees of marine influence.

The Scottish sea lochs vary greatly in the proportion of the total area which is intertidal and this is not always related to the depth of the loch. The proportions of the various units within the intertidal will affect the organic exports from this area. The imports of inorganic nutrients from the water body of the loch will be similarly affected. The fauna and flora of a particular loch will be crucially dependant on both the balance between the various physico-chemical parameters, as outlined above, and on the organic, nutrient and sediment exchanges between the intertidal and the water-body. The properties and the exchanges clearly have an environmental component in the form of climatically-mediated controls.

In marked contrast to many English salt marsh sites the sediment supply to these salt marsh sites in Scottish lochs is limited or, sometimes, very limited. Loch Moidart is predominately an area of fine sediment but, except under extreme storm conditions the sediment load of the water is low and thus there is limited accretion. Many of the lochs are predominantly areas of coarse or very coarse sediments ranging from sand (head of Loch Ailort) to shingle (Loch nan Ceall) with little annual deposition. In consequence of this the salt marsh areas are far less dynamic than in estuarine situations further south. To varying extents the accumulation of peat deposits can and does partially compensate for the lack of incoming sediment. Otherwise, apart from the few lochs with a good supply of fine sediment, such as Loch Moidart, the loch salt marshes must be regarded as approaching "fossil" status, having little active growth. This has considerable implications for the management of these marshes as it would imply that they are unlikely to have the self-repairing features of normal dynamic salt marsh sites. They are nevertheless areas of a unique habitat with a very limited distribution along the whole of the west coast of Scotland.

Although the study and monitoring of terrestrial-marine fluxes in Scottish lochs is a key factor in the management and conservation of unique areas of biodiversity it has much wider implications in the study and modelling of salt marsh processes and in the development of management policies.

The various studies performed under this part of Work Package 6 were formulated to provide information for the interpretation and modelling of salt marsh organic fluxes and to permit the application of data and models to as wide a range of salt marshes as possible. The Decision Support System being developed under Work Package 7 requires the construction of models covering the various salt marsh processes. It also needs the necessary background data for the production of a DSS that is both comprehensive in its scope and applicability and as user-friendly as possible. This part of the report is based specifically on the need to fill gaps in the existing salt marsh data gathered under the two previous projects to enable the required models to be constructed. It should be noted that some of the information acquired specifically for the DSS is not included in this report.

2. METHODS

2.1. ANCOSM MESOCOSMS

The experimental approach was to isolate large cores of marsh soil as "*in situ*" mesocosms, together with the vegetation, using sections of plastic piping, and to determine the organic and mineral contents by taking small core samples at intervals through time and space. The size of the large cores, forming the mesocosms, was selected to ensure that these are larger than the size of the estimated extent of the root zones of individual salt marsh plants. It was proposed that the standard isolated core would be deep enough to take in the effective root zone of the salt marsh plant species. It was proposed that the organic fluxes would be modified in various ways including the selective blocking of inputs such as primary plant production, surface litter and sediment accretion. This would enable the major components of the organic fluxes to be determined. Changes in the various soil components were determined at quarterly intervals. The holes left within the mesocosms by this core sampling were filled with material from spare small cores taken from areas of salt marsh subjected to similar treatments.

A preliminary study was made of the soil organic matter and of the main plant rooting depth to verify the assumptions made in the proposed design of the mesocosms. Soil cores were taken to a depth of 200 mm and the Loss-on-Ignition (LoI) was determined to indicate the organic content at 10 mm intervals. Soil samples were taken across the experimental area at Tollesbury, Essex and the vegetation type associated with each sample was also recorded. The site chosen for the mesocosms was in the main marsh at Tollesbury used in the earlier studies. This area had been classified as Lower marsh (Boorman, 1994) and it is dominated by various mixtures of *Puccinellia maritima* and *Halimione portulacoides*. Full information on this important salt marsh study site is available in the reports of the two previous projects carried out in the area (Boorman, 1994 & Lefeuvre *et al*. 1993 & 1996). The various treatments which were applied to the mesocosms are detailed below (Table 1).

Table 1. Details of the different treatments applied to the mesocosms established at Tollesbury under the ANCOSM project

Ref.	Treatment	Method of application
T1	Control	Full normal vegetation
T2	Control - algae	Algae removed by hand
T3	Litter excluded	Coarse net cover and litter removed
T4	Sediment & litter excluded	Fine net cover
T5	No aerial plant growth	Plants cut off at surface
T6	No plant growth	Core filled with old sediment
T7	No plant growth & no litter input	Old sediment + coarse net
T8	As above + no sediment input	Old sediment + fine net cover

The treatments were based on the mesocosm cores 190 mm (approx. 7.5") in diameter and extending to a depth of 200 mm (the active root zone). The liners had an internal diameter of 190 mm and an external diameter of 200 mm. The total depth of liner was 250 mm. The liners extended approximately 25 mm above the soil surface but there were four 12 mm drainage holes at ground level. There was also approximately 25 mm of the liner below the 200 mm depth within which sampling occurred.

The samples of soil for analysis were taken with a 20 mm (0.75") diameter corer providing a sample volume of 60 ml. With a mesocosm volume of approximately 6.8 l this sample size ensured that a maximum of 12% of the original material would be removed over the course of the experiment. The holes left by the sample corer were re-filled with similar material taken from spare mesocosms. The samples were taken quarterly with two sample cores taken from each mesocosm each time. Each treatment was replicated five times together with an additional set of treated but unrecorded cores to provide replacement material to fill the holes left by sampling. There were thus 8 x (5+1) = 48 mesocosms in total.

The ANCOSM mesocosms were installed during the first two weeks of August, 1998 using a special wooden inserting tool which protected the liner while it was driven into the soil to the appropriate depth. Where the treatment involved 'old sediment' the soil inside a mesocosm was removed and replaced with salt marsh taken from a depth of 300 mm or greater.

The core samples from the recorded mesocosms (2 x 48 = 144 per quarter) were analysed to determine dry weight and ash-free dry weight of each sample (an estimate of organic C content). Previous studies had indicated that the optimum treatment was to dry the samples at 220^{o}C and subsequently to ash them at 450^{o}C. Each core sample was divided into four sub-samples (0 - 50 mm, 50 - 100 mm, 100 -150 mm and 150 - 200 mm). There were thus 2 x 4 x 40 = 320 sub-samples per quarterly sampling. The sampling took place quarterly starting in August 1998. At the same time as the sampling took place the various treatments were renewed as appropriate.

It was considered that additional data on nitrogen levels in the various parts of the system were needed in order to support the building of the NITROMOD model (see Part B of this report, pps 40-48). Samples of water, soil, recently deposited sediment and various plant tissues were therefore collected from the Lower Marsh at Tollesbury in conjunction with the ANCOSM studies. The samples were collected from the ANCOSM mesocosm site in August 1999, October 1999 and January 2000. The soil samples were collected using plastic corers 800 mm long and 60 mm in internal diameter which were pushed 500 mm into the marsh soil. The sampler was withdrawn and the cores were extruded. The cores were divided into 100 mm sections for analysis. Bulk vascular plant, litter and algae samples were also collected from surface of the Lower Marsh in the same area. Samples of new, recently deposited, sediment were collected from areas of bare mud adjacent to the mesocosm site. Water samples were collected in 500 ml plastic bottles from an adjacent creek at high water. The samples were then stored in a deep-freeze. All the samples were sent to the Université de Rennes for analysis using their standard analytical methods.

2.2. SALT MARSH SOIL COMPACTION PROCESSES

Previously reported studies (Boorman *et al*. 1998) on the rates of sediment accretion at Tollesbury, Essex, and Stiffkey, Norfolk, had been based on the use of 2 metre long reference transects made between pairs of blocks (Feno™ markers) anchored at 600 mm depth in the marsh. It had been assumed that this depth would provide a stable level for reference purposes. It had become clear from the existing data and from preliminary calculations that these assumptions obscured important processes in salt marsh development and growth and that it was necessary to define more precisely the position and magnitude of the processes of soil compaction.

Two approaches were used to gain some insight. The first was a study of the changes in the bulk density of the various layers of the salt marsh sediment and the second involved the relative changes in position between markers anchored in different marsh layers.

A series of 60 mm diameter cores were taken at Tollesbury to a depth of 500 mm and, when fully inserted, the depth of the core from the top of the corer tube was recorded to allow for compression during sampling. The corer was then filled with sea water and the tube was sealed with a cork and then the tube and sample were withdrawn, sealed in polythene and returned to the laboratory for detailed examination. It was found that the process of sampling resulted in the compression of the core by approximately 15 % . A correction was applied for this compression in the analysis of the data obtained from these cores.

The blocks (Feno™ markers) anchored at 600 mm depth (yellow) in the marsh were supplemented by the addition of further blocks anchored at 400 mm (white) and 1000 mm (red) depths. The new markers were set out in conjunction with the existing yellow markers giving nine sets of blocks, each set consisting of two yellow and one each of the red and white blocks. A portable precision level with a digital depth gauge was designed and constructed to measure the relative levels between the blocks at each of the nine stations to an accuracy of better than 0.5 mm. The system was established in August 1998 and the blocks were measured six times over the following 15 months.

2.3. SCOTTISH LOCH STUDIES

The sampling programme was based on that being used at Tollesbury but simplified to get the maximum information from a necessarily limited sampling programme. Valuable site information including descriptions of the vegetation and site maps were provided by Scottish Natural Heritage. The main sampling was completed in August, 1999 with additional information and vegetation mapping in October of that year. The plant species composition of the main salt marsh zones was recorded using the Domin scale of cover and abundance.

Soil cores were taken, in the main area of the marsh and on the adjacent flats, to a depth of 250 mm or the actual depth of the soil if less. Clip samples of the vegetation were taken to estimate the primary productivity of the marsh vegetation. Samples were taken of the adjacent seawater. The soil, vegetation and soil samples were taken back to the laboratory for detailed analyses. The main sample sites that were used in this part of the study are given in the table below (Table 2).

Table 2. Study Sites in Lochaber, examined in the Scottish lochs study, 1999.

Site Name	Grid Reference	Area Km^2	% Intertidal	Salt Marsh Area (Ha)	Salt Marsh Area %
Kentra Bay	642678	3.3	81	40.7	12.3
Loch Moidart	707722	6.5	75	17.4	2.7
Loch Ailort	763820	8.2	24	8.9	1.1
Loch nan Ceall	660862	2.8	10	3.0	1.1

In addition information and samples were taken from Loch Beag, Skye where the building of a road bridge across the mouth of the loch had potentially altered the hydrodynamics of the system and which therefore was considered likely to be a significant source of information of relevance to salt marsh management.

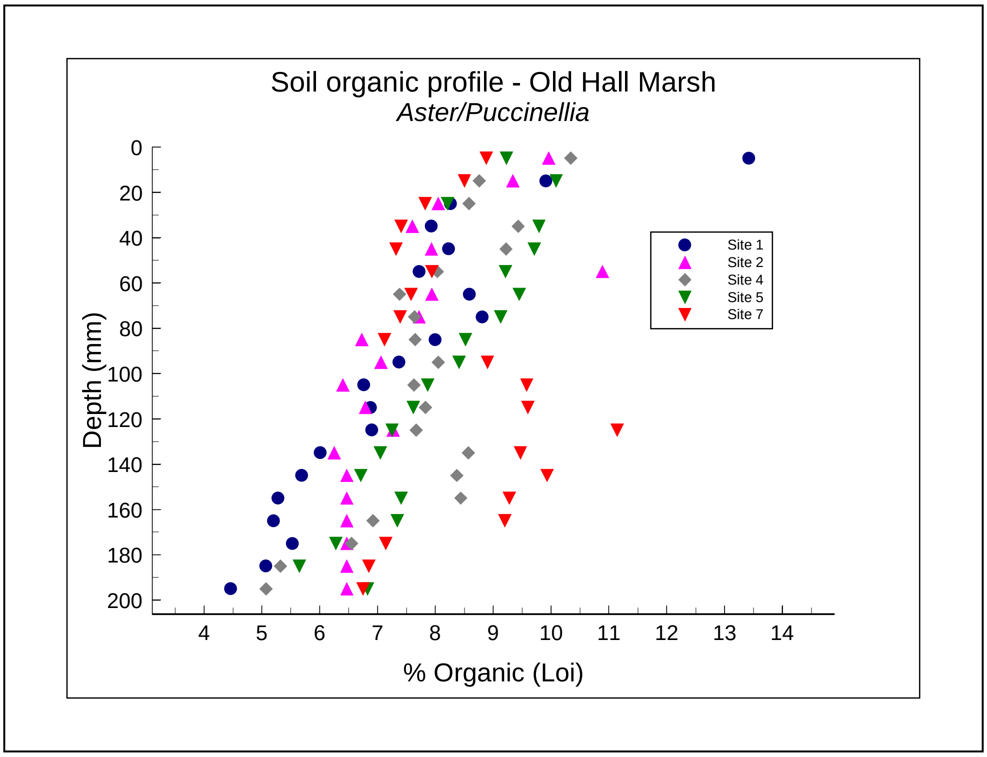
At each of the Lochaber Scottish study sites measurements were made using a Stanley Compulevel™ to determine the vertical range of the major salt marsh vegetation zones. Because of the remote nature of the location generally there were not sufficient Ordnance Survey reference points to locate the levels absolutely to OD (Newlyn). At each site the level of High Water Mark Spring Tides (HWMST) was determined from the drift line debris and from the available tidal data. The level of HWMST was then estimated in terms of OD. No such data was collected for Loch Beag in Skye but it seems likely that the vertical distribution of the main plants communities were similar to those of the mainland sites.

3. RESULTS

3.1 ANCOSM MESOCOSMS

The preliminary soil sampling showed that the bulk of the soil organic content occurred in the top 100 mm of the soil and this coincided with the observed zone of maximum occurrence of living roots and rhizomes. The organic content of this layer was generally between 8 % and 14 % expressed on a dry weight basis. Below this level there was a rapid reduction in the organic content to less than 5 % at or around the 150 - 200 mm depth (Fig. 1). Some dead root remains were, however, visible at these depths and the occasional living root could be found even at depths of 1000 mm. The details of the soil organic profile did, however, differ considerably from sample site to sample site but there did not appear to be any correlation between the composition of the vegetation and variations in the soil organic content.

Figure 1. Soil organic profile of the salt marsh study sites at Tollesbury Essex.



The vegetation samples taken confirmed the previous findings regarding the primary productivity of this area (Boorman and Ashton, 1997) although the contribution by algal growth was generally rather higher than in the previous studies with a very significant contribution by the brown algal species *Bostrichium scorpioides*.

The first sampling of the ANCOSM mesocosms was completed on the 12th August, 1998, immediately after the completion of the process of their installation. Subsequent sampling was carried out on the 12th December, 1998; 2nd March, 1999; 24th May, 1999; 4th August, 1999; and on the 25th October 1999. At this stage the disturbance created by the taking of the sample cores appeared to be likely to have an effect on the growth of the vegetation and on the sampling process itself and the experiment was therefore terminated.

Examination of the data confirmed that the depths of the mesocosm were sufficient to include all of the active root zone. This was indicated by the generally lower organic content of the lowest (150 - 200 mm depth) soil samples (Table 3). There was significant variation in the organic content of the soil in the different blocks. The data were analysed with and without the bottom layer of samples but as there was no increase in precision with the exclusion of this layer the mean value of the LoI from all four sub-samples was taken.

Table 3. Organic content of the natural soils in the ANCOSM mesocosms at Tollesbury, Essex, at the start of the experiment in August 1998.

DEPTH	BLOCK A	BLOCK B	BLOCK C	BLOCK D	BLOCK E	MEAN
0-50 mm	12.96	12.45	12.25	14.92	14.55	13.43
50-100	12.07	13.38	10.91	16.57	12.74	13.13
100-150	13.29	10.28	9.74	13.70	11.61	11.73
150-200	8.86	8.31	6.90	9.35	9.63	8.61
MEAN	11.80	11.11	9.95	13.63	12.13	11.72

The samples were analysed as they were taken and there was considerable visual evidence of variations in organic content in the form of both roots and partially decayed root remains. These local accumulations of organic material were by no means randomly distributed and contributed significantly to the variation observed in soil organic content (Table 3). For this reason it was decided to compare the mean values from the first two samplings (August and December 1998) with the means of the last two samplings (August and October 1999) as this reduced the variability of the experimental results (Table 4.)

The organic content of the control mesocosms (T1) decreased during the period of the experiment (approximately 12 months). The organic content fell by an average of 0.40 percentage points but this amounted to a change of 3.2 % (mean organic content 12.59 %). The mesocosms filled with old soil showed a decrease in the organic content (-0.52 percentage points) although as the organic content of the soil was lower (mean value 6.86 %) it amounted to a larger percentage change (a decrease of 7.6 %).

There did not appear to be any significant difference in the changes in the organic content of the old soils under the three different treatments (T6 - untreated, T7 - no litter and T8 - no sediment) although the decrease in organic content was least under T6 where litter was deposited on the surface of the soil. Given the relatively small amount of sediment that would have been deposited over that period (approximately 3.6 mm on top of soil 200 mm deep) it is perhaps not surprising that there was no observed effect from sediment addition. It would appear that for the old soil, with an organic content of around 7 %, mineralisation was removing approximately 8 % of the organic matter per year. The old soil was packed into the mesocosms as tightly as possible but it was clear from the volume of soil that each mesocosm required that the old soil in the mesocosm had a higher porosity that the same soil *in situ*. The rate of mineralisation of organic matter in the active upper layer of the salt marsh soil (0-200 mm) at Tollesbury had previously been estimated at 13% per year (Boorman, 2000).

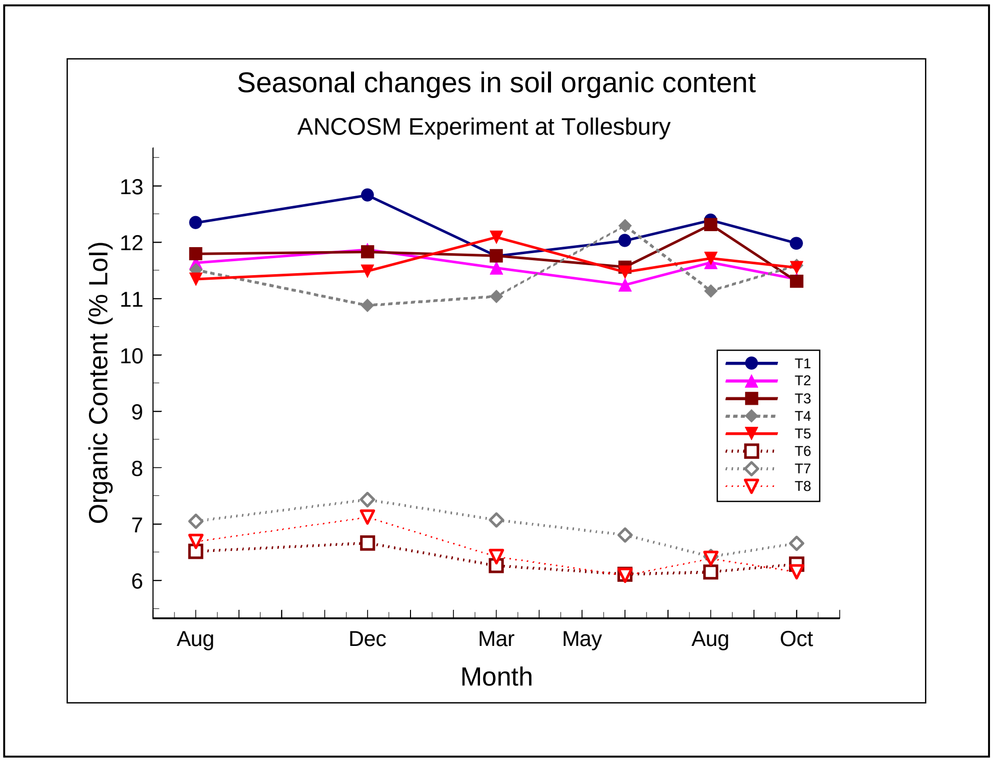
Table 4. Changes in the percentage of soil organic content in the ANCOSM mesocosms at Tollesbury between 1998 and 1999. The comparisons are between the means from the August and December readings in 1998 and the means from the August and October readings in 1999.

BLOCK A	BLOCK B	BLOCK C	BLOCK D	BLOCK E	Mean	Treatment
0.624	-0.192	-0.020	-0.864	-1.560	-0.402	**T1**
-0.469	-0.573	-0.085	0.276	-0.422	-0.255	**T2**
0.173	-0.798	0.015	-0.139	0.729	-0.004	**T3**
0.621	-0.985	1.146	-0.040	0.105	0.169	**T4**
-0.586	-0.508	1.257	0.561	0.353	0.215	**T5**
-0.895	-0.190	-0.528	-0.439	0.193	-0.372	**T6**
-2.352	-0.591	-0.801	-0.509	0.961	-0.658	**T7**
-1.422	-0.735	-0.224	-0.013	-0.218	-0.522	**T8**
-0.538	-0.572	0.095	-0.146	0.018	-0.229	**MEAN**

The decrease in the organic content of the control mesocosms (T1) at first seems surprising but it should be remembered that from earlier studies the marsh has be classified as an over-mature marsh. It may be that the continued growth of salt marsh plants stimulates the activities of bacteria and fungi which promote the breakdown of organic matter. Plant growth can be seen to help aerate the soil through the plant root system and the voids left after root death and this would facilitate aerobic microbiological of organic matter. Under T5, where plants had been cut off at the surface, there was an increase in organic matter over the experimental period and this is what might be expected if plant growth had been responsible for the activation of microbiological breakdown of the processes in the way described.

A serious limitation of the ANCOSM study has to be recognised. As it was only possible to run the experiment for 15 months because of the effect of taking the sample cores it was not possible for any sort of equilibrium situation to have been reached and therefore it has to be acknowledged that any conclusions drawn have to be regarded as provisional. In addition there was considerable variation between the organic content of the soils in the different mesocosms T1 - T6 and this is shown well by the differences between the initial organic content under the various treatments (Fig. 2). Both these difficulties could probably be overcome in the future by the use of larger mesocosms although it might be very difficult to find a suitable large area of uniform marsh that could accommodate the larger mesocosms.

Figure 2. Seasonal changes in soil organic content in the ANCOSM mesocosms at Tollesbury, Essex.



The results of the nitrogen analyses for the top 200 mm of the soil are summarised in Table 5. The data show the high levels of total-nitrogen in living plant tissue (vascular plants and algae) and also in plant litter however nitrate and ammonium-nitrogen levels are very much lower and are comparable to those in non-living material. The seasonal changes in the nitrogen content of all types of plant material were small with few significant differences although the autumn samples tended to have the highest levels of total-nitrogen.

Table 5. Nitrate-nitrogen, ammonium-nitrogen and total-nitrogen content of incoming sediment, salt marsh soil, water, plants and algae at the Tollesbury ANCOSM site. Values are expressed in mg per g dry weight except for the water samples which are expressed in mg per litre (±SD).

1. ***Incoming sediment***

SAMPLING	NO_3-N	NH_4-N	Total-N
AUGUST	0.05±0.00	0.00±0.00	0.41±0.04
OCTOBER	0.03±0.00	0.00±0.00	4.40±1.72
JANUARY	0.04±0.01	0.00±0.00	4.05±0.19

2. ***Salt marsh soil (0-200 mm)***

SAMPLING	NO_3-N	NH_4-N	Total-N
AUGUST	0.09±0.05	0.00±0.00	0.95±0.35
OCTOBER	0.09±0.03	0.00±0.00	9.36±1.30
JANUARY	0.06±0.01	0.00±0.00	9.75±0.98

3. ***Tidal water***

SAMPLING	NO_3-N	NH_4-N	Total-N
AUGUST	0.66±0.20	0.40±0.05	4.10±1.19
OCTOBER	0.76±0.03	0.08±0.02	0.75±0.08
JANUARY	1.43±0.06	0.11±0.05	1.16±0.05

4. ***Vascular plants***

SAMPLING	NO_3-N	NH_4-N	Total-N
AUGUST	0.12±0.06	0.00±0.00	28.77±6.78
OCTOBER	0.09±0.03	0.00±0.00	33.09±4.87
JANUARY	0.10±0.04	0.00±0.00	30.00±2.20

5. ***Litter***

SAMPLING	NO_3-N	NH_4-N	Total-N
AUGUST	0.10±0.10	0.00±0.00	29.45±4.89
OCTOBER	0.09±0.04	0.01±0.00	32.86±3.78
JANUARY	0.14±0.13	0.00±0.00	26.10±1.79

6. ***Algae***

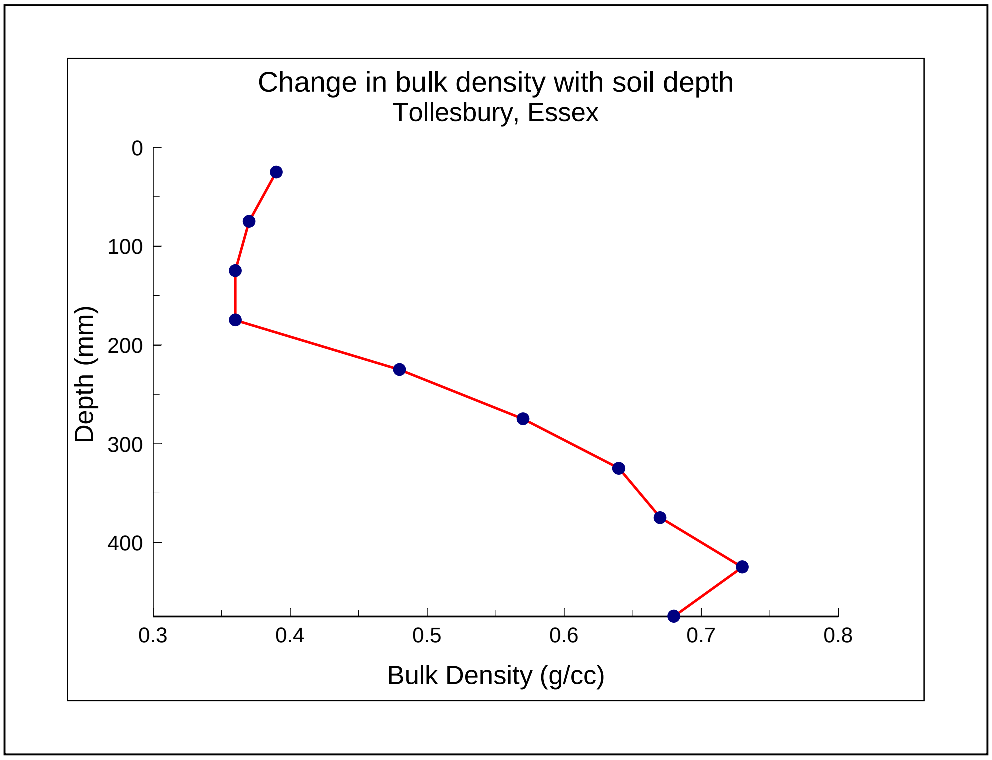
SAMPLING	NO_3-N	NH_4-N	Total-N
AUGUST	0.07±0.01	0.00±0.00	36.63±1.56
OCTOBER	0.31±0.14	0.00±0.00	43.60±4.27
JANUARY	0.07±0.02	0.00±0.00	42.15±5.34

The total-nitrogen content of the incoming sediment was approximately half that of the salt marsh soils suggesting that it was probably not the major source of nitrogen for the marsh. The August samples of the soil and sediment while having similar nitrate-nitrogen contents had low total-nitrogen levels; for each these were approximately one tenth of the October and January samples. This seemed to suggest that there might have a systematic error in these analyses. The data from these nitrogen analyses and the implication are further considered in the section on nitrogen modelling (Section 10.2 - page 50).

3.2. SALT MARSH SOIL COMPACTION PROCESSES

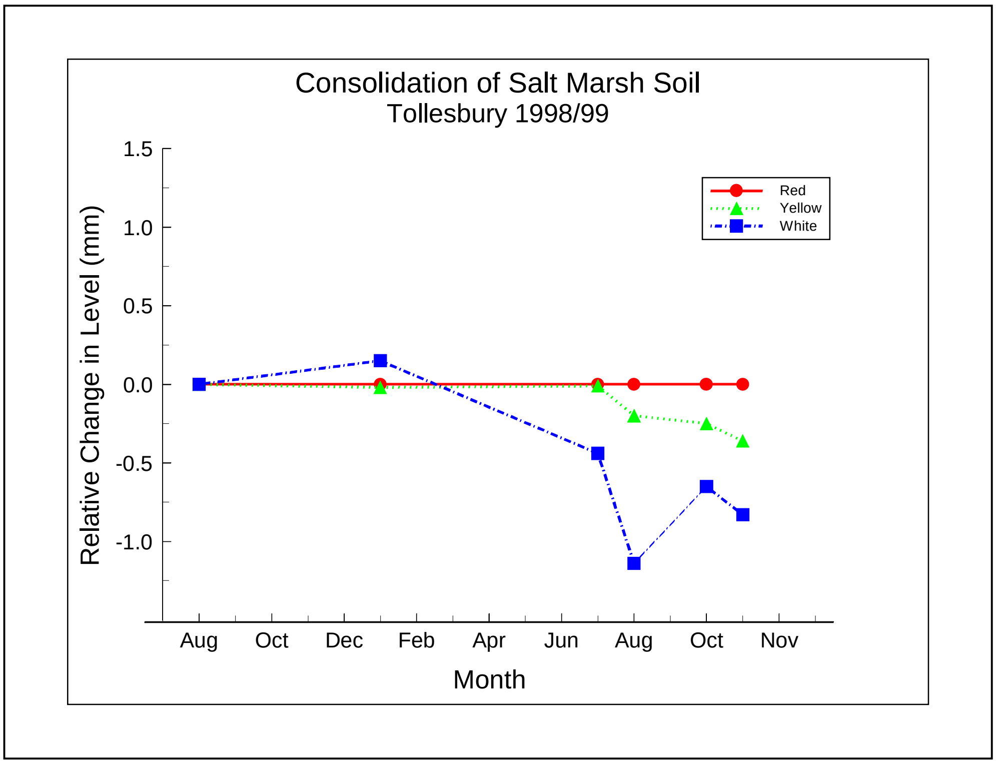
The cores taken to study changes in the bulk density of the salt marsh soil were also examined for their organic content. The results confirmed the conclusions drawn from the preliminary studies for the ANCOSM project. The organic content near the surface was around 10% but in the deeper layers it was 4% and the transition zone between these two extremes was at depths of 200 to 250 mm. The bulk density of these surface layers was low, usually around 0.35 g cm^{-3}. As with the organic content there was a marked difference between the soil above and below a depth of 200 mm. Below a depth of 400 mm the bulk density was as high as 0.7 g cm^{-3}. As with the soil organic content the transition zone was in the layers just below the 200 mm depth (Fig. 3). This increase in the bulk density of the soil with increasing depth represents a compression of up to 100 % of the volume occupied by the freshly deposited material.

Figure 3. Changes in soil bulk density with increasing depth in the salt marshes at Tollesbury, Essex.



The studies on soil compaction were recorded over a period of 15 months. The red markers anchored at a depth of 1000 mm were taken as the reference points. The yellow markers, used in previous studies to determine the rates of accretion, generally showed only small changes in comparison with the red markers. This was taken to indicate that the main changes in soil consolidation were occurring at depths of less than 600 mm. This view was supported by the way in which the white blocks, anchored at a depth of 400 mm, settled relative to the red blocks. Over a period of just over one year the salt marsh soil at Tollesbury between the surface and a depth of 400 mm became compacted by around one millimetre (Fig. 4). Although it will be apparent that some of this consolidation could have occurred at greater depths the data run is not long enough to be certain on this point. The data certainly do show the importance of any measurement of accretion being made with reference points which are anchored at least 1000 mm below the surface. If the changes with reference to the yellow markers (green line on the graph) are continued then the current determinations of sedimentation at Tollesbury could conceal an under-estimate of at least 0.25 mm per year.

Figure 4. Consolidation of a salt marsh soil at Tollesbury, Essex. The red marker, taken as the reference level is anchored at 1000 mm, the yellow at 600 mm and the white at 400 mm.



3.3. SCOTTISH LOCH STUDIES

3.3.1. Kentra Bay

The area was sampled 10.08.99 Samples were taken around the area of marsh to the south of Eileanan nan Gad and north of Bruach na Maorach mostly around NGR 643679. The whole area was very heavily sheep grazed with close sward that left very little to cut when sampling vegetation. The substrate was generally sandy with some small stones mixed in, particularly in the deeper layers which made sampling difficult. The flats had a limited thin covering of finer material but essentially it was a sand based system with the distinct possibility of blown sand contributing to the surface of the salt marsh. Three distinct vegetation zones were recognised:-

I. **Pioneer Marsh**. 2-4 m wide along the front edge of the marsh with *Puccinellia maritima* dominant but with scattered individuals of *Salicornia europaea*, *Armeria maritima*, *Fucus* spp., *Pelvetia* spp., and *Bostrichia* spp. (mostly at cover/abundance Domin scale 3 or 4).

II. **Middle Marsh**. Forms 75% of the width of the marsh often around 80 m wide. Species present - *Armeria maritima* dominant (Domin 8) with *Glaux maritima* (D3, locally 5-6), *Bostrichia* (D3), and *Puccinellia* (D3).

III. **High Marsh**. Rather more limited and generally less than 25% of the width of the marsh. *Festuca rubra* dominant (D8), *Carex* sp. (D5 - D6), *Armeria maritima* (D6), *Plantago coronopus* (D4), *Glaux maritima* (D2), and *Plantago maritima* (D3). Merges into non-saline grassland at upper edge.

Soil samples were taken from each of the above zones (CT1S1-10, CT2S1-10, CT3S1-10) and from the sand flats below the marsh (CT01-10) and vegetation samples from each of the zones above (CT1V1-10, CT2V1-10, CT3V1-10). It should be noted that the samples for soil and vegetation were not taken from the same points. The soil samples were taken to the depth of the corer or as deep as possible where the samples were over a hard layer or semi-liquid wet sand. The vegetation samples were taken from an area 250 cm x10 cm (0.025 m^2). In addition five 500 ml water samples were taken on the flood tide but there were no obvious suspended solids present in the incoming water.

3.3.2 Kinloch Moidart

Sampled 11.08.99. Samples were taken around the marsh to the south west of Cnoc Aird Molach . The most prominent area of marsh first visited is a large island mostly of high marsh just covered at spring tides. The surface is irregular and its dissected by deep pools which are apparently the remains of old creeks. The edge is cliffed with a drop of around 0.75 m but the edge is often quite rounded. The vegetation (Zone I) is mostly 20-40 cm high but there are some quite short patches, probably the result of the goose grazing. The smaller islands of marsh to the west are lower and wetter with the edge eroded along the west and north sides with bays with sand or shingle deposits. The marsh on the north side, just to the south of the river, is at rather higher level and more densely vegetated (including *Leontodon autumnale*). On the south and west side there is some pioneer marsh with *Puccinellia maritima* often dominant (Zone II). Further to the south there are pioneer clumps of *Armeria maritima* on a sandy spit in an area 40 m x 10 m. The clumps of vegetation have accumulated a shallow dome of mud but underneath there is sand. The area as a whole was notable for the very gradual slope and the vast areas of mud although generally the mud formed a shallow layer of sloppy mud over a firm mixture of sand shingle and rock.

The area around the stream Allt na Glaice Moire, in the south east corner, was also visited. The description provided by Scottish Natural Heritage emphasised the extent of stands of *Iris pseudacorus* which were actually far less than at other sites with only two very small dense stands (approximately 6m x 3m) and scattered individuals elsewhere. Further seawards the fresh water wetland graded into an area which was was soft and hummocky and where soft mud was being colonised by *Puccinellia maritima*. The tenant farmer noted that the area was grazed by about 30 cattle in the winter (also fed concentrates) but in addition it was frequently grazed by deer and by a flock of grey geese from Loch Shiel. Three distinct vegetation zones were recognised which were:-

I. **High Marsh**. Tall vegetation with *Juncus gerardii* the dominant species here (D8) but with some diversity with *Festuca rubra* (D7), *Glaux maritima* (D5), *Plantago maritima* (D5), *Leontodon autumnale* (D3 in the higher parts), *Puccinellia maritima* (D3-6 in the lower areas especially around the edge), *Agrostis stolonifera* (D2), *Aster tripolium* (D1), and *Cochlearia* sp. (D1).

II. **Middle Marsh**. The middle marsh is dominated by *Puccinellia maritima* (D6), with *Glaux maritima* (D6), *Armeria maritima* (D5), *Plantago maritima* (D6), *Bostrichia* sp. (D5) and *Aster tripolium* (D1).

III. **Pioneer Marsh**. The pioneer marsh varies from dense *Puccinellia* (D8) to open clumps of *Puccinellia maritima* (D4-D5) and also some scattered *Armeria maritima*.

10 soil and 10 vegetation samples were taken from the main marsh but not at the same points (LM1S1-10, LM1V1-10). 10 soil and 10 vegetation samples were taken at the same points from within the Lower/Pioneer marsh (LM2V1-10). No water samples were taken.

3.3.3 Loch Ailort

Sampled 12.08.99. The site overall formed a marked contrast from Kinlochmoidart in that it was a very clean site with little in the way of fine sediment. The samples were taken from the area of marsh south of the river Ailort. The whole area was based on coarse sand and shingle although there was a higher area of marsh based on finer material and some old bare salt marsh mud adjacent to the small stream to the south. The main area of the marsh is to the south of the river. Further up the river there is a more or less similar range of communities. In one area, immediately to the south of the river, an area of Zone III is to be found based on a boulder bed island with old marsh mud exposed at the edges. Four distinct vegetation zones were recognised and these were:-

I. **Pioneer marsh**. This area is of open *Puccinellia* with some *Armeria* in clumps on a sandy/shingle beach. The material appears to be more glacial than marine in origin.

IIa. **Lower Marsh** (patchy). Again *Puccinellia maritima* is dominant (D8) but with other species notably *Armeria maritima* (D7), *Glaux maritima* (D6), *Bostrichia* spp. (D6), *Cochlearia* (D2) and *Spergularia* (D2). There are however some open stony patches.

IIb. **Lower Marsh** (closed). The sward is very similar to that of IIa, but essentially closed vegetation although with a few pans and scattered patches of bare ground. It is at a slightly higher level than IIb.

III. **High marsh**. Typical high marsh with *Juncus gerardii* dominant (D8) forming a fringe along the top of IIb but still on a stony base although there is a deeper soil in places with less grazing. Other species present include *Agrostis stolonifera* (D7) *Glaux maritima* (D7), *Leontodon autumnale* (D2), *Plantago maritima* (D4) and *Armeria maritima* (D6). The high marsh merges into the drift line covered in *Fucus* spp. and then into short turf and finally *Juncus* dominated rough grazing

Soil and vegetation samples were taken from the same points in IIb, and III (samples LA2V1-10, LA2S1-10 and LA3V1-10, LA3S1-10). Water samples were taken on the ebb (LAW1-5). Other zones were very stony and it was very difficult to take core samples.

3.3.4 Loch nan Ceall (Arisaig Bay)

Sampled 13.08.99. The site was very stony with some coarse sand but unlike Loch Ailort there was a definite admixture of mud with a distinct layer in places, sometimes quite thick. Areas of fine sand occurred on the lower shore. The slope was comparable to or rather steeper than Loch Ailort. The whole area appeared to be eutrophic, presumably the result of sewage outfall(s). There appeared to be virtually no grazing in the area although a few plants had apparently been eaten. As well as the zones described below there was also a shallow pool on the upper shore with scattered individuals of *Salicornia*, *Spergularia*, *Puccinellia* and *Plantago* in a few centimetres of water (even at low tide). Five distinct vegetation zones were recognised and these were:-

I. **Pioneer Marsh**. This consisted of clumps of *Plantago maritima* and *Puccinellia maritima* with occasional *Aster tripolium* merging into the next zone. The highest areas formed a more or less closed sward but the soil was very thin over a stony base with some open stony patches.

II. **Middle Marsh**. The main marsh was a more or less continuous cover of *Triglochin/Plantago/ Puccinellia* mixture but still with some open stony patches. The vegetation consisted of *Triglochin maritima* (D5), *Plantago maritima* (D7), *Puccinellia maritima* (D7 and locally 8), *Aster tripolium* (D4), *Glaux maritima* (D6 and very locally D8), *Pelvetia* (D6), and *Armeria maritima* (D3).

III. **High Marsh**. The vegetation here was dominated by *Juncus gerardii* (D7-8) with *Aster tripolium* (D5), *Plantago maritima* (D7), *Triglochin maritima* (D6), *Glaux maritima* (D6-7) and *Armeria maritima* (D4).

IVa. **Marsh Transition**. This was found where there was a backing of rocks (this with a rocky base). The sward was *Festuca rubra* dominated (D7), with *Plantago maritima* (D6), *Glaux maritima* (D6), *Aster tripolium* (D5) Cochlearia (D5) and *Armeria maritima* (D5).

IVb. **Marsh Transition**. This was at a higher level than the previous zone and formed the transition to rough grassland with *Juncus* spp. and *Iris pseudacorus* etc.

Soil and vegetation samples were taken from the same points in II and III (samples LC2V1-10, LC2S1-10 and LC3V1-10, LC3S1-10). No water samples were taken.

3.3.5 Loch Beag, Struan, Skye

Sampled 16.08.99 at the suggestion of N. Beaton of Bailemeanach, Skye. The marsh regime had been changes in the 1960's when the new road bridge lower down the loch had been built (see map). There appeared to be about 2 ha of fairly high marsh and probably 0.5 ha of lower marsh (it was not possible to examine the latter in detail because of the state of the tide). The higher marsh had a hummocky surface together with some deep pools from the old creeks. Above the high marsh there was a transition to damp grassland with *Iris* and *Juncus* etc.. The whole area was moderately sheep grazed. Three distinct vegetation zones were recognised which were:-

I. **Lower Marsh.** Largely dominated by *Armeria maritima* (D7), but with *Glaux maritima* (D5), *Puccinellia maritima* (D5), *Pelvetia* and *Bostrichia* (D5), and *Plantago maritima* (D4).

II **Upper Marsh**. Dominated by *Festuca rubra* (D7-8) also *Agrostis stolonifera* (D6-7), and with *Plantago maritima* (D5), *Armeria maritima* (D6), *Cochlearia* (D3), *Glaux maritima* (D5), and *Leontodon autumnale* (D4).

Soil and vegetation samples were taken from the same points in I. (samples LBS1-7 and LBV1-7). No water samples were taken from this site.

As will be seen from the descriptive information on the Scottish sites given above there is considerable variation in the soils on which these salt marshes have developed and the profiles of organic matter in the salt marsh soil show this in graphic detail. For this reason data on the distribution of organic matter in the soil profiles are given in some detail (Figs. 5-9).

The salt marsh at Kentra Bay has developed on a predominantly sandy soil and therefore the accumulation of organic matter in the soil can be attributed almost entirely to the development of the salt marsh vegetation. The sand flats are almost entirely inorganic although there are occasionally some buried layers with an enhanced organic content (Fig. 5). The profiles taken from the successive salt marsh zones illustrate the way in which marsh development is paralleled by the accumulation of organic matter, in some cases to quite high levels.

Loch Moidart, in contrast to Kentra Bay, is built primarily on fine sediments and the development of the salt marsh has not depended on the accumulation of organic matter near the soil surface as it has at Kentra (Fig. 6). The bioturbation of the accumulated deposits of fine sediment has resulted in a deep soil profile with small but persistent levels of organic matter even at some depth. The organic content of the upper layer at around 8 % in much lower than that at Kentra where near the surface it exceeds 20% but at depth there is still significant organic matter.

Figure 5. Soil organic profiles at Kentra Bay, Lochaber

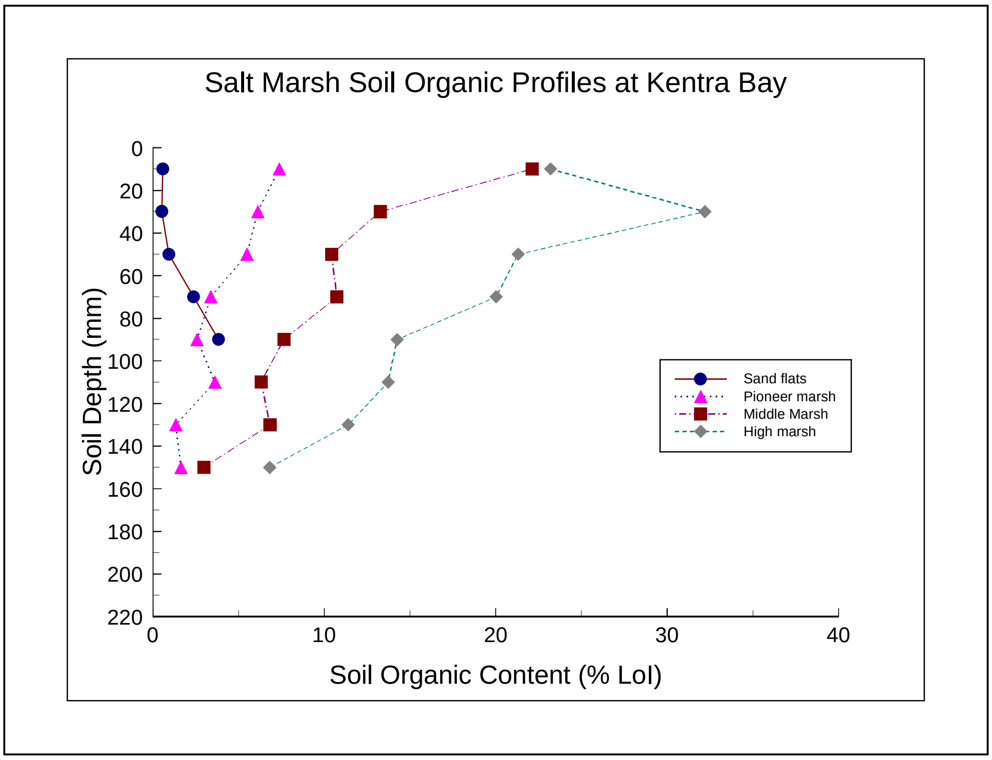


Figure 6. Soil organic profiles at Loch Moidart, Lochaber

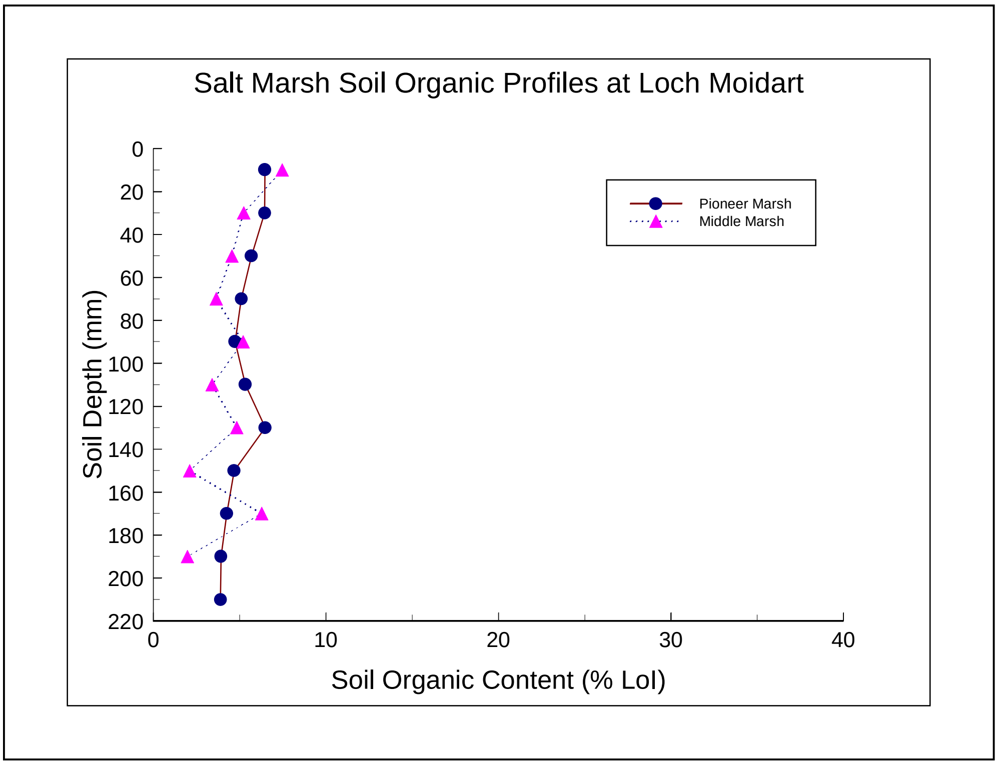


Figure 7. Soil organic profiles at Loch Ailort, Lochaber

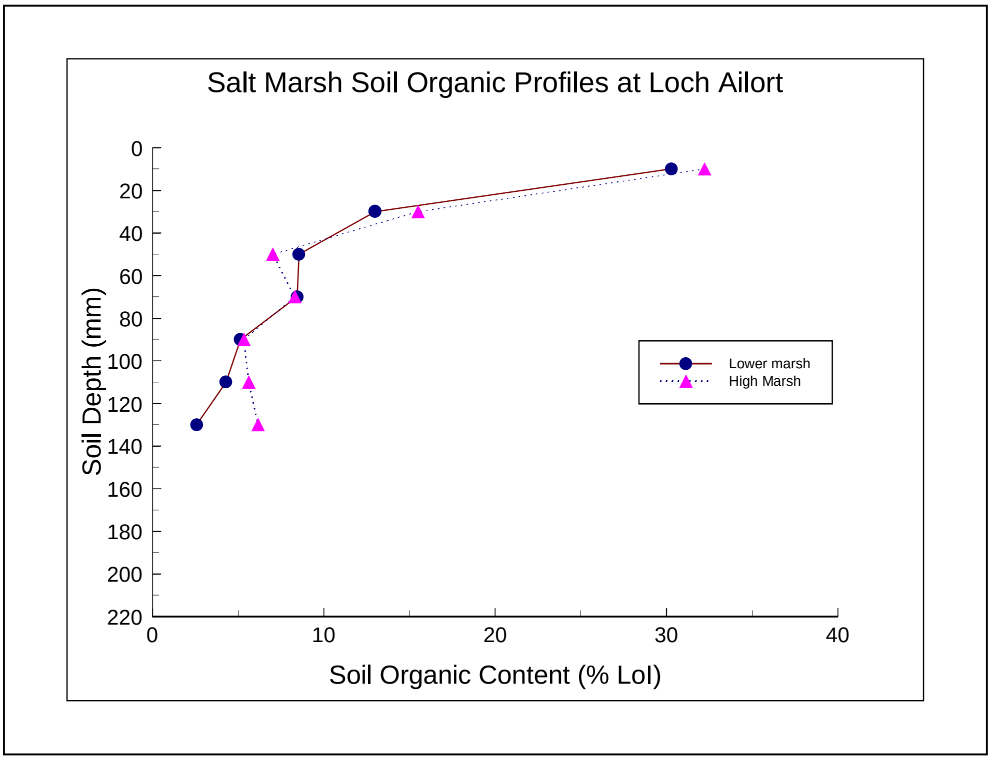


Figure 8. Soil organic profiles at Loch nan Ceall (Arisaig Bay), Lochaber

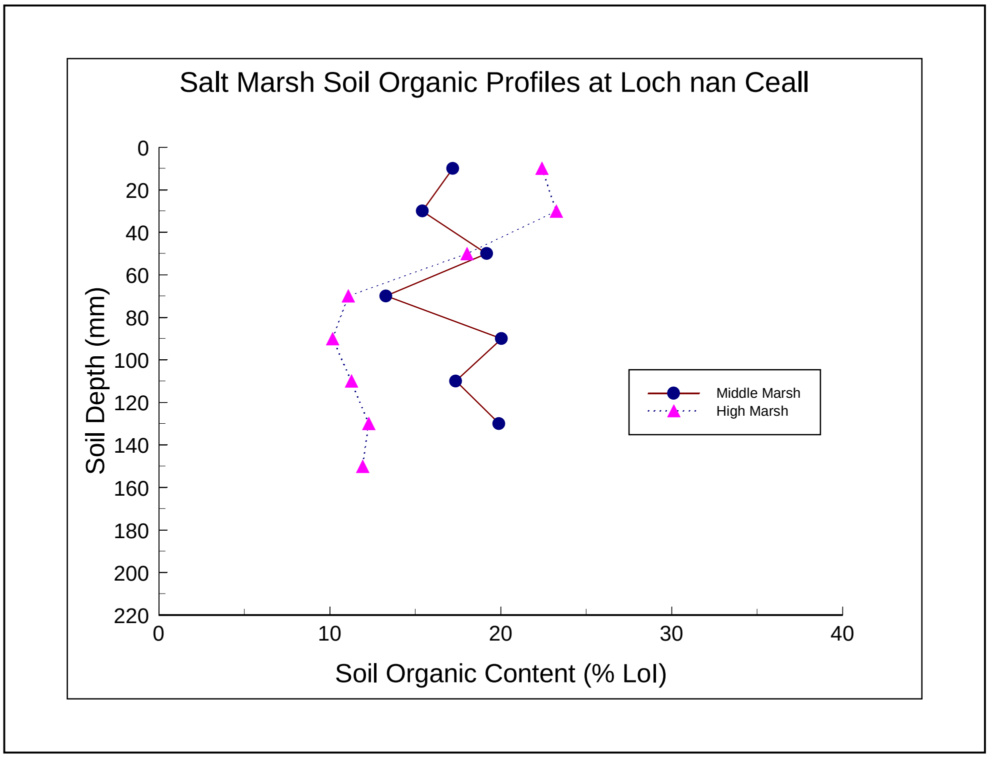
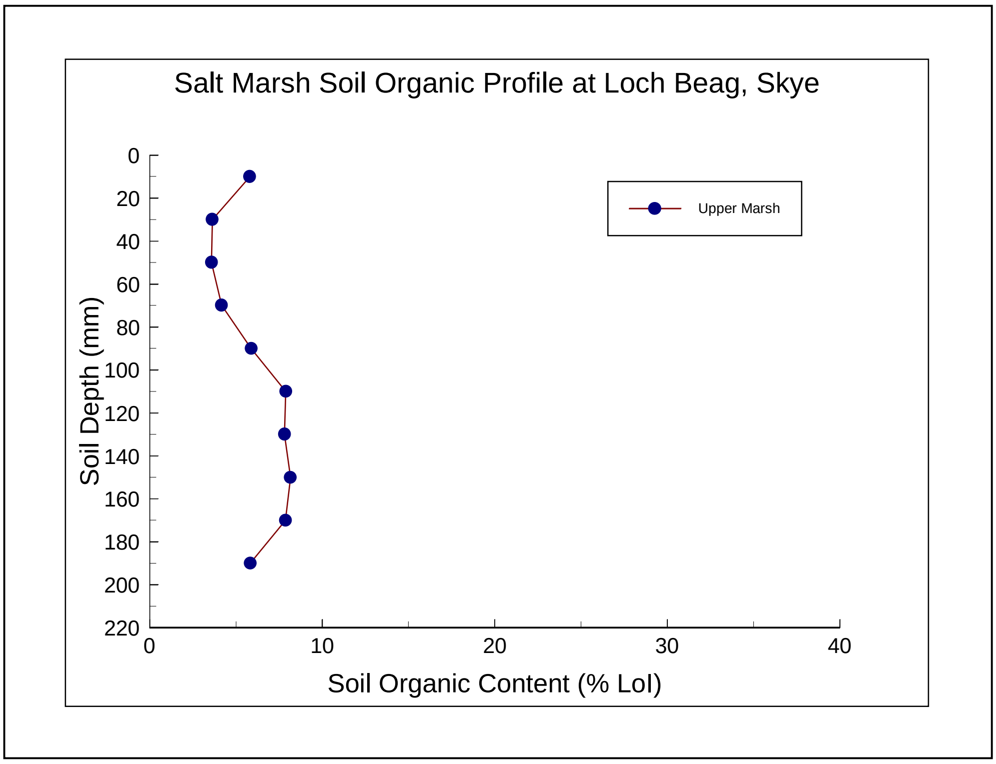


Figure 9. Soil organic profiles at Loch Beag, Skye



The profiles obtained from Loch Ailort are comparable with those from Kentra Bay with very high levels near the surface decreasing rapidly with depth to very low values (Fig. 7). Again the development of the marsh is based on the accumulation of organic matter in the surface layers but the very high organic carbon levels contrast with near zero layers only a short distance below.

Loch nan Ceall (Arisaig Bay) has patchy salt marsh over a very rocky base and there is quite a high organic content even at some depth (Fig. 8). It is more difficult to interpret the development of marsh here in terms of the gradual accumulation of organic matter and it seems likely that there is both a mixing of sediment types and some reworking of existing sediments.

The picture regarding the distribution of organic matter with depth in the marsh at Loch Beag (Fig. 9) is an interesting one with higher organic content both near the surface and at some depth. It seems possible that the high organic content at depths of 120 to 180 mm represent a period of salt marsh surface stability followed by the rapid accumulation of coarse sediments with low organic content before this sedimentation slowed sufficiently to allow organic matter to accumulate again. The road works mentioned earlier could explain the change in circumstances and this would imply a period in which sediment accumulated at a rate of around 4 mm per year which does not seem unreasonable. Further evidence is being sought on this point.

Despite considerable variations in geomorphology and vegetation between the four main Scottish sites the vertical ranges of the zonation of the main vegetation zones were quite similar (Table 6.). While in general the ranges of the zones were very similar at the four sites it was notable that not all zones occurred at each of the sites. Sometimes a particular zone was completely absent at a specific site. At three of the sites (Kentra, Moidart and Arisaig Bay) the marshes lacked any Low Marsh; the Middle Marsh showed an abrupt transition to Pioneer Marsh. It was notable at Loch Ailort, however, that there was no clear Middle Marsh as there was a cliff edge from the characteristic High Marsh vegetation down to typical Low Marsh.

What was of particular interest was that the vertical extent of the vegetation of all four of the Scottish sites was very similar to that of Tollesbury in Essex despite the considerable differences in sediment and geomorphology. The effects of the greater tidal range in Essex were apparently offset by the restrictions imposed by the sea wall on the development of high marsh communities.

Table 6. Vertical heights ranges (m - OD Newlyn) of the main vegetation zones in the four Scottish study sites in comparison with the salt marshes at Tollesbury Essex, together with the tidal ranges (m). The heights given are of the top of the marsh and of the bottom of each of the four zones.

AREA	TOP	HIGH	MIDDLE	LOW	PIONEER	TIDES
Kentra Bay	2.4	2.0	1.4	-	1.0	4.3
Loch Moidart	2.4	2.1	1.6	-	1.1	4.3
Loch Ailort	2.4	1.4	-	1.0	0.7	4.3
Arisaig Bay	2.4	1.8	1.5	-	1.2	4.2
Tollesbury	2.8	-	-	2.1	1.0	4.6

What is also notable, however, is that there appears to be a greater range of pioneer marsh communities including pioneer zones comprising high marsh species such as *Plantago* and *Armeria*. This is in marked contrast to the situation further south and it contrasts with the difficulties experienced in salt marsh creation when such species will only grow after a marsh has reached some degree of floristic maturity and soil development.

4. DISCUSSION

The work covered under Work Package 6a, and described in this part of the report, falls into two distinct areas. Firstly there are the studies centred on the fluxes of organic matter relating directly to the ANCOSM project and subsidiary studies. Secondly there are the various more general studies which have arisen because the development of the broad concepts on the creation and distribution of organic matter has been based on a single English study site - Tollesbury, Essex (Boorman *et al.*, 1994 & 1996). The breadth of knowledge of salt marsh processes that has been build up over ten years of studies of the salt marshes at Tollesbury do, however, provide valid grounds for the continued use of the site.

It has to be recognised, however, that if the results of these studies are to be relevant to the understanding and modelling of salt marsh processes more generally and especially if they are to be used for developing and improving techniques for salt marsh creation and management they need to be set on a much broader base. This is specifically where the data from the study of the salt marshes in the Scottish lochs has its specific relevance. It is important both because, as already described, the sites are isolated and distinct and also because the marshes have been built up in an environment largely based on coarse grained material that is predominantly chemically and biologically inert in contrast to the active clay soils that form the foundation of the Essex marshes such as Tollesbury.

Both the ANCOSM studies and the broader studies have limitations since they are essentially based on a single season but provided that this limitation is recognised the data from these studies certainly provide important markers and signposts for extending our understanding of fluxes of organic matter in salt marshes. Both groups of studies also provide the foundations on which longer term and more detailed studies are being developed.

While the early results from ANCOSM must be regarded as tentative the complex interaction between the processes of sediment deposition, sediment compaction and biogeochemical soil processes are clearly of major importance (Brown *et al.*, 1999 and Boorman *et al.*, 1999). It has become clear from both the Tollesbury studies and the related Eloise project ISLED (Anon, 2000) that the measurement of accretion of sediment to the salt marsh surface is in fact a small part of the overall picture of salt marsh development and change. While the net gain or loss of sediment, as demonstrated in the earlier studies, is clearly crucial to the overall picture and thus to the fate of the system as a whole, it is the processes within the marsh which determine the subsequent fate of each of the components of the salt marsh system.

While the success of a salt marsh can be described in terms of the vertical growth of that marsh as measured by the addition of sediment to the surface this is a misleadingly simple part of the picture. It is more informative than simply looking at the net gain or loss of sediment to an area but it is still only the beginning of the whole process of salt marsh function. It has become clear from these studies and from the related ISLED studies that there is almost always a major re-working of the sediment which comes in with the tide. The general building up of the salt marsh surface is accompanied by the development of the drainage system in the form of creeks. The development of the creek system is not simply a lack of accretion along the line of a developing creek. Generally there is also erosion of material as the creek system cuts into the underlying sediment and this material then becomes available for secondary deposition. Furthermore there is often some erosion of the seaward edge of the marsh with material being re-deposited on the more landward areas. This process is particularly important at the present time with persistently rising sea levels. It has already been noted that the deposition of sediment on the surface is only part of the process of the upward development of the salt marsh.

Salt marshes can not only be categorized by the way they facilitate the accumulation of sediment; they are also portrayed in terms of the accumulation of organic material. This can result from the deposition of incoming sediment with a significant organic content and from the surface deposition of litter from aerial primary production within the marsh but also from the below-ground primary productivity of the salt marsh plants. The addition of sediment to the marsh surface has to be seen in terms of the net balance between sediment deposition and sediment erosion (noting that sediment erosion in one place may result in deposition elsewhere).

The input of organic material to the marsh surface has to be viewed in a similar light. Clearly as a proportion of the sediment can be reworked so to can the organic fraction of the sediment. The earlier studies in this series of projects underline the fact that a significant proportion of the organic material resulting from the salt marsh primary productivity is exported from the system. The remaining plant litter that falls to the surface of the marsh will be redistributed by the wind and tide and the invertebrate processors before it is finally incorporated into the marsh soil. The below-ground primary productivity will not be subjected to these process in the same way although some will be processed by soil invertebrates and a small proportion may be released in the form of dissolved organic carbon (DOC). Nevertheless only a proportion of the organic matter in the soil remains unchanged; a significant proportion will be lost by the process of mineralisation through the activities of the soil microflora assisted by the soil microfauna on a largely physical basis.

The overall gain of organic matter to the salt marsh, the proportion of the organic fraction that contributes to the vertical growth of the salt marsh, will be determined by the balance between the processes of production and mineralisation. Plant production, both aerial and below-ground, is determined by environmental conditions and in general little can be done in terms of the application of management techniques to change the overall levels of plant productivity. But even if the production of organic matter is not readily susceptible to change then the break-down processes certainly are susceptible to environmental processes and thus may be affected by, if not modified by, any management process. As well as the direct effects of the treatments applied in the ANCOSM experiment there will also be secondary effects. Any increase in the mineralisation of soil organic matter will also have the effect of increasing the availability of mineral nutrients in the soil with the possibility of enhancing plant growth and productivity. In addition conditions which stimulate or reduce mineralisation, particularly soil porosity and thus the redox potential, will themselves have other effects on bio-geochemical processes. For example living plants help to increase the soil redox status at least locally by radial oxygen loss from plant roots while the channels left by the death and decay of plant roots can provide addition channels for soil drainage. Soil drainage itself can also provide a route for the fluxes of dissolved organic and mineral material.

The processes of soil compaction begin with the very thin layer of sediment left by a single tide drying out and continue in various ways right through to the physical compression of the soil at depths of one metre or more. The observed occurrence of some living roots at these depths is surprising as it is clear that the bulk of the living roots are found in the upper 200 - 250 mm of soil. It is not clear what is the function of the very long roots penetrating to such depths, although roots have been shown to occur at similar depths in terrestrial clay soils. In the latter situation they may contribute to plant survival under drought conditions. In salt marshes the surface layers of the soil certainly dry out considerably under drought conditions although the permanently wet layers are almost always to be found with 100 - 200 mm of the surface. It may be that there are sources of brackish or fresh water at the greater depths or it may be that there are mineral nutrients present there which are absent from the surface layers of the soil.

5. CONCLUSIONS

5.1 CONCLUSIONS ON SALT MARSH ORGANIC FLUXES

Previous studies have underlined the range and significance of salt marsh fluxes of organic matter and mineral nutrients. The current studies are designed to show the complexity of the way in which these fluxes are inter-related. The current studies do not provide answers as to which are the critical controlling factors but they do indicate the lines on which the fluxes can realistically be modelled. The current studies certainly do provide signposts which can guide us through some of the more complex interactions between the physical, chemical and biological processes in the soil which govern and control salt marsh establishment and development. The implications of salt marsh organic and nutrient fluxes for the practical creation and management of salt marshes will be discussed in the next section (5.2). While the studies described in this report are on-going they have already provided vital information as to the optimum course for future studies on soil-plant interactions in the salt marsh ecosystem.

The principle of the use of *in-situ* mesocosms for the study of soil-plant interactions has now been established. The experience gained under ANCOSM will enable such mesocosms to be used even more effectively in the future. The benefits and limitations imposed by the use of different sizes of mesocosm have already been discussed. The studies have also indicated the need to follow the changes by the monitoring of as wide a range of parameters as possible.

The studies on the process of soil compaction at different depths indicate the need for caution in the use of accretion monitoring techniques. They also indicate key points to be taken into account in the construction of comprehensive models integrating the processes of sediment deposition and re-deposition, the range of organic contributions to salt marsh development and the influence of mineral nutrient levels on both salt marsh plant growth and on the overall development of salt marshes.

The studies undertaken in the Scottish sea lochs have broadened significantly the otherwise Essex-based foundation studies. Both the role of salt marshes fluxes between land and sea and key details of the processes of salt marsh establishment and development can be seen in a new light. It is clear that the future scientific output from these studies on what are fundamentally simplified systems will contribute significantly to the understanding of salt marsh function.

5.2 CONCLUSIONS FOR SALT MARSH CREATION

5.2.1 Introduction

Recent losses of salt marsh (Boorman, 1995b) in the south-east of England have further raised the possibility, in certain circumstances, of re-creating salt marsh by a strategic realignment of the sea wall and the flooding of agricultural land (Boorman & Hazelden, 1995). The primary benefit of salt marsh creation would be a reduction in the costs of maintaining existing standards of sea defence. There would also be other benefits. Salt marshes might make an even greater contribution towards the maintenance of coastal ecosystems, through the export of organic matter (Boorman *et al*., 1994 & 1995a), and the conservation value of the marshes might also be increased.

Marine flooding of an area results in the rapid death of non-salt tolerant vegetation. Re-colonisation by salt marsh plants will, however, be slow if left to natural processes. Until the exposed mud acquires a vegetation cover, there is a continuing risk of serious erosion. Techniques to hasten the re-establishment of key species include both the improvement of micro-habitat conditions to enhance the natural invasion and establishment of plant species, and the sowing and planting of salt marsh plants. Whilst both approaches have been used for a number of years for terrestrial habitats such as woodland and grassland their application to intertidal vegetation is new. The large scale propagation of planting material and the collection and sowing of seeds of salt marsh plant species present particular challenges. Success does not just depend on the practical application of new techniques. Especially in the long term, success depends on a careful survey and the evaluation of a wide range of site attributes, and the selection of the most appropriate techniques (Boorman & Hazelden, 1995).

This contribution is mainly based on the large scale, and experimental, managed re-alignment at Tollesbury, Essex, funded by the Ministry of Agriculture Fisheries and Food and English Nature (Boorman, 1995b and Boorman & Garbutt, 1996). Information from other managed retreat experiments has also been taken into account, including the earlier small scale experiment at Northey Island, the large scale project at the Orplands site (opposite Tollesbury on the south side of the Blackwater) and the experimental work done at Saltram, Devon.

5.2.2 Selection of Site

In most cases the selection of the site will be based largely on the economic implications of flood defence. Nevertheless there may sometimes be the opportunity to take the ecological aspects more fully into consideration. Ecological aspects must at least be considered as there may, indeed usually will, be some cost implications if it is necessary to ensure the solution of special problems at particular sites. This will be especially true if decisions on managed realignment come to be taken on a whole estuary basis and take the form of requiring the creation of a certain total area of salt marsh. In this case there are more likely to be the opportunities to make some choices between sites on ecological grounds.

The most important site attribute for successful salt marsh creation is the altitude of the site and the corresponding frequency and duration of tidal inundation. From the fate of sites where marsh re-establishment occurred naturally, as a result of flooding following failure of the seawall during a storm surge, it is clear that the chances of success are greater for areas where inundation is limited to spring tides (Burd, 1995). The lower-lying areas, even though they are within the range of levels of natural middle and lower marsh, are much less likely to be colonised naturally. As we shall see later special measures are needed in such situations to ensure the successful recolonisation of these areas.

Given the presence of a suitable area for recolonisation, the process will be greatly influenced by the availability of plant propagules, mainly floating seeds, of the appropriate species. In the major salt marsh areas, where extensive areas of natural salt marsh remain, it is not likely to be a limiting factor but if there is little or no salt marsh remaining, or if it has never been present, then the rate of arrival of propagules could be a significant limiting factor. While there is in principle no problem of importing suitable material there are cost implications especially for the larger sites.

The state of the land surface at the time of inundation could affect the rate of natural recolonisation. At the Tollesbury site comparisons are being made into the rates of colonisation on ground where, at the time of flooding, there was grass cover, cereal stubble, bare ground or a rough broken surface. Even with the arrival of fresh sediment the former state of the surface could affect the microhabitat conditions that determine seed germination, seedling establishment and subsequent plant growth.

The rapid drainage of sea water from the site, and the absence of pools of standing water, will greatly improve the chances for the development of a good cover of vegetation. Although it occurs only rarely, the survival of the original creek system would greatly facilitate marsh development. An efficient drainage system usually develops naturally but only very slowly. Where there is inadequate natural drainage steps have to be taken to provide it. The existence on a site of at least a rudimentary drainage system is certainly advantageous.

Among the wide range of obstacles that might be encountered, mention should be made of physical disturbance to the sediment surface caused by trampling by man, livestock or even wild geese, soils contaminated with agricultural or industrial chemicals, and extreme exposure to marine erosion (wave action or high current velocities). The presence of one or more of these factors may not prevent marsh establishment but it will call for special attention and will almost certainly have cost implications.

5.2.3 Site Survey

As a first step a detailed site survey is required covering both the topography and details of existing and potential sediment quality and supply. The topography needs to be mapped, usually to an accuracy of the order of at least +/- 50 mm, and the relation to Ordnance Datum (Newlyn) and the local tidal datum reference levels has to be established. The number and spacing of the survey points has to be considered in relation to the topographic variability of the site. Where the site slopes in one direction a series of widely-spaced transects down the slope will be sufficient. Extra points may need to be established where there is any deviation from the general slope or to locate particular features. The longitudinal and transverse profiles of any existing drainage system need to be carefully established as this information is crucial to the establishment of an efficient new drainage system.

The survey will obviously be tied into the nearest Ordnance Survey bench marks during the course of the planning and execution of salt marsh creation. A network of reference points of auxiliary bench marks will be of great value in locating particular points in the field. As it is important that these reference markers are easy to find, it is advantageous from a practical point of view for them to be located in some regular pattern.

Not only is the topographic survey important for directly forecasting and planning the establishment of salt marsh vegetation, the information will also be needed for the design of the optimum size and location of the breach (Burd, 1995) and for the location and design of any counter wall to restrict the landward extent of the site. The design of the topographic survey will thus need to take into account any special requirements in these respects.

In the case of the Tollesbury site detailed information on the vertical zonation of the key salt marsh species, particularly their lower limits, had already been established during the course of research on adjoining salt marsh areas (Boorman, - unpublished data). If this is not the case then a series of transects across the adjoining marsh would also be needed to establish these limits.

While most salt marsh plants have both a lower and an upper altitude limit, the upper limit is determined by the competition of the more vigorous species that are associated with the higher marsh (Bertness, 1991). During re-colonisation, where competition is at a minimum because of the low plant density, the upper limit of any species is effectively the upper limit of the saline influence, the level reached by high water spring tides (HWST). This means it is the lower limit of each salt marsh species that is critical in determining the precise areas where establishment may occur.

Distinctions must be drawn between the extreme range of isolated individuals of a particular species and the much narrower range of the significant stands that form the general zone of that species (Table 7). Within the managed realignment site everything will be done to ensure optimal conditions for plant growth. It is very unlikely though that any species will be able to grow at a lower level than that found in the adjoining natural salt marsh. In practical terms the lower limit of the main stands of that species may be taken as a practical lower limit for its re-establishment. The extreme lower limit, as shown by isolated individuals, will imply that at these levels there are only limited possibilities of success when conditions are particularly favourable.

In many parts of the Essex marshes, including Tollesbury, there are areas within the marsh where the zonation of the vegetation is restricted to something less than the general limits of the species concerned (Boorman, - unpublished data). This phenomenon is visible in the form of the existence of areas of bare ground at suitable levels for plant growth. In many cases it represents a considerable restriction in the potential of that species (Table 7). It appears that special environmental circumstances are operating on a very local scale. These circumstances may apply only locally but the situation should be taken as a warning of potential difficulties.

Table 7. Lower altitude limit of the four main salt marsh plant species at Tollesbury, Essex (Ordnance Datum - m). The general level of the upper areas of the marsh is at approximately 2.8 m OD.

Species	General Zone	Individuals	Restricted
Limonium vulgare	2.1	1.8	2.3
Puccinellia maritima	1.9	1.7	2.1
Aster tripolium	1.6	1.4	1.7
Salicornia europaea	1.0	0.8	1.5

Note:- 'General Zone' - the lower limit of main area of the marsh occupied by that species: 'Individuals' - the lower limit of scattered, often depauperate, individuals of that species: 'Restricted' - the lower limit of stands of that species when under special ecological stress (such as in an area of eroding marsh).

5.2.4 Planting And Sowing

Theoretically if, following tidal innundation, suitable conditions are provided then natural colonisation will result in the establishment of natural or semi-natural salt marsh plant communities. This assumes, however, that an adequate supply of seeds or other propagules are available for dispersal over the site. Early experiments tended to suggest that the supply of propagules for natural re-colonisation was adequate if there was extensive salt marsh adjoining the experimental site. As this observation was based on the early studies done on small sites it could not be assumed that managed retreat involving large areas (and a corresponding need for large numbers of propagules) would be equally successful.

The work at Tollesbury included the experimental sowing and the planting of large numbers of individual salt marsh plant species. While this work was initially successful, although labour intensive and time consuming, the survival of these introduced species, planted or sown, was very low. After a few years there was, nevertheless, a good cover of vegetation over the higher parts of the area and this was almost entirely the result of natural plant colonisation.

It had earlier been noted that at Northey Island colonisation had been by the usual pioneer species characteristic of the low salt marsh such as *Salicornia* spp., *Aster tripolium* and *Suaeda maritima* even though the land opened up to the flow of the tides and available for plant colonisation was at the level of high marsh. The initial assumption was that this could be explained on the basis of the availability of the propagules of these pioneer species with high rates of seed production. While this is undoubtedly an important contributory factor the experience of the planting and sowing experiments at Tollesbury clearly indicated that there were other factors to be considered (Boorman, 1999).

5.2.5 Conclusions

The situation is that the initial colonisation of an area will be by pioneer salt marsh species even when a salt marsh creation site is at the level of upper or high marsh and when seeds or plants of species characteristic of mature salt marshes are introduced. This strongly suggests that the substrate (soil) on a managed retreat site has to develop a degree of maturity before non-pioneer species are able to colonise. The processes involved in these changes are by no means clear but it is likely that microbiological processes in the developing soil, particularly the development of a balanced bacterial and fungal micro-flora, are of great importance. The decay of plant material is based on the activity of fungal and bacterial species (Newell, 1996, Newell & Palm, 1998). It is already known that some salt marsh plant species are mycorrhizal; that is they have specific plant-fungal associations that stimulate plant growth (Rozema *et al*., 1986). Thus it would be reasonable to assume that lack of these organisms would inhibit the processes of salt marsh development. At present there does not appear to be any information on their likely rate of spread. Bare mud is normally colonised by microalgae which contribute significantly to the stability of the surface of the sediment (Underwood, 1997) however under certain conditions the establishment of mat-forming algae could actually delay the establishment of salt marsh macrophytes. Areas of bare mud would also encourage the invasion of marine invertebrates such as *Corophium*, the presence of which can inhibit subsequent plant colonisation (Gerdol & Hughes, 1993).

While in general managed retreat schemes have so far all been moderately successful to successful, with regard to the development of vegetation cover, the question of the achievement of soil maturity and the development of the stable plant communities normally associated with higher level salt marshes could still benefit from further research both in terms of the development of new techniques for salt marsh creation and management and also methods for the quick and effective assessment of the progress achieved (Boorman, 1999).

Generally the salt marshes of the east coast notably lack extensive high marsh communities and the salt marsh terrestrial transition communities. This is particularly because the marsh succession is normally truncated by the position of the sea wall. The Orplands experience, where the existence of rising ground behind the experimental area meant that a new secondary sea wall was unnecessary, has shown how managed retreat can re-create these high level and transitional communities that are now rare or entirely absent.

A common concern when an area is opened to tidal innundation is the potential risk of serious erosion of the existing substrate not to say concern about the effects of the deposition of the extra sediment in places where it is not wanted such as on oyster or mussel beds or in harbour channels. There was no significant erosion at Tollesbury, in fact the rates of accretion in the set-back area have been and are remaining high with sustained build-up of the salt marsh soil surface. However, considerable efforts were made (in the form of hydrodynamic modelling) to ensure that the likelihood of any erosion was kept to a minimum. It must be noted that some erosion, in the form of the development of a creek system and the consequent improvement in the drainage of the site is an essential part of salt marsh development.

It has been suggested that the development of salt marsh could benefit by artificially creating a suitable system of creeks. Certainly the drainage of areas of standing water and saturated soils can be seen to benefit plant growth. It also seems that the natural development of a creek system is a relatively slow process particularly when the natural gradients of a site are low; flat areas with pools of water or very soft mud are very persistent. It would, however, be a time-consuming and costly exercise to dig out a natural looking creek system from scratch. The cost-benefit analysis of such an approach would need to be carefully examined on a case by case basis. It has been suggested that there are benefits in taking measures to accelerate the natural development of a drainage system (Burd, 1995).

A possible approach is suggested by observations from the natural retreat site at North Fambridge where very small differences in level of the ground when it was still agricultural land (caused by the installation of field drainage) have, over the course of a hundred years of tidal innundation, resulted in the development of a major creek system cutting deep into the underlying soil. It would appear that an effective creek system of natural appearance could be achieved by creating a rudimentary creek system artificially and then allowing further development to occur naturally. This has been done at the managed retreat site on the south side of the Blackwater at Orplands and there do appear to be some benefits, at least in the short term, in terms of habitat diversity and rate of plant colonisation. It will be some while, however, before it is possible to make a long-term assessment of the relative merits of the different approaches at Tollesbury and Orplands (Dixon, *et al*., 1998).

We do not know, however, how long the process took particularly in the crucial early stages but it does rather suggest that there could be effects, beneficial for subsequent creek development, from quite modest initial surface drainage systems.

The first results on the artificial creation of new salt marshes in certain encouraging (Dixon, *et al*., 1998). The studies involved in the early attempts are also contributing significantly to our understanding of the processes involved in the development of salt marsh vegetation. The experience that we have gained and will continue to gain in the coming years will increase our range of management options to safeguard our salt marshes (Boorman & Hazelden, 1995).

7. REFERENCES

Anon, 2000. *L . A. B. Coastal: Second Annual Report*. Holywell, Cambridgeshire.

Bertness, M.D. 1991. Interspecific interactions among high marsh perennials in a New England salt marsh. *Ecology*, 72: 125-137.

Boorman, L.A. 1995a. Sea level rise and the future of the British coast. *Coastal Zone Topics: Process,Ecology & Management*, **1,** 10-13.

Boorman, L.A. 1995b. *Large Scale Experimental Set Back.* 1994/5 Annual R&D Report. Ministry of Agriculture, Fisheries and Food: London.

Boorman, L.A. 1999. Salt Marshes - present functioning and future change. *Mangroves and Salt Marshes*: 3, 227-241.

Boorman, L.A. 2000. The functional role of salt marshes in linking land and sea. In: *British Saltmarshes*. Ed. B. Sherwood. Linnean Society Special: London. pp 2-24.

Boorman, L.A., Hazelden, J., Andrews, R. & Wells, J.G. 1994. Organic and nutrient fluxes and associated primary productivity in four north-west European salt marshes. In: *Changes in Fluxes in Estuaries*. Eds. K.R.Dyer and R.J.Orth. ECSA22/ERF Symposium. Olsen & Olsen: Fredensborg.

Boorman, L.A. & Hazelden J. 1995. Salt Marsh Creation and Management for Coastal Defence. 5th Conference of the European Union for Coastal Conservation. In: *Directions in European Coastal Management.* Eds. Healy, M.G. and Doody, J.P. Samara Publishing: Cardigan. pp. 175-184.

Boorman, L.A., Hazelden, Loveland, P.J., Wells, J.G. & Levasseur J.C. 1995. Comparative relationships between primary productivity and organic and nutrient fluxes in four salt marshes. In: *Comparative Studies on Salt marsh Processes.* Eds. J.E.Lefeuvre and R.F.Dame, Final Report, Volume III. University of Rennes. 305 pps. pp. 181-199.

Boorman, L.A. & Garbutt R.A. 1996. *Large scale experimental set-back.* Second Annual Report. Ministry of Agriculture, Fisheries and Food: London. 15 pps.

Boorman, L.A., Pakeman, R.J., Garbutt, R.A. & Barratt, D. 1996. *Effect of Environmental Change on European Salt Marshes: Structure Functioning and Exchange Potentialities with Marine Coastal Waters.* Volume 5. Results of the Institute for Terrestrial Ecology, England. Environment Research Programme (1990-1994) Contract EV5V/CT 92-0098. University of Rennes: France.

Boorman, L.A., Garbutt, R.A., Barratt, D., Myhill, D., Evesham, B. Reading, C., Cox, R & Rothery, P. 1997. *Large scale experimental set-back.* Final Report. Ministry of Agriculture Fisheries and Food. Volume 1, Tollesbury, Essex. MAFF: London.

Boorman, L.A. & Ashton, C. 1997. The productivity of salt marsh vegetation at Tollesbury, Essex and Stiffkey, Norfolk, England. *Mangroves and Salt Marshes* 1:113-126

Boorman, L.A., Garbutt, A. & Barratt, D. 1998. The role of vegetation in determining patterns of the accretion of salt marsh sediment. In*: Sedimentary Processes in the Intertidal Zone*. Geological Society of London Special Publication No. 139, pp. 389-399.

Brown, S.L., Warman, E.A., McGrorty, S., Yates, M., Pakeman, R., Boorman, L.A., Goss-Custard, J.D. and Gray, A.J. 1999. Sediment fluxes in intertidal biotopes. *Marine Pollution Bulletin:* 37, 173-181.

Burd, F. 1995. *Managed retreat: a practical guide.* English Nature: Peterborough.

Clarke, R.T., Gray, A.J., Warman, E.A. & Moy, I.L. 1993. *Niche modelling of salt marsh plant species*. ITE, Furzebrook Contract Report to ETSU (Agreement Number E/5A/4125/2961).

Dixon, A.M., Leggatt, D.J. & Weight, R.C. 1998. Habitat creation opportunities for landward coastal re-alignment: Essex case studies. *Journal of the Chartered Institute of Water and Environmental Management* 12:102-112.

Gerdol, V. & Hughes, R.G. 1993. Effect of the amphipod *Corophium volutator* on the colonisation of mud by the halophyte *Salicornia europaea*. *Marine Ecology Progress Series* 97:61-69

Lefeuvre, J.C., Dankers, N., Boorman, L.A., Loveland, P. & Bettancourt, A. 1993. *Comparative Study on Salt Marsh Processes*. EEC Contract EV4V-0173-F University of Rennes., France.

Lefeuvre, J.C. & Dame, R.F. 1994. Comparative studies of salt marsh processes in the New and Old Worlds: an introduction. Pp. 169-179. In: Mitsch, W.J. (ed), *Global Wetlands: Old World and New*. Elsevier: Amsterdam.

Lefeuvre, J.C et al., 1996. *The effects of environmental exchange on European salt marshes: structure, functioning and exchange potentialities with marine coastal water*. Vols. 1-6. University of Rennes, France.

Newell, S.Y. 1996. Established and potential impacts of eukaryotic mycelial decomposers in marine/terrestrial ecotones. *Journal of Experimental Marine Biology and Ecology* 200: 187-206.

Newell, S.Y. & Palm, L.A. 1998. Response of bacterial assemblages on standing-decaying blades of Smooth Cordgrass to additions of water and nitrogen. *International Review of Hydrobiology* 83:115-122.

Rozema, J. Arp, W., Letschert, A., Esbroek, S. van & Punte, H. 1986. A comparison of the mineral relations of a halophytic hemiparasite and holoparasite. *Acta Botanica Neerlandica* 35:105-109.

Underwood, G.J.C. 1997. Microalgal colonisation in a salt marsh restoration scheme. *Estuarine, Coastal and Shelf Science* 44: 471-481.

PART B. MODELLING OF ORGANIC AND NITROGEN FLUXES

7. INTRODUCTION

7.1 ANCOSM

'ANCOSM' is a spreadsheet model which uses MS Excel. The model examines the organic matter changes, mineralization and fluxes within a salt marsh and relates these to changes in marsh height relative to mean sea level. The model considers both above ground accretion of sediment and organic matter and the below ground accretion of organic matter from plant roots.

7.2 NITROMOD

'NITROMOD' was constructed by examining published nitrogen models and using parts of them, adapted where necessary, to build a model that was applicable to salt marshes. The model uses the software ModelMaker 3 (Cherwell Scientific Publishing Ltd. 1997), and its structure is shown in Figure 10. For many salt marsh sites there are only limited data and it was decided that the model had to be able to run with the available data. It deals, therefore, only with those parts of the nitrogen cycle for which we have adequate information. Many models dealing with the nitrogen cycle have been designed for agricultural crops and farmland, and so are concerned with very different conditions from those which are found on salt marshes. It was necessary, therefore, to consider the ways the processes within the salt marsh differ from those in terrestrial habitats. In addition many published nitrogen models have been designed to examine aspects of nitrogen cycling such as the efficient use of fertilizers and the reduction of nitrate leaching loss in order to protect water supplies, and so have limited relevance to the salt marsh. There are models which examine nitrogen in wetlands (e.g. Jørgensen, 1994) but these are commonly concerned with the removal of nitrogen from water flowing through the wetland.

Since 1990 the EUROSAM teams have collected data on plant productivity, standing crop biomass, and nutrient and sediment fluxes, usually on a monthly timestep. However, these data are limited and only short, and often incomplete, runs of data are available. NITROMOD has been constructed using the data collected from the lower marsh at Tollesbury in the UK (Lefeuvre *et al*. 1993, 1994, Boorman *et al*. 1994a, 1994b, Boorman 1996, Hazelden & Loveland 1996). Some additional data on water, soil, sediment and plant nitrogen were collected from the lower marsh at Tollesbury in conjunction with the ANCOSM studies.

It was regarded as important to try to fit the model around our data rather than to model theoretically processes about which there is little information. The site at Tollesbury is similar to many European salt marshes but very different to those in the Baie de Mont St. Michel (Vivier 1997). Some aspects of nitrogen cycling have not been modelled as they are allowed for in the input data (e.g. plant uptake). The model is still being developed.

8. METHODS

8.1 ORGANIC FLUXES

8.1.1 The Model

The ANCOSM model takes measured or estimated values (from the experiments at Tollesbury) of the following parameters:- sedimentation rate, sediment density, soil and sediment organic matter content, net aerial primary productivity (NAPP), percentage NAPP exported, rate of litter decay, benthic productivity, mineralization rate of organic matter (both in the sediment and benthic mineralization), and below ground plant productivity. The model is constructed on an interlinked series of MS Excel spreadsheets. The model is based on the Tollesbury site and data collected both from the current ANCOSM mesocosms and from studies at this site under the two earlier EU projects. After the various parameters are set the model then uses these to calculate changes in the soil/sediment organic matter content, and thus the consequential changes in marsh surface height. ANCOSM uses a monthly timestep and runs are of one year's duration. The calculations assume an active soil depth of 200 mm as was demonstrated by the preliminary studies for the ANCOSM mesocosms.

8.1.2 Organic Fluxes

The model calculates net monthly organic matter input to the soil from benthic production, allowing for mineralization. It also calculates (from the NAPP remaining after some has been lost through export) the amount of above ground plant litter accumulating on the soil surface which will subsequently be incorporated in to the soil. These, together with the below ground production and with allowances made for litter decay and for subsequent mineralization within the soil, represent the total organic matter added to the soil (below ground), in units of g m^{-2} $month^{-1}$. The density of the organic component of the incoming sediment is problematic but is assumed to be the same as that of the mineral component of the sediment and of the upper active layers of the soil itself i.e. 0.8 (otherwise there would be some separation but this has not been observed). These figures are then transformed to estimate the height increase of the marsh surface due to below ground organic accumulation. The yearly rate of surface accumulation of sediment has been measured and so the total increase in marsh height, and the proportion due to below ground organic matter accumulation, can thus be calculated and is expressed as a percentage.

8.2 NITROGEN FLUXES

8.2.1 The Model

The structure of the model (NITROMOD) is shown in Fig. 10 (page 43). In previous studies we had determined that the majority of the roots of the marsh plants at Tollesbury were in the top 200 mm of the soil (Boorman *et al*. 1994a, Hazelden and Loveland 1996). As an approximation, therefore, NITROMOD treats the soil as a single layer 200 mm thick.

The ways in which the model deals with three of the main processes – ammonification, nitrification and denitrification are described below. The units used are g m^{-2} unless otherwise stated. Rates of change are expressed in g m^{-2} $month^{-1}$.

8.2.2 Ammonification

This is dealt with in two parts. The dominant process is the breakdown of plant and root litter. This is dealt with as a first-order rate reaction controlled by the rate of litter decomposition and the amount of litter carbon present (TotalLitC) (e.g. Johnsson *et al*. 1987, Bergström & Jarvis 1991, Hutson & Wagenet 1991). The root litter is assumed to be equal to the above ground litter and it is assumed that all the root litter and 50% of the above ground litter is incorporated into the soil. The organic carbon content of this litter is taken as 45%. The decomposition rate is influenced by both soil moisture and soil temperature, and the model allows for these variables. Soil moisture is controlled as in Johnsson *et al*. (1987) by a factor (moist_am) which varies from 0 to 1, declining from 1 if the soil is either too wet or too dry. When the soil is wetter than optimum, i.e. between THs and (THs-dTH2) the equation is

$$\text{moist\_am} = es+(1-es)(THs-TH)/dTH2$$

where THs is the water content (%) at saturation (-0.01 kPa), dTH2 is the range over which the decomposition rate decreases in wet soils (15%) and es is the value of moist_am at saturation (0.6). When the soil is within the optimum range, i.e. between (THs-dTH2) and (THw+dTH1), then

$$\text{moist\_am} = 1$$

When the soil water content is lower than the optimum range then

$$\text{moist\_am} = (TH-THw)/dTH1$$

where THw is the water content (%) at wilting point (-1500 kPa) and dTH1 is the range over which the decomposition rate reduces from 1 to 0 in dry soils (20%). The salt marsh soils at Tollesbury do not generally dry out sufficiently for this last condition to operate.

Temperature is controlled by a factor which similarly varies between 0 and 1 and is defined as

$$\text{temp\_s} = 2^{((SoilT-20)/10)}$$

where SoilT is the mean monthly soil temperature. This assumes a factor change of 2 for a temperature change of 10° C (e.g. Campbell *et al.* 1984) and an optimum temperature of 20° C. Soil temperature was not measured but is derived from air temperature (measured at Tollesbury) according to the equation

$$SoilT = (AirT-0.29)/1.13$$

where AirT is the mean monthly air temperature (degrees C) (Henriksen & Jensen 1979); this relationship was derived for soils in similar temperatures to those at Tollesbury.

The rate of decomposition of soil litter carbon (LitCarD) is then given by

LitCarD = kl x moist_am x temp_s x TotalLitC

where kl is the rate constant for this reaction, here set at 0.4 month^{-1} from measurements made at Tollesbury. The rate of NH_4-N mineralization or immobilisation (LitterNDecomp) is then determined by the C:N ratios of the litter and of the microbial biomass

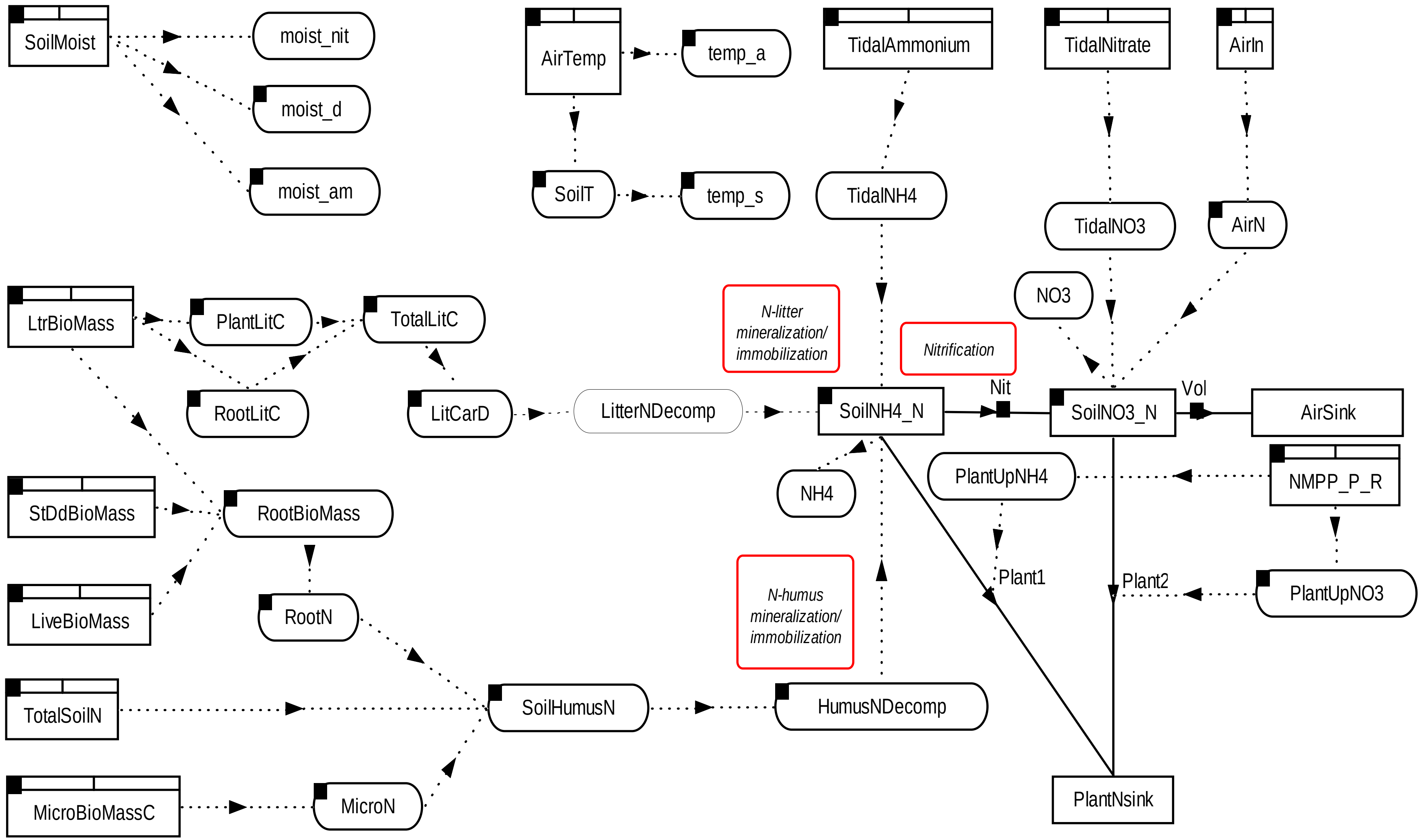
LitterNDecomp = ((PlantN_percent/PlantC_percent)-(fe/MicroC_N)) x LitCarD

where fe relates to the efficiency of the microbial biomass in using the decomposing plant litter (set at 0.6 from data collected at Tollesbury). It is assumed here that the percentage of N and C in the live plant and litter material are the same.

The second process modelled is the breakdown of soil humus to give ammonium-nitrogen. This is done in a similar way with the reaction controlled by the rate of breakdown (kh – estimated at 0.02 month^{-1}) of soil humus and the amount of humus nitrogen present (SoilHumusN), as in Johnsson *et al*. (1987). The amount of humus nitrogen present is determined from the total soil nitrogen minus that in the roots and in the microbial biomass. The total soil nitrogen and the biomass N are regarded as constant as we do not have sufficient data to treat these differently. Thus, the rate of decomposition, HumusNDecomp, is given by

HumusNDecomp = kh x moist_am x temp_s x SoilHumusN

Figure 10. The structure of the NITROMOD model



8.2.3 Nitrification

Some nitrogen models (e.g. Johnsson *et al*. 1987, Bergström & Jarvis 1991, Hutson & Wagenet 1991) derive soil NO_3-N content by assuming a constant ratio, subject to minimum concentrations, of NH_4-N to NO_3-N. This treatment is inappropriate for anaerobic salt marsh soils and so nitrification is dealt with differently here and following the method of Bradbury *et al.* (1993). The process is again treated as a first-order rate process, missing out the nitrite intermediary, and the rate is modified according to soil moisture and air temperature.

Soil moisture is treated in a somewhat different way using a factor moist_nit which varies between 0 and 1. It is assumed that nitrification will take place at its optimum, although slow, rate as the soil dries from field capacity (THfc, -5kPa) to –100kPa (TH1). Thus if THfc>TH>TH1

moist_nit = 1

If TH <TH1, then

moist_nit = 1-(1-s)((TH1-TH)/(TH1-THw)

s is set at 0.6 and moist_nit approaches 0.6 as TH approaches THw. However, in salt marsh soils, TH is often greater than THfc, and in this range conditions are similarly less than optimum, although this possibility was not addressed by Bradbury *et al*. (1993) who were working in a very different environment. Thus, if THs>TH>THfc

moist_nit = 1-((TH-THfc)/(THs-THfc))

The temperature modifier used is that of Jenkinson *et al*. (1987). This modifier, temp_a, is defined as

$$temp\_a = 47.9/(1+e^{(106/(AirT+18.3)})$$

where AirT is the air temperature in degrees C. The rate of nitrate formation from NH_4-N (rateNO3) is given by

$$rateNO3 = SoilNH4\_N(1-e^{(-kn \times moist\_nit \times temp\_a)})$$

where SoilNH4_N is the amount of NH_4-N in the soil at the beginning of the month and kn is a rate constant set at 0.54 month^{-1}. The rate constant used by Bradbury *et al*. was 0.6 week^{-1}, but Aziz and Nedwell (1979), working on the Essex marshes, concluded that there was very little or no nitrification (and so no denitrification), and so the rate (kn) has been set much lower than that used by Bradbury *et al*. (1993).

8.2.5 Denitrification

This is again a first-order rate reaction controlled by the potential denitrification rate (kd – set at 0.34 month^{-1} from the data of Aziz and Nedwell (1979); data from Portugal (Bettancourt, pers. comm.) report much higher rates, up to 8.0 g month^{-1} in the Mira estuary) and the amount of NO_3-N in the soil (e.g. Johnsson *et al*. 1987, Bergström & Jarvis 1991, Hutson & Wagnet 1991). The rate constant is modified to allow for temperature and soil water content, the latter as an expression of soil aeration. The temperature modifier, temp_s, is the same as used previously, but the moisture modified is different as denitrification is an anaerobic process. The modifier, moist_d, varies between 0 and 1 as before. If TH<THd, then

moist_d = 0

where THd is the water content below which there is no denitrification (set at 20%). If TH>THd, then

$$moist\_d = ((TH-THd)/THs-THd))^{d}$$

where d is an empirical constant, here set at 1. The denitrification rate (rateDeNO3) is then

rateDeNO3 = kd x moist_d x temp_s x (SoilNO3_N/(SoilNO3_N+cs))

where SoilNO3_N is the NO3-N content of the soil and cs is the half-saturation constant, set here at 1.

8.2.6 Input data

The model is controlled by the data tables which are derived from the work carried out by the EUROSAM project and its predecessors. We do not have enough detailed data to allow proper monthly time-steps in all cases and so the monthly input or output has been estimated or treated as constant (e.g. biomass, tidal fluxes, aerial input).

The model is driven by the plant biomass figures, which are given in the look-up tables. There are separate figures for living plant material, standing dead material and for litter. Root biomass is assumed to be the same as that above ground, and in the same three categories. Microbial biomass is regarded as constant at Tollesbury, but this was not the case at Stiffkey (Hazelden & Loveland 1996).

The biochemical processes are affected by soil moisture and soil temperature; moisture figures are provided from a look-up table in the model and temperature is derived from air temperatures (Henriksen & Jensen 1979) measured over the sampling period.

Tidal fluxes of ammonium- and nitrate-nitrogen are estimates from data collect at Tollesbury between 1990 and 1994. There are not enough data to provide reliable estimates of monthly figures, which are probably dominated by storm events of which we have no record, but an indication of the suggested monthly pattern is shown in the estimated values given in the look-up tables. It could be argued that constant values should be used. Indeed, the aerial input of nitrogen (Goulding 1990, Koerselman &Verhoeven 1992) to the system is regarded as constant as rainfall is fairly uniform and we have no other data.

Estimate of the uptake of nitrogen by plants has been made from the Net Annual Primary Production (NAPP), which was measured at Tollesbury. The plants use both NH_4-N and NO_3-N in proportion to their relative concentration. However, zones around the roots of the salt marsh plants are often relatively aerobic, partly due to the pores formed by the roots themselves, so nitrogen uptake may be biased towards NO_3-N.

There are some elements of the nitrogen cycle missing in the processes described above, but these are currently effectively included in the input data. For instance, the breakdown of litter gives CO_2 and humus as well as mineral N. CO_2 is lost to the atmosphere and the humus adds to the humus pool in the soil. However, humus N is calculated monthly from the soil total N, microbial N and root N, so it is not modelled in NITROMOD.

The marsh surface at Tollesbury is accreting and this sediment brings with it some nitrogen. Data from the Tollesbury managed retreat site shows that the total N in new sediment is about the same as in the salt marsh soil, but that there is very little NO_3-N present. To some extent this input is covered in the tidal fluxes, but also this model considers only the top 200 mm of soil and so the data on which the model was constructed has included this component.

9. OUTPUT OF MODELS

9.1 ORGANIC FLUXES - ANCOSM

The surface height gain in the marsh at Tollesbury as a result of the net accumulation of organic matter was estimated as being in the range of 0.4 to 1.0 mm per year with the actual value depending on a number of different parameters. The significance of this increase will clearly depend on the rate of accretion resulting from the input of sediment to the marsh. Currently overall annual rates of accretion at Tollesbury vary between 1 and 4 mm with some indications of trends towards the lower figure. Clearly when sediment accretion is only one or two millimetres per year then the contribution from organic matter production would be very significant. The data from the model presented here are based on an assumed rate of sediment accretion of 4 mm per year unless otherwise stated.

The below-ground accumulation of organic matter is mainly attributed to the below-ground primary production (of roots and rhizomes) and while the accumulation of litter does supplement this the contribution is relatively small. Consequently any changes in percentage of the NAPP which is exported (initially assumed to be 20%) have relatively little effect on the overall accumulation of organic matter. Similarly the contribution of benthic production is small and changes in benthic mineralisation have a very limited effect.

No direct data were available for the below-ground primary production for the Tollesbury site but taking all the available evidence it seems likely that it will be equal to the NAPP which has been studied at Tollesbury over a number of years (Boorman & Ashton, 1997). The initial assumption taken in the model is that below-ground productivity is 100% of NAPP. Clearly if the below-ground production is significantly higher then its contribution to the increase in marsh height will be correspondingly greater.

The crucial factor affecting the contribution of below-ground productivity to the vertical growth of the salt marsh appears to be the rate of mineralisation of the organic fraction of the sediment. This is shown in Fig. 11, which shows that a high rate of mineralisation of soil organic matter significantly reduces the percentage contribution made by soil organic matter to vertical marsh growth. The ANCOSM mesocosms have indicated that the annual rate of mineralisation in old soil, from below 300 mm depth, is of the order of 8 %. No direct measurements have been made of rates in upper and organically richer soils (or of rates in the soils of the younger marshes) but it would seem possible that the higher organic content would facilitate a more active bacterial population and higher rates of mineralization (the initial figure used in the model was 20% but this was probably rather on the high side and 15 % might be a more realistic figure). The rate of mineralization in the sediment will be considerably affected by factors such as the soil temperature, water content. It should further be noted that the model is based on a mature (or degenerating) salt marsh with an active bacterial flora and the predictions made would not necessarily apply to a young marsh with a poorly developed microflora.

9.2 NITROGEN FLUXES - NITROMOD

Figures 12 and 13 compare the results from the model with measured values from the Tollesbury salt marsh (lower marsh) for soil NH_4-N and NO_3-N respectively. These are the data around which the model was constructed. To test the model against other data not used in its construction, NITROMOD has been run with the data from the pioneer zone at Tollesbury (Figures 14 and 15) and the middle marsh at Stiffkey (Figures 16 and 17). These outputs are discussed below. The model has not been run with data from the French, Dutch or Portuguese marshes as there is not sufficient soil nitrogen data from these sites against which to calibrate the model.

Figure 11. Effect of rates of mineralization of organic matter in salt marsh soils on the contribution of organic production to marsh growth.

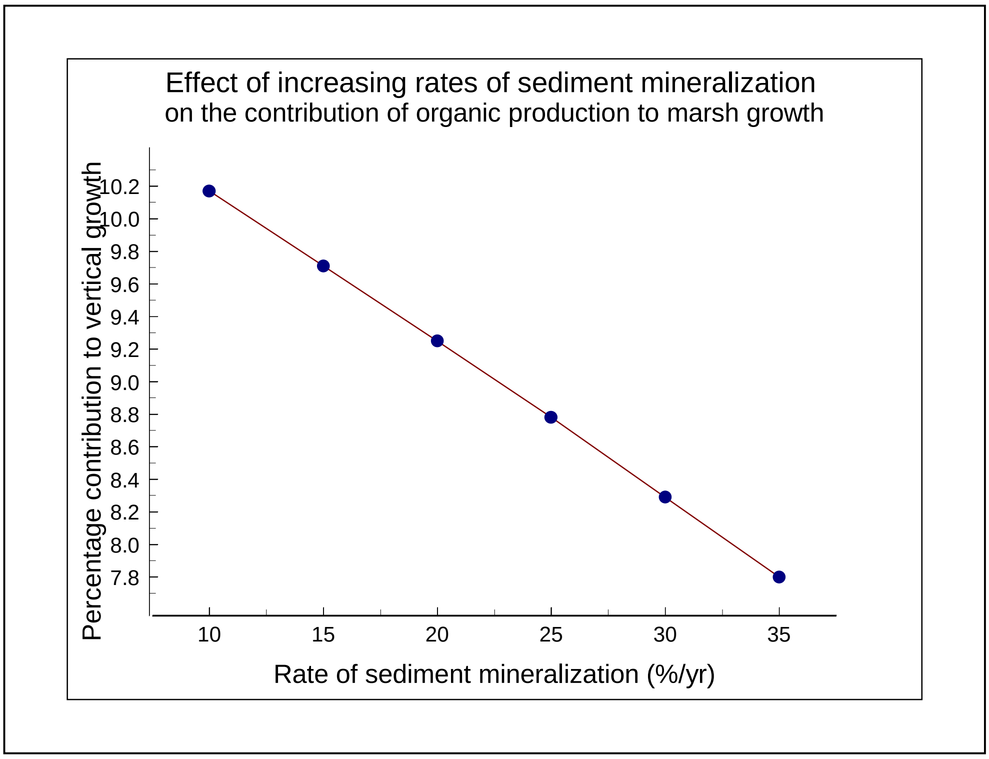


Figure 12. Comparison of modelled and real soil NH_4-N data (±SE) for Tollesbury Lower Marsh

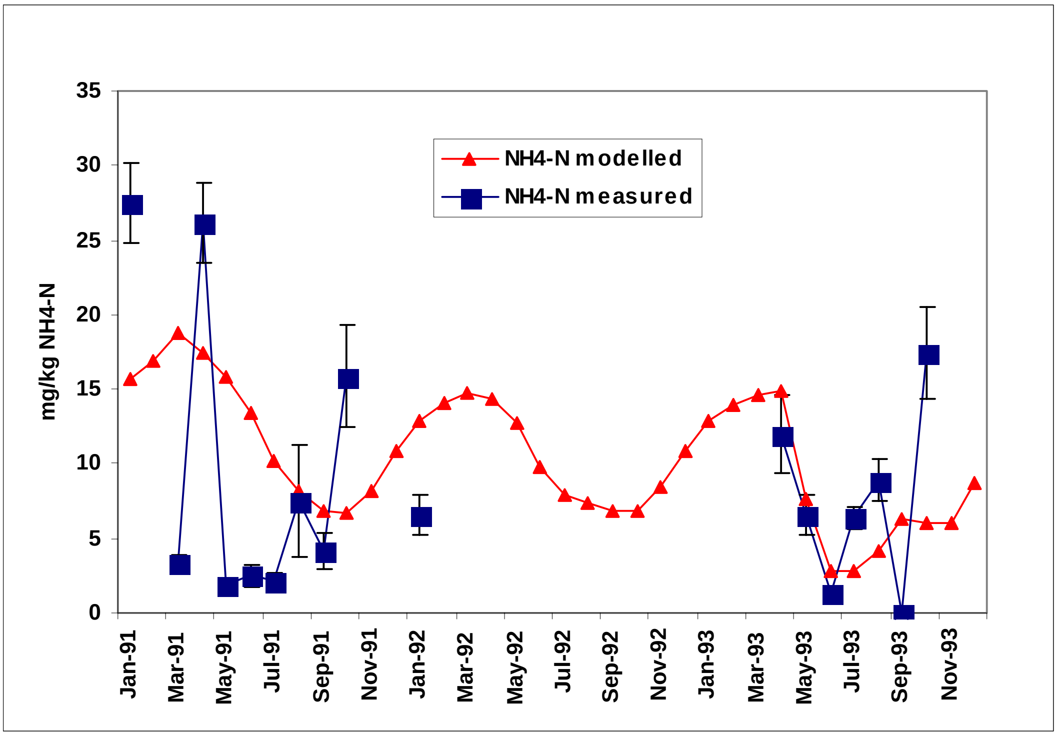


Figure 13. Comparison of modelled and real soil NO_3-N data (±SE) for Tollesbury Lower Marsh

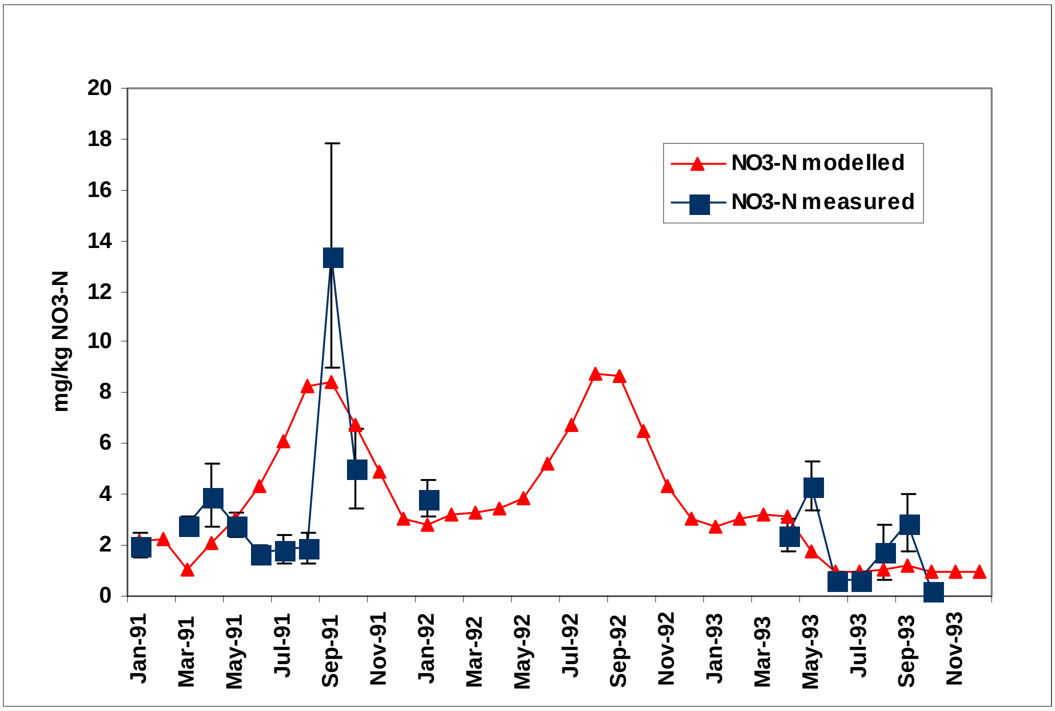


Figure 14. Comparison of modelled and real soil NH_4-N data (±SE) for Tollesbury Pioneer Zone

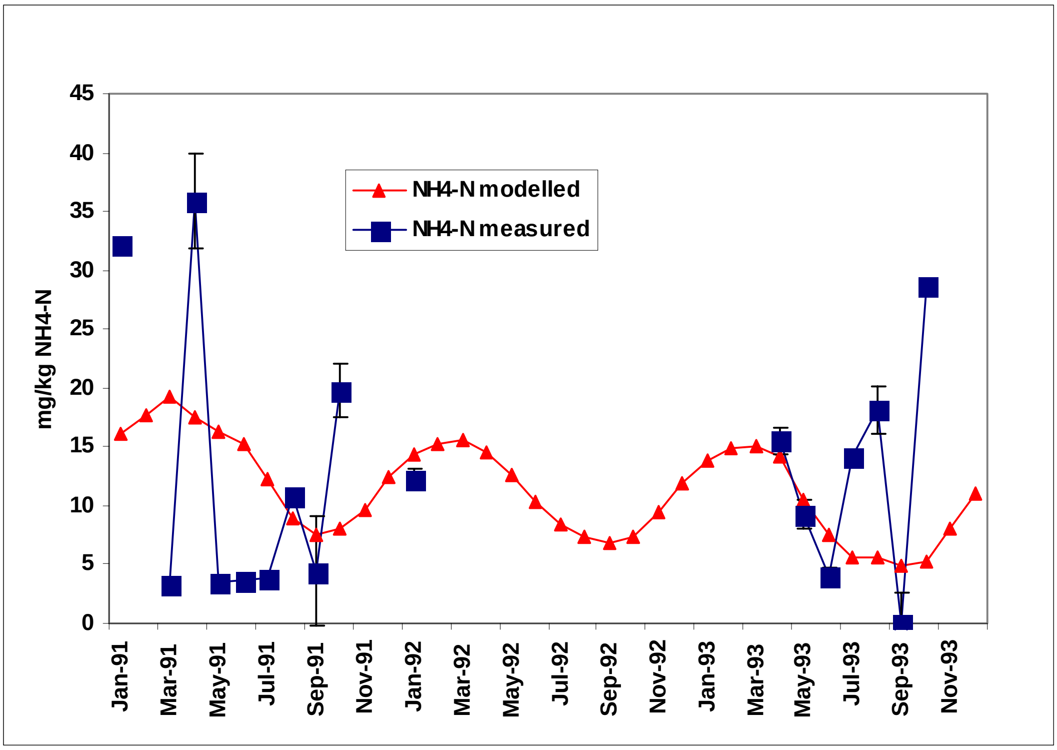


Figure 15. Comparison of modelled and real soil NO_3-N data (±SE) for Tollesbury Pioneer Zone

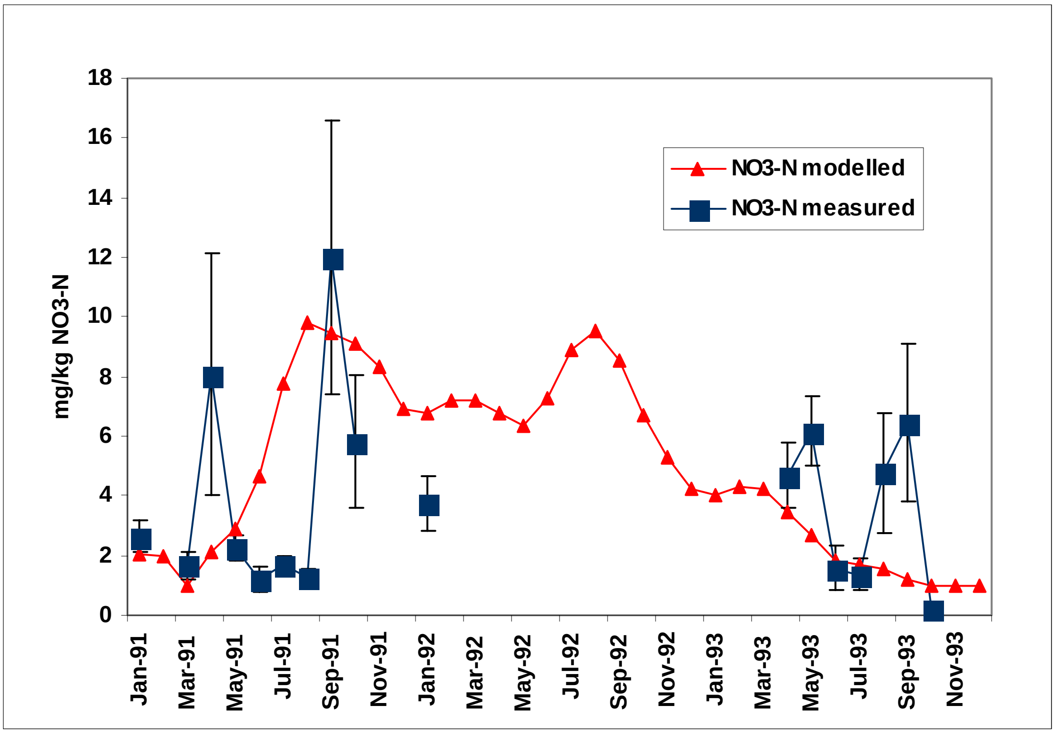


Figure 16. Comparison of modelled and real soil NH_4-N data (±SE) for Stiffkey Middle Marsh

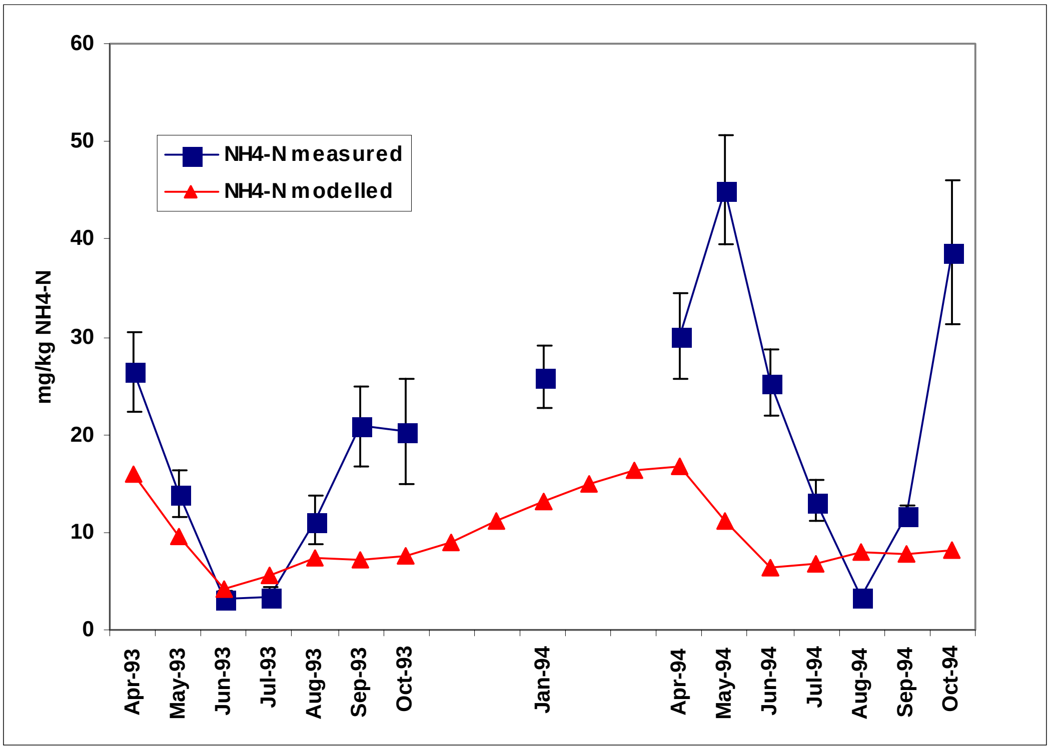
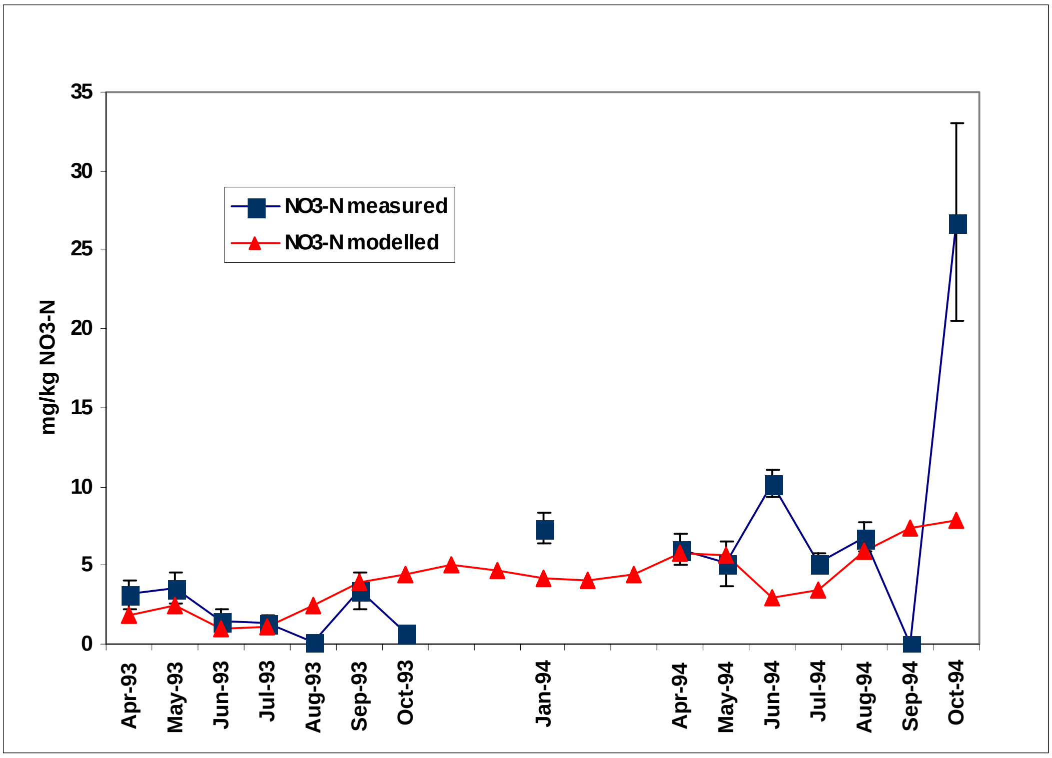


Figure 17. Comparison of modelled and real soil NO_3-N data (±SE) for Stiffkey Middle Marsh



The fluctuations in, and the incomplete nature of, the measured data meant that it was not practical to carry out statistical tests of goodness of fit or to use the optimization routines available within ModelMaker 3. Optimisation of some parameters which had been estimated rather than measured was carried out by running the model many times with the different values until the best fit was found.

10. DISCUSSION

10.1 ORGANIC FLUXES

The relative contribution of below-ground production to marsh growth is clearly a factor to be included when considering salt marsh management or re-creation. At low rates of sediment accretion it could amount to as much as 35% and even with relatively high rates of sediment accretion organic matter accumulation can easily contribute up to 10% of marsh vertical growth. The control of factors favouring plant below-ground productivity and reducing rates of mineralization can thus be considered to be important to salt marsh development and survival. However while low rates of mineralization may increase the build up of organic matter they are also likely to reduce the supply of nutrients to the salt marsh plants. Thus from the point of view of the growth of the plants (the primary producers) a higher rate of mineralisation will be beneficial. The picture is however complex as evidence from Tollesbury also suggests that the mineral nitrogen is immobilised by microbial activity during the breakdown of litter.

10.2 NITROGEN FLUXES

The actual values of soil NH_4-N are much more variable than the values modelled by NITROMOD in Figure 12, although the overall trends appear much the same. The measured NO_3-N values are slightly less variable and somewhat closer to the modelled figures (Figure 13).

There are many possible explanations for the discrepancies seen in Figures 12 and 13. The model seems capable of predicting soil nitrogen concentrations of the correct order, but the concentrations of the relative nitrogen species change very rapidly in response to changes in soil temperature, moisture and aeration, and to plant uptake. The model uses a monthly timestep and so cannot predict these fluctuations. A timestep of a day or even one of a few hours would be much better, but we do not have detailed enough data for most of the attributes to be able to run the model in this way.

In addition to the length of timestep, there are several possible explanations for the discrepancies seen in Figure 12 and 13. Our earlier studies suggested a strong direct link between the amount of litter and soil NH_4-N (Lefeuvre *et al*. 1993, Boorman *et al*. 1994a), but this was not supported by subsequent studies, possibly because of changing patterns of vegetation (Boorman 1996, Hazelden & Loveland 1996). The distribution and relative amounts of the various salt marsh species influence the levels of soil NH_4-N, probably by affecting the way plant litter is trapped on the marsh surface. In addition, different species have different C:N ratios and their litter will have different rates of breakdown which it has not been possible to build into the model at this stage. Soil moisture data from samples collected for other analyses have been used in the model and these may be unrepresentative in that the marsh is inundated regularly by spring tides and so the pattern of soil wetness is much more complex than allowed for here.

For the pioneer marsh at Tollesbury, the measured data are again much more variable than the model predicts. However, the model predicts values of the correct order, and so the discrepancies are probably due to the same reasons as those given above. At Stiffkey the model predicts much lower soil NH_4-N figures than were actual recorded, although the pattern is similar. There are probably many reasons for this, but there is less available data for Stiffkey than for Tollesbury and it may be that the data driving the model need correction. At Stiffkey, as at Tollesbury, the model is better at predicting soil NO_3-N than soil NH_4-N.

11. CONCLUSIONS

11.1 ORGANIC FLUXES

ANCOSM demonstrates the relative importance of below-ground organic matter accumulation to the increase in height of the salt marsh surface. Increasing rates of mineralization of organic matter may reduce the vertical growth but this process may be cancelled out by higher plant productivity resulting from increased turnover of organic matter resulting in the more rapid release of plant nutrients.

11.2 NITROGEN FLUXES

NITROMOD works reasonably well, particularly for soil NO_3-N, but could be substantially improved. Data collected more frequently, and for longer complete runs, which would allow the model to function with a much shorter timestep, may help reduce some of the differences between the apparently erratic real data and that which has been modelled. Also, the model needs to be able to run spatially to enable it to take account of different vegetation patterns across the marsh.

12. REFERENCES

Aziz, S.A.Abd. & Nedwell, D.B. 1979 Microbial nitrogen transformations in the salt marsh environment. In: R.L. Jeffries & A.J. Davy (eds) *Ecological processes in coastal environments*. Blackwell, Oxford, 385-398.

Bergström, L. & Jarvis, N.J. 1991 Prediction of nitrate leaching losses from arable land under different fertilisation intensities using the SOIL-SOILN models. *Soil Use and Management*, 7, 79-85.

Boorman, L.A. & Ashton, C. 1997. The productivity of salt marsh vegetation at Tollesbury, Essex and Stiffkey, Norfolk, England. *Mangroves and Salt marshes* 1:113-126

Boorman, L.A., Hazelden, J., Loveland, P.J., Wells, J.G. & Levasseur, J.E. 1994a Comparative relationships between primary productivity and organic and nutrient fluxes in four European salt marshes. In: W. J. Mitsch (ed.) *Global Wetlands: Old World and New*. Elsevier, Amsterdam, 181-199.

Boorman, L.A., Hazelden, J., Andrews, R.P. & Wells, J.G. 1994b Organic and nutrient fluxes in four north-west European salt marshes. In: K.R. Dyer and R.J. Orth (eds.) *Changes in Fluxes in Estuaries: Implications from Science to Management*. ECSA 22/ ERF Symposium, Olsen and Olsen, Fredensborg, Denmark, 243-248.

Boorman, L.A., 1996 *The effects of environmental change on European salt marshes: structure, functioning and exchange potentialities with marine coastal waters*. Final Report of EC contract no. EV5V CT92 0098, Volume 5. Laboratoire d'évolution des systèmes naturels et modifiés, Université de Rennes, France.

Bradbury, N.J., Whitmore, A.P., Hart, P.B.S & Jenkinson, D.S. 1993 Modelling the fate of nitrogen in crop and soil in the years following application of 15N-labelled fertilizer to winter wheat. *Journal of Agricultural Science*, 121, 363-379.

Campbell, C.A., Jame, Y.W. & Winkleman, G.E. 1984 Mineralization rate constants and their use for estimating nitrogen mineralization in some Canadian prairie soils. *Canadian Journal of Soil Science*, 64, 333-343.

Cherwell Scientific Publishing Limited. 1997 *ModelMaker 3.* Oxford, UK.

Goulding, K.W.T. (1990) Nitrogen deposition to land from the atmosphere. *Soil Use and Management*, 6, 61-66.

Hazelden, J. & Loveland, P.J. 1996. *The effects of environmental change on European salt marshes: structure, functioning and exchange potentialities with marine coastal waters.* Final Report of EC contract no. EV5V CT92 0098, Volume 4. Laboratoire d'évolution des systèmes naturels et modifiés, Université de Rennes, France.

Henriksen, K. & Jensen, A. 1979 In: R.L. Jeffries & A.J. Davy (eds) *Ecological processes in coastal environments.* Blackwell, Oxford, 373-384.

Hutson, J.L. & Wagenet, R.J. 1991 Simulating nitrogen dynamics in soils using a deterministic model. *Soil Use and Management*, 7, 75-78.

Jenkinson, D.S., Hart, P.B.S., Rayner, J.H. & Parry, L.C. 1987 Modelling the turnover of organic matter in long-term experiments at Rothamsted. In: J.H. Cooley (ed.) *Soil organic matter dynamics and soil productivity*. INTECOL Bulletin 15, 1-8.

Johnsson, H., Bergstrom, L., Jansson, P-E. & Paustian, K. 1987 Simulated nitrogen dynamics and losses in a layered agricultural soil. *Agriculture, Ecosystems and Environment*, 18, 333-356.

Jørgensen, S.E. 1994. A general model of nitrogen removal by wetlands. In: W. J. Mitsch (ed.) *Global Wetlands: Old World and New*. Elsevier, Amsterdam, 575-583.

Koerselman, W. & Verhoeven, J.T.A. 1992 Nutrient dynamics in mires of various trophic status: nutrient inputs and outputs and the internal nutrient cycle. In: J.T.A. Verhoeven (ed.) *Fens and bogs in The Netherlands: vegetation, history, nutrient dynamics and conservation.* Kluwer Academic Publishers, Dordrecht, The Netherlands, 397-432.

Lefeuvre, J-C., Dankers, N., Boorman, L., Loveland, P.J. & Bettencourt, A. 1993 *Comparative study on salt marsh processes*. Final report of EEC research contract no. EV4V-0172-F(EDB). Université de Rennes, France.

Lefeuvre, J-C., Bertru, G., Burel, F., Brient, L., Creach, V., Guerné, Y., Levasseur, J., Mariotti, A., Radureau, A., Retière, C., Savouré, B. & Troccaz, O. 1994 Comparative studies of salt marsh processes: Mont St Michel Bay, a multi-disciplinary study. In: W. J. Mitsch (ed.), *Global Wetlands: Old World and New*. Elsevier, Amsterdam, 215-234.

Vivier, J-P. 1997 *Influence du Paturage sur la Disponibilité de l'Azote pour l'Exportation dans un Marais Salé (Baie du Mont-Saint Michel),* Thesis, Université de Rennes, France.

13. ACKNOWLEDGEMENTS

The authors wish to express their thanks to the individuals and organisations who have made these studies possible, especially to colleagues in the Institute of Terrestrial Ecology (now Centre for Ecology and Hydrology), in Scottish Natural Heritage and to the various landowners for permitting site access, and also many colleagues across Europe for their help and encouragement. The authors gratefully acknowledge the financial support of DG XII of the Commission of the European Community received under Grants EV4V-0172F, EV5V-CT92-0098 and ENV4-CT97-0436.