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IMPACTS OF ADDITIONAL AERIAL INPUTS OF NITROGEN TO SALT MARSH AND TRANSITIONAL HABITATS

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Mae'r adroddiad hwn yn seiliedig ar ymchwiliad desg i lenyddiaeth a data ar effeithiau nitrogen yn yr aer/nitrogen atmosfferig (NO_X ac NH_3) ar forfeydd heli a chynefinoedd cyfnewidiol eraill, gan gydnabod bod y cynefinoedd hyn hefyd yn derbyn maetholion yn aml o ffynonellau/llwybrau dyfrllyd. Nodwyd mai nid nod y gwaith oedd herio'r llwythau critigol sydd wedi'u derbyn a'u cyhoeddi (*h.y.* 20 – 30 kg N ha^{-1} yr^{-1}) ar gyfer morfeydd heli (Bobbink a Hettelingh, 2011) ond yn hytrach ystyried cyfraniadau cymharol y ffynonellau atmosfferig a dyfrllyd o nitrogen at y cynefinoedd yma a sut ddylai hyn ddylanwadu ar y defnydd o lwythau critigol o nitrogen a lefelau critigol o amonia yn yr asesiad o'r mewnbwn ychwanegol yn yr aer o ffynonellau nitrogen newydd. Roedd yr astudiaeth yn ceisio penderfynu ar y llwyth critigol mwyaf priodol o nitrogen i'w roi ar forfeydd heli o fewn yr ystod pendant o 20 – 30 kg N ha^{-1} yr^{-1}. Hefyd, byddai'r astudiaeth yn penderfynu a yw'n briodol ystyried lefelau critigol o nitrogen mewn perthynas ag asesiadau effaith. Daw'r data a ystyrir o ystod eang o forfeydd heli tymherus gogleddol ond gyda phwyslais arbennig ar y rhai ym Mhrydain Fawr a gogledd orllewin Ewrop. Cyflwynir y darganfyddiadau gyda chyfeiriad arbennig at sefyllfaoedd y morfeydd heli yng Nghymru.

Mae data sylweddol ar gael, wedi a heb eu cyhoeddi, am lefelau nitrogen a chylchu perthnasol i gynefinoedd o forfeydd heli. Oddi mewn i amserlen y prosiect hwn dim ond asesiad cyffredinol o'r cyfresi data a ddewiswyd oedd posib ei wneud. Nid oedd amser i unrhyw integreiddio mathemategol manwl na modelu'r cyfresi data amrywiol. O ystod eang o astudiaethau o forfeydd heli daeth yn eglur bod morfeydd heli yn cynnwys amrywiaeth o gynefinoedd sy'n gymharol gyfoethog mewn nitrogen o gymharu â chynefinoedd naturiol eraill. Mae cronfeydd nitrogen sylweddol yn y pridd ac mae'r cynefin wedi'i nodweddu gan lefelau uchel o gylchu maetholion, gan gynnwys cylchu nitrogen yn ei ffurfiau amrywiol.

Mae lefel y nitrogen a ddefnyddir gan y cymunedau amrywiol o blanhigion ar y morfeydd heli yn isel o gymharu â'r cronfeydd helaeth o nitrogen yn y pridd a lefel y nitrogen sy'n rhan o'r cylch maetholion cysylltiedig. Yn y system o forfeydd heli dim ond newidiadau cymharol fychan a geir yn y cydbwysedd net rhwng mewnforion ac allforion nitrogen. O'r data cymharol gyfyngedig sydd ar gael o arbrofion maes uniongyrchol, yn gyffredinol, roedd yn glir bod angen mewnbwn o nitrogen sy'n fwy na'r llwythau critigol mae'n bur debyg er mwyn i newidiadau sylweddol ddigwydd i'r llystyfiant.

Hefyd, dangosodd yr astudiaethau o fflwcsau a chyfnewidiadau nitrogen bod unrhyw ymateb i newidiadau mewn lefelau nitrogen yn debygol o amrywio gyda statws datblygiadol y morfa heli, fel y dynodir gan y cymunedau o blanhigion o dan sylw ac oedran swyddogaethol y morfa. Mae'r mewnbwn blynyddol o nitrogen yn yr aer a bennir gan y llwythau critigol rhagnodol yn fach o gymharu â lefel y nitrogen sy'n cael ei storio yn y pridd. Nid oes llawer o dystiolaeth i awgrymu bod mewnbwn ychwanegol o nitrogen o dan y lefelau llwyth critigol yn debygol o gael unrhyw effaith niweidiol mawr ar statws nitrogen y morfa, nac ar dwf ei lystyfiant. Er hynny, awgrymir bod rhai mecanweithiau ar gael ar gyfer cael gwared ar nitrogen gormodol o'r system. Gall ffurfiau ar nitrogen hydawdd ym mharth gwreiddiau planhigion y morfa heli naill ai gael eu defnyddio gan y planhigion neu eu golchi allan gan y llif llanwol rheolaidd

Ar forfeydd ar dir isel, mae mewnbwn y nitrogen drwy lawiad a'r dyddodiad sych yn gyfyngedig i ddyddodiad uniongyrchol yn yr ardal o forfa ei hun, gan mai ychydig iawn o'r dalgylch o amgylch sy'n draenio'n uniongyrchol ar arwyneb y morfa. Er hynny, mewn ardaloedd o dir

uchel (bryniog), mae'r sefyllfa'n wahanol oherwydd gall y dalgylchoedd ddraenio'n uniongyrchol ar draws tir y morfa. Yma, gallai'r mewnbwn fod yn llawer iawn mwy, gan ddibynnu ar faint dalgylch lleol y morfa unigol.

Y casgliadau a wneir gan yr awduron ar ôl archwilio'r data yw ei bod yn annhebygol bod y mewnbwn nitrogen yn ôl y llwythau critigol penodol yn cael unrhyw effaith niweidiol ar forfeydd heli Cymru (neu yn unrhyw le arall yn y DU). Yn llystyfiant tal y cymunedau caeedig uchaf o forfeydd y mae unrhyw effeithiau posibl fwyaf tebygol i'w canfod, ble ceir y gystadleuaeth fwyaf rhwng y rhywogaethau. Felly awgrymir defnyddio gwerth o 30 kg ha^{-1} yr^{-1} gyda'r rhan fwyaf o'r morfeydd a lefel is o 20 kg ha^{-1} yr^{-1} gyda'r morfeydd uchaf sydd â llystyfiant mwy trwchus a'r ardaloedd o forfa y mae nitrogen yn llifo'n uniongyrchol iddynt o ddalgylchoedd cyfagos.

Mae morfeydd heli'n amrywio'n sylweddol o ran eu sefyllfaoedd daearyddol a geomorffolegol ac o ran dylanwad y cynefinoedd cyfnewidiol cyfagos arnynt. Felly, mae'n rhaid ystyried asesiadau o effaith mewnbwn nitrogen sy'n uwch na'r llwythau critigol sydd wedi'u diffinio fesul pob morfa unigol. Nid oedd digon o amser yn y prosiect hwn i ystyried yn fanwl effeithiau nitrogen ar y lefelau critigol neu uwch ond, yn gyffredinol, mae'n ymddangos yn debygol y byddai effeithiau cronnol yr effeithiau tymor byr hyn yn foddhaol drwy ddefnyddio'r llwyth critigol.

Yn ystod y gwaith ymchwil ar gyfer yr adroddiad hwn daeth yn eglur y byddai'r mater cyffredinol o bennu cyfyngiadau llwyth critigol a rheoli llystyfiant yn y sffêr arfordirol, yn enwedig mewn perthynas â morfeydd heli, yn elwa o ragor o wybodaeth o safon uchel. Byddai hyn yn gwella dibynadwyedd yr wybodaeth ac yn arwain at weithredu'n fwy effeithiol y darganfyddiadau mewn rheolaeth natur ymarferol a ddefnyddir mewn sefyllfaoedd penodol. Felly, daw'r adroddiad i'w derfyn drwy gyflwyno pump argymhelliad ar gyfer astudiaethau pellach.

EXECUTIVE SUMMARY

This report comes from a desk-based investigation of the literature and data on the impacts of aerial/atmospheric nitrogen (NO_X and NH_3), on salt marshes and other transitional habitats, recognizing that these habitats often also receive nutrients from aqueous sources/pathways. It was specified that the work was not to challenge the accepted published critical loads (*i.e.* 20 – 30 kg N ha^{-1} yr^{-1}) for salt marshes (Bobbink & Hettelingh, 2011) but rather to consider the relative contributions of atmospheric and aqueous sources of nitrogen to these habitats and how this should influence the application of the nitrogen critical loads and ammonia critical levels in the assessment of additional aerial inputs from new nitrogen sources. The study set out to determine the most appropriate nitrogen critical load to apply to salt marshes within the defined range of 20 – 30 kg N ha^{-1} yr^{-1}. In addition the study would also determine whether it is appropriate to consider critical levels of nitrogen in relation to impact assessments. The data considered are drawn from a wide range of north temperate salt marshes but with special emphasis on those in Great Britain and north-west Europe. The findings are given with particular reference to situations of the salt marshes of Wales.

There is a considerable amount of data available, both published and unpublished, on nitrogen levels and cycling relating to salt marsh habitats. Within the time frame of this project it has only been possible to make a general assessment of selected data sets. There has not been time for any detailed mathematical integration and modelling of the various data sets. From a wide range of salt marsh studies it has become clear that salt marshes include a range of habitats which are relatively nitrogen-rich when compared with other natural habitats. There are significant nitrogen reserves in the soil and the habitat is characterized by high levels of nutrient cycling, including the cycling of nitrogen in its various forms.

The levels of nitrogen uptake by the various salt marsh plant communities are low compared with the magnitude of nitrogen reserves in the soil and the levels of nitrogen involved in the associated nutrient cycling. Within the salt marsh system there are only relatively small changes in net balances between imports and exports of nitrogen. From the rather limited data available from direct field experiments it was clear that, in general, for significant changes to occur to the vegetation, inputs of nitrogen in excess of the critical loads were likely to be needed.

Furthermore, the studies on nitrogen fluxes and exchanges indicated that any response to changes in nitrogen levels was likely to vary with the developmental status of the salt marsh as indicated by the plant communities concerned and by the functional age of the marsh. The annual aerial inputs of nitrogen set by the prescribed critical loads are small compared with the levels of nitrogen stored in the soil. There is little evidence to suggest that additional inputs of nitrogen within the critical load range are likely to have any major detrimental effect on the nitrogen status of the marsh, or on the growth of its vegetation. It is suggested that there may be some mechanisms through which excess nitrogen can be removed from the system. Forms of soluble nitrogen within the rooting zone of salt marsh plants can either be taken up by the plants or they could be washed out by the regular tidal inundation.

For lowland marshes the nitrogen inputs by rainfall and dry deposition are limited to direct deposition within the area of the marsh itself, as very little of the surrounding catchment drains directly onto the marsh surface. However, in upland (hilly) areas the situation is different as catchments may drain directly across marshland. Here inputs could be greatly increased by a whole order of magnitude depending on the extent of the local catchment of an individual marsh.

The conclusions that the authors draw from the data examined are that it is unlikely that nitrogen inputs at the set critical loads will have any damaging effect on the salt marshes of Wales (or elsewhere in the UK). Any possible effects are most likely to be found in the tall vegetation of the closed upper marsh communities where interspecific competition is at its greatest. Thus it is suggested that the value of 30 kg ha^{-1} yr^{-1} be applied to most of the marsh with the lower level of 20 kg ha^{-1} yr^{-1} being applied to the more densely vegetated upper marsh and to areas of marsh subjected to direct run-off from adjacent catchments.

Salt marshes vary greatly in their geographical and geomorphological situations and in the influences of adjacent transitional habitats upon them. Thus assessments of the impact of nitrogen inputs above the defined critical loads really need to be considered on a marsh by marsh basis. There was insufficient time within this project to consider in detail the impacts of nitrogen at or above the critical levels, but it seems likely that the cumulative effects of these short term impacts would, in general, be adequately covered by the application of the critical load approach.

During the research for this report it became clear that the whole question of the setting of critical load limits and the management of vegetation in the coastal sphere, particularly in relation to salt marshes, would benefit from further good quality information to improve the reliability of the interpretations and to implement more effectively the findings in practical nature management applied to specific situations. The report therefore concludes by presenting five recommendations for further studies.

1 GENERAL INTRODUCTION

This report comes from a desk-based investigation of the literature and data on the impacts of aerial/atmospheric nitrogen, including ammonia, on salt marshes and other transitional habitats, recognizing that these habitats often also receive nutrients from aqueous sources/pathways. It was specified that the work was not to challenge the accepted published and lower critical loads (*i.e.* 20 – 30 kg N ha^{-1} yr^{-1}) for salt marshes (Bobbink & Hettelingh, 2011) or the ammonia critical level for the protection of vegetation (*i.e.* 3µg/m^3), but rather to consider the relative contributions of atmospheric and aqueous sources of nitrogen to these habitats and how this should affect/influence the application of the nitrogen critical load and ammonia critical level in the assessment of additional aerial inputs from new nitrogen sources. The study was to determine the most appropriate nitrogen critical load to use on salt marshes within the defined range of 20 – 30 kg N ha^{-1} yr^{-1}. In addition the study would also determine whether it is appropriate to apply the critical levels of nitrogen in impact assessments. During the course of the study it became apparent from the available data that there were a number of important new factors to be brought into consideration both in terms of routes of nitrogen fluxes and the interpretation of their effects on particular salt marsh communities.

The report layout is based on that indicated by the prescribed tasks (Section 2) but as the scientific literature was studied and assessed it became clear that some adjustments were needed in order to cover all relevant aspects of the subject while answering the specific questions set by CCW. This introduction will set out a general background of the subject in terms of the effects of mineral nutrition on plant species and plant communities with special reference to the maintenance of species diversity; the classification of vegetation relevant to vegetation management; salt marsh structure and function and an outline of aerial deposition of nitrogen and the concept of critical loads (Sections 1.1 to 1.4). Section 2 describes the tasks set out for this study.

The next section (Section 3) presents in some detail the latest scientific data on nitrogen and salt marshes relevant to this study. Firstly it describes the general aspect of salt marsh nutrient budgets (Section 3.1); it then goes on to describe in detail nitrogen sources and inputs (Section 3.2); nitrogen outputs (Section 3.3) before going on to discuss nitrogen reserves and sinks (Section 3.4). The report then considers the various factors which can affect the functional nitrogen status of a salt marsh and the consequential effects on plant growth and plant species diversity (Section 3.5). The effects of nitrogen on the plant species diversity of salt marshes are considered next (Section 3.6). The plant communities that make up the salt marshes have generally been described in terms of the National Vegetation Classification (Rodwell, 2000) but the European work on the application of critical loads uses the European Nature Information System (EUNIS) and therefore these two systems, as they apply to salt marshes, are described and compared in the next section (Section 3.7) before going on to outline the salt marsh communities to be found in Wales and their classification (Section 3.8). The final two sections consider firstly the general effects of aerial nitrogen deposition on salt marshes (Section 3.9) and salt marsh diversity and secondly the Welsh perspective (Section 3.10).

The conclusions reached from the corpus of information which has been gathered during this study are given in Section 4 before going on to make recommendations for future studies that deserve priority in this field (Section 5). The report concludes with acknowledgements and the references.

1.1 Plant communities, competition and diversity

Wild plants generally occur in stands with a number of different species, species which have in common special adaptations to that particular habitat. Most natural and many semi-natural habitats have a level of plant nutrients that is sub-optimal. If the nutrient levels are increased the plants become more vigorous and the total productivity (standing crop) increases. However, there are nearly always some plants in any plant community which show only a limited response to a rise in nutrient levels. As the nutrient level rises the plants that can continue to grow more vigorously thrive at the expense of those that are unable to respond and the plant community loses some of its species richness. Typical examples of this can be seen in sand dune communities. When there are low levels of plant nutrients this can be a species-rich community with perhaps 20 or more species in each 10 cm x 10 cm square. When fertilizer was added the standing crop increased but the number of species fell to 4 species in each 10 cm x 10 cm square with only the most vigorous grasses and a few vigorous weed species remaining (Boorman & Fuller, 1982). In unfertilized habitats the competition between individual plants and plant species is low and diversity is maintained. Anything that increases the intensity of inter-species competition will reduce the species diversity.

1.2 The classification of vegetation

The preceding paragraph mentioned the concept that wild plants grow together in groups of species that are suited to a particular habitat and collectively they are referred to as a plant 'community'. Continental plant ecologists have gone as far as suggesting that a plant community has its own special properties greater than the sum of the individual species and have developed names for the communities in the same way that the species themselves were named and classified. In the UK the approach has rather been to recognize particular plant associations and classify these. There were differences between the classifications as used by different botanists but, particularly for distinctive habitats like salt marshes (composed of those plants able to withstand immersion in saline conditions), there was a reasonable uniformity between different workers. A big step forward in the classification of the UK plant communities happened between 1991 and 2000 with the publication of five volumes of 'British Plant Communities'. In this national vegetation survey (NVC) the whole range of plant communities found in the British Isles was described and classified in a uniform system that could be understood and used by all workers in the field. The system was, however, only applicable to the UK. Subsequently the needs of Europe as a whole were met by the appearance of the European Nature Information System (EUNIS). As yet the system is still in its early stages and lacks the detail available under NVC on the definition of particular plant communities. There is also the problem that the two systems place salt marshes in separate categories; NVC regards salt marshes as maritime while EUNIS classifies them as marine but regards the transitional communities as terrestrial.

1.3 Salt marsh structure and function

Salt marshes are formed by the accumulation of fine-grained marine sediments stabilized by the establishment and growth of higher plants. There is a limited range of species (halophytes) which have become adapted to withstand the stress of regular immersion in salt water. A salt marsh typically has a range of habitats each with distinctive plant species. Each habitat occurs at particular levels in relation to the tide. The lowest plant community in relation to sea level, the pioneer marsh, is composed of those species able to withstand the longest period of immersion. Other salt marsh species cannot withstand these conditions but in time the sediment, caught by the vegetation, builds up the surface level of the marsh and the duration of immersion decreases. This enables other species, those typical of the lower marsh, to colonise. At this stage the density of the plant cover is low and the pioneer species are generally able to survive here. On the other hand at the upper edge of the marsh, while the salinity in the soil still keeps non-salt tolerant species out, competition between the plants is much greater and only the most vigorous saline species can survive.

The salt marshes physically form a broad boundary between the land and the sea but they do more than just define a physical boundary. The marshes receive sediment, organic matter and plant nutrients (including nitrogen) as well as pollutants and they form not just a barrier but a dynamic living link between land and sea (Boorman, 2000). Salt marshes act as processors of organic and mineral material while at the same time they provide reserves of sediments, mineral nutrients and organic carbon. Salt marshes can contribute significant quantities of organic matter to adjoining marine systems and thus play a key role in the estuarine system as a whole. Thus salt marshes also form a vital dynamic barrier between land and sea

1.4 Human impacts on salt marshes

Humans have been exploiting salt marshes for many millennia but initially this was at the level of subsistence fishing and shellfish gathering. It is only over the last few hundred years that man has had a major impact on salt marshes through the large scale construction of earth banks to keep the sea out and thus to convert the marshes to land available for cattle grazing and more recently for growing agricultural crops and for industrial developments (Boorman, 2002a). The loss of marshes to agriculture or to industrial development has become even more serious recently with rising sea levels as a result of global warming. In completely natural situations salt marshes can adapt to rising sea levels by a process of erosion at the seaward edge and the re-deposition of this material in the higher areas of the marsh. By this process the marsh can effectively move landwards and up the coastal slope to find a new equilibrium. However, there are many places where there is a fixed barrier in the form of the sea wall that limits natural adjustments of the salt marshes to sea level rise. Salt marshes can also be affected by a wide range of agricultural chemicals and industrial pollutants and they are also very sensitive to the effects of human trampling and other such direct disturbance.

1.5 Aerial deposition of nitrogen and critical loads

It has been documented that over the last 150 years there has been an acceleration in the emission of nitrogen compounds and this has increased the aerial deposition of nitrogen in various forms altering the water quality and the functioning of terrestrial and aquatic ecosystems world-wide (Holland 2005). The nitrogen is deposited in various forms based on ammonia and oxides of nitrogen including nitric acid. Some of the depositions are water-based being washed out by rain while others form dry deposition in the form of fine particles and gases. In the United States the nitrogen mainly comes from the burning of fossil fuels and industrial processes and is in the oxidised forms of nitrogen. In Britain and Europe the deposition has a much higher proportion of reduced nitrogen (in the form of ammonia and ammonium compounds) and comes mainly from agricultural sources. The ratio in the UK has recently been estimated to be approximately 50/50 (Anon, 2010). The nitrogen deposition processes work on a world scale and it is suggested that some of the UK nitrogen load comes from the United States (Holland *et* *al.,* 2005). As described above increasing nitrogen levels can affect the species richness of plant communities. Correspondingly, harmful effects are not likely to occur below the critical load range according to current knowledge. This report considers the situation with regard to salt marshes.

2 INTRODUCTION TO TASKS

The CCW Research Contract Technical Specification (R002431) outlines a series of tasks for the study and these are given below (paragraphs 2.1 to 2.5). These tasks were reconsidered at the First Project Meeting and it was agreed that the work should concentrate on Task 1 but addressing the items in Task 4 (paragraphs 2.4.1 to 2.4.4) and most importantly in Task 5 (paragraphs 2.5).

2.1 Critical loads and salt marshes

Collate available information on the nutrient budgets of salt marsh systems (both within and outside the UK) and quantify the contribution/relative proportion of aerial nitrogen inputs (including ammonia and NOx) and nitrogen inputs via the water.

2.2 Critical loads along the coast

Determine (through discussion with the critical load community) whether the 20 – 30 kg N ha^{-1} yr^{-1} critical load takes account of marine sources of nitrogen.

2.3 The nutritional status of salt marsh systems

Classify the nutrient status of salt marsh systems in Wales and England and compare with the systems in The Netherlands and UK used to set the critical load.

2.4 Key questions

Consider and answer the following questions, making clear where there is evidence to support your answer and where your answer is based on professional judgement:

2.4.1 Marine influence

Are sites that have a high marine influence less sensitive to aerial nitrogen input than those sites that receive the majority their nitrogen input through run-off, tidal inundation and denitrification?

2.4.2 Marsh age

If the age of the salt marsh is a factor in tolerance to nitrogen, should pioneer and low – mid salt marshes be assessed using the lower end of the critical load range?

2.4.3 Marsh status

How does/should the current status of a salt marsh site influence how the critical load should be applied? Would a low nutrient system need to have the lower end of the critical load range applied to protect it? How do the trophic statuses of salt marsh systems in the UK relate to the systems used to set the critical load and what implications does this have?

2.4.4 Salt marsh categorization

Is it possible to categorize salt marshes based on factors such as their trophic status, age, other sources of N *etc*., with a view to assigning which part of the nitrogen critical load range (*i.e*. 20 – 30 kg N ha^{-1} yr^{-1}) is the most appropriate for a salt marsh within a particular category? Is it necessary to apply the critical levels of ammonia and NOx or does applying the nitrogen critical load approach give sufficiently protection?

2.5 Provision of recommendations

Based on the above, provide recommendations on how critical loads and levels should be applied to salt marsh systems in the UK, when assessing the potential impact of additional atmospheric sources of nitrogen on an individual site.

3. SALT MARSHES AND NITROGEN

3.1 Salt marsh nutrient budgets

A key feature of salt marshes is that they are one of a limited number of plant communities that can be classified as primary colonizers of newly available plant habitats. As such the growth of salt marsh vegetation starts on areas of fine-grained sediments carried in by tidal action and then stabilized by the development of vegetation (Hazelden & Boorman, 1999). The growth of this vegetation cover increases the rate of sediment addition by slowing the water flow over the marsh. The fine sediments whose deposition enabled the primary colonization of the area by higher plants are relatively low in their mineral nutrient content and the gradual build-up of nutrient levels in both mineral and organic forms is critical both for the development and function of salt marsh plant communities as well as the wider functions of salt marshes within the coastal zone (Boorman, 1999). While there are some broad similarities between saline (salt marshes) and other tidal freshwater wetlands the chemistry of sea water, notably the presence of sulphate, leads to significant biogeochemical differences in processes such as the oxidation of organic carbon and the cycling of nitrogen, phosphorus and other plant nutrients (Tobias & Neubauer, 2009).

The cycling of key elements is only a part of the functioning of salt marsh ecosystems as fluxes and exchanges occur both within the salt marsh system and between the marsh and a wide range of neighbouring terrestrial and marine ecosystems (Boorman, 2000). Comparative studies were made in a range of marshes in England, France and The Netherlands of primary productivity and of the fluxes of sediment, the various forms of organic matter and the two major plant nutrients nitrogen and phosphorus (Boorman *et al*., 1994). These studies showed that there were wide seasonal variations in the fluxes within and between marshes and other ecosystems and that these variations were even more marked when the different forms of nitrogen were taken into account. There were also variations as to whether nitrogen or phosphorus was the main limiting factor for determining plant growth and there were also circumstances in which, with adequate supplies of both, other elements such as silicon could become the limiting factor. Generally the release of nitrogen and phosphorus from the salt marsh occurs as a result of the decomposition of organic matter. Direct losses by leaching of nitrogen and phosphorus from living plant tissues can also occur (Turner, 1993).

The development of salt marsh fluxes and exchanges is paralleled by the development of the salt marsh plants and the salt marsh plant communities. If the community of scattered individuals of *Salicornia* spp. is compared with the dense sward of *Elytrigia aetherica* along the upper edges of many salt marshes or with the diverse mid-marsh communities with many species such as *Limonium*, *Aster*, *Armeria*, *Plantago etc*. then a concept of salt marsh maturity is obtained. However, while normally the maturity of a community is assessed in terms of the chronological age of that unit, but particularly in the case of salt marshes, there is a functional aspect that has to be considered. The age of a salt marsh is a rather poor indicator of the true state of development of the marsh (Adam, 1990). Studies of salt marsh fluxes and exchanges led to the development of the concept of functional maturity (Hazelden & Boorman, 1999). This concept was based on the hypothesis that in the course of salt marsh development there are corresponding changes in the way that the marsh functions particularly with respect to the links between the salt marsh and its exchanges with adjacent communities and ecosystems. The concept of salt marsh classification by function was formulated in which the age of the marsh was considered to be subordinate to the functional parameters of the marsh (Table 3.1.1).

Table 3.1.1 Salt marsh maturity as defined in relation to specific marsh functions as opposed to chronological age (adapted from Boorman, 2000).

Marsh function	'Young'	'Mature'	'Old'
Tidal Regime	Flood dominant	Ebb dominant	Ebb dominant
Sediment Flux	Import	±Import	Export
Nutrient Fluxes	Export	Neutral	Import
Organic Fluxes	Import	Export	Export
Soil Bacterial Activity	Low	Medium	High
Productivity	Low-High	High	Medium

Notes: - 'Young' refers to salt marshes with the functions as defined and such marsh areas have open vegetation composed mainly of pioneer marsh plant species. 'Mature' refers to salt marshes with a range of closed plant communities. 'Old' marshes also have a range of closed plant communities but there may also be areas of open ground, sometimes with pioneer salt marsh species.

One reason for this approach was the observation that, within marshes regarded as having mature communities, regeneration could occur whereby parts of an old marsh could regain activities that were usually associated with chronologically young systems (Boorman, 1999). It became clear that actively extending marshes tended to be flood dominated and net importers of sediment and organic matter. These actively extending marshes are mainly to be found along the seaward edges of a marsh system but they can also occur following the loss of middle or high marsh by erosion. Reversion of areas of marsh though regeneration also results in the regeneration of the functional properties associated with 'young' or pioneer marshes. Marshes that were not extending their area tended to be ebb-dominated and net exporters of organic matter and sometimes even sediment. These latter marshes termed 'old' were considered to be mature or even, when showing signs of decay, over-mature in contrast to the immature marshes that were still growing (Hazelden & Boorman, 1999).

Salt marsh nutrient budgets are thus not only important for the function of the marshes themselves but have to be considered in relation to the place of salt marshes relative to other coastal ecosystems. They are best seen as processors of organic and mineral material while at the same time providing reserves of sediments, mineral nutrients and organic carbon. Salt marsh plants, like other plants, require a balanced supply of major and trace nutrients to maintain their position in marsh communities. Reduced levels of any of the required nutrients will inhibit plant growth and thus no one nutrient element can be regarded as critical for plant nutrition, a balanced supply of all major and trace elements is required. Nitrogen is often regarded as the potential limiting factor for plant growth but in salt marshes phosphorus, although needed at lower concentrations than nitrogen, can also be the limiting nutrient. Comparative studies of productivity in salt marshes of NW Europe showed that while nitrogen was the usual limiting factor, there were some Dutch estuaries where phosphorus was found to be the major limiting factor. This may partly be due to inherently low soil phosphate levels but the main factor is that high pH levels in most salt marsh soils result in calcium phosphate being the dominant form of inorganic phosphorus and this form is not directly available for plant uptake (Van Wijnen & Bakker, 1999). In general there needs to be a balance between the levels and availability of the various plant mineral nutrients.

3.2 Nitrogen sources and inputs

This section will describe the many different sources of nitrogen and the various different routes by which nitrogen reaches salt marshes. Nitrogen occurs in nature and from artificial sources as solids, liquids or gases. Nitrogen compounds, as with other nutrients and pollutants together with marine and terrestrial sediments, are transported by a range of vectors from sea and land (Boorman, 2009). The liquids are transported to the marshes in solution or as aerosols while the gases are carried directly by the wind. The solids are transported as particulate forms, associated with sediment and organic matter, by fresh and salt water and occasionally by the wind. Nitrogen is also brought to salt marshes by the wind through rainfall and dry deposition and the nitrogen from the atmosphere can be fixed in various ways by bacteria, algae and fungi. There are five common forms of inorganic nitrogen namely gaseous nitrogen, ammonium salts, nitrates and nitrites and the various gaseous oxides of nitrogen. Organic nitrogen is found in a variety of compounds particularly proteins, amino acids, amines, amides and urea. The chemistry of the transformations of nitrogen between the various forms will be considered under the sources and inputs involved.

3.2.1 Tidal flow (sea water)

More than 30 years of coastal research has shown that the regular ebb and flow of the tide is generally regarded as dominating the mass fluxes of nitrogen between salt marshes and adjoining ecosystems (Tobias & Neubauer, 2009). However, most of these studies indicate that the magnitude and direction of these exchanges can reverse even over short time periods thus it is difficult to predict whether a particular marsh will import or export particular forms of nitrogen at any given time. Comparative studies in England, France, The Netherlands and Portugal showed variable results (Hazelden & Boorman, 1999). At the salt marsh sites in England and in The Netherlands there were only small differences between imports and exports contrasting with the situation at the site in France where there were generally exports of all forms of nitrogen. At the Portuguese site nitrogen levels were generally low but there were small net imports of nitrogen. All the sites studied showed that there was great short term variability both in the direction of exchanges and in the forms of nitrogen involved.

The forms of nitrogen involved include nitrates (and low levels of nitrites), ammonium nitrogen, dissolved organic nitrogen (DON) and also particulate organic nitrogen (PON). A range of studies showed that imports were mainly in the form of PON and DON with much lower amounts of ammonium and nitrate nitrogen (Tobias & Neubauer, 2009). The largest imports of PON were observed in younger marshes (Valiela *et al*., 2000). The whole question of imports and exports of the various forms of nitrogen is complicated by changes in nitrogen forms during the exchanges process. Childers *et al*., (2000) showed that tidal amplitude could affect these exchanges. Net imports of nitrate-nitrogen during neap tides could be reversed by high rates of loss of ammonium-rich pore water which could be rapidly oxidized to nitrate-nitrogen and thus readily exported.

The transport by tidal flow of any component exchanged between salt marshes and the sea (including tidal flows within the estuary) will be affected by the levels of high and low water.

Plants are only able to colonize the mud flats when accretion has brought them to a level at which the surface is no longer covered by every tide. This enables seedlings of pioneer salt marsh plants to become sufficiently well rooted for the plant to be firmly attached to the substrate and thus able to withstand the ebb and flow of the tide (Boorman, 1999). Salt marshes can extend upwards as far as the level reached by at least a few of the highest tides and thus maintain the saline influence which excludes more vigorous non-saline tolerant plant species. Between these two extremes there is the potential for considerable differences in nitrogen imports. The total period of submersion will determine the time period within which nitrogen imports can be received, although this will also result in a similar period for potential nitrogen losses (*q.v.*). Against this the longer period of immersion will also give more time for the deposition and/or uptake of nitrogen. The lowest (pioneer) salt marsh can receive imports of nitrogen for each of the twice-daily tides except a few of the smallest neap tides. The highest marshes on the other hand will only have the opportunity to receive tidal imports (or provide exports) for an hour or so during the highest of the spring tides at the time of the equinoxes.

This will greatly limit the potential and actual imports of nitrogen and the other components in the ecosystem which are transported by water. The import of particulate nitrogen is also affected by the ability of the marsh vegetation to trap the sediment carried in by the tide. The vegetation also plays a key role in the retention of the sediment after the initial deposition (Boorman, 1999). Clearly nitrogen imported as PON will have a greater possibility of retention than will the various soluble forms of nitrogen. The retention of imported particulate nitrogen will normally be increased by the rate of burial of the deposits *i.e.* by the overall rate of accretion. This in turn will be related to the duration of submergence; pioneer marshes show burial (accretion) rates of 14-33 mm yr^{-1}, while higher marshes may only grow by a few mm yr^{-1}. However, storms can result in high levels of turbidity and episodes of increased accretion rates with the associated possibility of increased particulate nitrogen imports.

The various imports of nitrogen are often relatively small in relation to the total pool of salt marsh nitrogen. The total pool of salt marsh nitrogen has been estimated to be 5 – 30 times the sum of all cycling reactions within a year (Rozema *et al*., 2000) and this situation will be of particular significance later when it comes to considering the impacts of additional nitrogen sources. The bulk of the nitrogen reserves are to be found in the soil with the plant biomass containing a significant proportion of this. Further details of this will be given in Section 3.4.

The dominant mass fluxes between salt marshes and adjacent ecosystems are usually tidal exchanges although the magnitude and duration of any particular flux can be very variable even over a short timescale within a single marsh (Tobias & Neubauer, 2009). There is variation both in the magnitude of the flux and in the form of nitrogen involved. In terms of net import particulate nitrogen appears to be the most important with a mean of 87 (range of 10 – 240) kg N ha^{-1} yr^{-1} and the net import of dissolved organic nitrogen is similar with a mean of 74 (range of 10 – 310) kg N ha^{-1} yr^{-1}. Both ammonium nitrogen (mean of 29 and range of 4-48) kg N ha^{-1} yr^{-1} and nitrate nitrogen (mean of 16 and range of 6 - 27) kg N ha^{-1} yr^{-1}) are much lower. Whether these results from the USA are similar to the European situation remains to be seen.

While this section is described as imports of nitrogen by tidal flows of sea water, in many cases this will be an indirect flow of sea water with the input being by way of an estuary. Thus the loading of nitrogen, in the various forms, associated with imports (and exports, *q.v.*) will be in the net result of the mixing of salt and fresh water, with their various nitrogen loads, from a number of different and distinct sources. These indirect transfers of nitrogen will be considered on the basis of the original sources and sinks rather than through the final vector of tidal flows. These considerations will be dealt with under the headings of the primary sources (Sections 3.2.2 – 3.2.11). The results of the nitrogen fixation and some other nitrogen flux studies (Sections 3.2.10-12, 3.3.10-14, and 3.4) have generally been published in terms of grams per square metre and this unit will be used in these sections (1 gram per square metre is equivalent to 10 kilograms per hectare).

3.2.2 Tidal flow (fresh water)

This section considers the import of nitrogen through the flow of fresh water. It is acknowledged that normally tidal flows to salt marshes are saline almost by definition. However, there are freshwater tidal marshes and these can reasonably be regarded under the heading of transitional habitats and are therefore within the scope of this report. The defining feature of these marshes is that while they are freshwater marshes they also have the vertical development associated with normal (salt water) tidal marshes even though in many places they are not regarded as a distinct type of coastal wetland and consequently they have suffered heavily from human activities (Whigham *et al*., 2009). Tidal freshwater wetlands are limited to the upper limit of the tide where coastal brackish water meets the flow from non-tidal rivers resulting in a freshwater zone where there is a bi-directional flow of fresh water. The vegetation of these zones is comprised of plants that are able to withstand considerable variations in water depth both tall growing species such a *Phragmites australis,* species with long petioles enabling the leaves to remain above the water level such as *Nupha lutea*, and also species that can tolerate periods of full immersion.

Tidal fresh water wetlands generally have a consistent level of high productivity being associated with a combination of lack of stress caused by salinity and the fresh water inflows generally carrying a considerable nutrient loading though association with urban and suburban areas with high nutrient loading rates, while at the same time having generally a high diversity of annual plant species (Whigham *et al*., 2009). It was shown that the internal cycling of nutrients, including nitrogen, is adequate even for the observed high productivity. Nutrient addition experiments appeared to show that production is not nitrogen limited and that the ecosystem has a high nitrogen status. Despite the nutrient budget of this ecosystem being largely self-contained and independent of the nutrient budget of the river, fresh water wetlands do show some accumulations of nitrogen during the summer months and a release of nitrogen during the autumn and winter months. Thus tidal fresh water wetlands have their own routes of uptake of nitrogen from terrestrial sources; subsequent releases of nitrogen in other forms can, in turn provide possibilities for nitrogen uptake in the salt marshes themselves (*q.v.*).

3.2.3 Stream flow

This section will consider the role played by the flow of freshwater stream into and through salt marshes in relation to their nitrogen nutrition. The term stream is used deliberately and is used in its 1806 definition as ‘a rivulet or brook’, in contrast to a river, to refer to freshwater running into a salt marsh directly without forming intermediate estuarine habitats. These streams acquire a nitrogen loading from the area of their headwaters which are generally highly populated or from coastal areas which are under intensive agriculture. The quantities of nitrogen involved, from sewage effluent and from agricultural fertilizers can be considerable (Hessen, 1999). At least in some areas, the levels of stream-borne nitrogen have been reduced by agricultural and urban best management practices, but these levels are still higher than desired (Howarth *et al*., 2002). Stream flow can also contribute to nitrogen inputs to salt marshes through groundwater flow but these will be considered separately (Section 3.2.4).

Large nitrogen sources are typically associated with agricultural activities but inputs from septic systems, leaky sewers and waste-water treatment plants can also be substantial (Wollheim *et al*., 2005). It has also been shown that often the smaller (2^{nd} and 3^{rd} order) streams carry proportionally higher loads than the larger streams and rivers (Ensign & Doyle, 2006). These authors suggest that these small streams are the best targets for restoration to reduce nitrogen loads. Even the presence of some of these smaller streams flowing into salt marshes is by no means always obvious particularly when the water flows are intermittent. It should be noted that there can be great variation in the timing of peak nitrogen loads through streams in different types of watershed. Generally higher nitrogen contributions occur during base-flow levels in agricultural watersheds while in urban, suburban and drained agricultural run-offs peak loads occur at high flow levels (Craig *et al*., 2008). While these data come from the United States and the field situations may be very different from those in the United Kingdom nevertheless they should not be ignored.

The form of nitrogen in streams from these sources is predominantly nitrate because it has a high solubility and it is readily leached from soils. Ammonium nitrogen is also common but it is less abundant in the water column because it is readily immobilized on clay particles or organic matter or it is nitrified. It can also be stored temporarily through uptake by bacteria, algae or vegetation with subsequent release by decomposition and re-mineralization (Craig *et al*., 2008). Nitrogen can also be stored physically in sediment in locations with reduced water movements again with the possibility of subsequent re-mobilization. It must be noted that stream flow is also an important vector for the onward transport of nitrogen inputs from atmospheric deposition with the potential for collecting nitrogen deposits over a wider area than the destination salt marsh itself. This will be considered in detail later (Section 3.2.9).

3.2.4 Groundwater flow

The surface flow of water over the land surfaces is the visible input of freshwater into salt marshes. The flow of groundwater below the soil surface may in fact have the greater impact at least in some salt marshes (Boorman & Hazelden, 2005). However, two conditions need to be fulfilled before groundwater flow into salt marshes can occur; the existence of a permeable layer or layers within the substrate and a sufficient water pressure to initiate the flow. The critical factor for the latter is the presence of higher ground adjacent to the salt marsh (Boorman, 2002). Typically this is found where marsh fringed estuaries are bordered by higher ground such as that of the estuary of the Stour in north Essex where the local upwelling of fresh ground water is marked by the invasion of *Phragmites australis* (Boorman, 2009).

Not all fresh groundwater flows will have any significant effect on the salt marsh surface or the salt marsh itself. The permeable layers under the marsh may sometimes extend to the edge of the marsh thus allowing the groundwater to discharge directly to the sea. In such a case the impact of the groundwater will be similar to that of any visible stream flow but rather more limited in extent. In upland areas marshes are very often surrounded by higher ground. However, the underlying material is very often impermeable bedrock. Generally in upland areas the higher rainfall experienced tends to reduce the significance of any subsurface water flows.

Even in areas with a flat terrain groundwater movements can occur through the driving force of tidal movements. Wilson & Gardener (2006) demonstrated the importance of tidal activity in maintaining the flow of groundwater through marsh sediments. These flows of groundwater could occur in the creek bank even when the marsh was covered by the tide. The magnitude and significance of groundwater movements were less in muddy sediments with decreasing particle size but additionally the sediment porosity could also be reduced by soil compaction. This occurs naturally with the accretion of the marsh surface but also as a result of human activities on the marsh surface particularly the passage of people or vehicles.

It is considered that groundwater inputs can be an important route of nitrogen delivery to salt marshes that are adjacent to nitrogen loaded watersheds with low evapotranspiration when there are both conductive soils and short flow paths (Tobias & Neubauer, 2009). The authors do point out that the discharges will occur either at the marsh-upland border, or into tidal creek beds or sub-tidally to the sea. Groundwater nitrogen fluxes are more likely to be of significance in fringing marshes than in large marshes with short stretches of marsh-upland borders. The net flux of nitrogen to salt marshes through flows of groundwater is estimated to be within the range of 2 to 1000 kg N ha^{-1} yr^{-1} but all but one data set fall within the much lower range of 2 to 280 kg N ha^{-1} yr^{-1} (Tobias & Neubauer, 2009). There was also variation as to the form of nitrogen involved. In eight sites studied, nitrate-nitrogen dominated in five, in three other sites the dominant form was ammonium-nitrogen, dissolved organic nitrogen, and unspecified dissolved inorganic nitrogen respectively.

3.2.5. Sediment Transport

Salt marshes owe their existence to the tidally driven imports of sediment. The key initial step in salt marsh formation is the establishment of vegetation on mud flats when these have reached a sufficiently high level for this to occur. The rates of accretion in the salt marsh are increased by the sediment imports becoming trapped on the marsh surface by the growth of the vegetation cover of salt marsh plants. The extent and rates of sediment trapping and sediment consolidation is dependant on the properties of the vegetation cover (Boorman, 1999). The rates of sedimentation vary considerably in different marshes even at the initial pioneer marsh level. The rates of accretion decrease as the surface level of the marsh increases thus reducing the frequency and depth of tidal cover. There are often considerable exchanges of sediment between the salt marshes and adjoining mudflats. These can be in the form of sediment losses from the marsh edge during periodic cycles of erosion but they can also occur, less frequently, by the breakdown and erosion of areas of old high marsh. Generally the major source of loss of marsh sediment occurs through the erosion of the marsh edge (Reed, 1988).

There are two parts to be considered in relation to the role of sediment transport in inputs of nitrogen to salt marshes; firstly there is the movement of nitrogen rich sediments into the marsh itself, then there are the various mechanisms for the exchange of nitrogen between the sediment and the water column. It has been estimated from a range of marshes that about 42 % of the net imports of nitrogen occur as particulate nitrogen, associated with the sediment flux, amounting to between 10 and 310 kg ha^{-1} yr^{-1} (Tobias & Neubauer, 2009). It is likely that the gross influxes are very much higher than these figures depending on the extent to which the incoming sediment is trapped by the vegetation and subsequently integrated into the marsh nutrient cycle. It is also difficult to separate the proportion of nitrogen associated with the sediment from that coming in with the tidal flow carrying that sediment, particularly given the mobility between the various forms of nitrogen. Even as the sediment particles are deposited on the marsh exchanges will be taking place between the various forms of nitrogen. It seems likely that the exchanges of nitrogen, both imports and exports, will be dominated by the exchange of soluble forms of nitrogen including soluble organic nitrogen. The figures quoted above for estimated annual totals are quite small when compared with the N-contents of the active root zone, estimated as being of the order of 4000-6000 kg ha^{-1} (Hazelden & Boorman, 1999).

3.2.6. Floating plant material

A brief inspection of any salt marsh is very likely to show the presence of floating plant material on the incoming tide. However, it is very much more difficult to quantify the net import of plant material, if any, or any contribution of nitrogen to the marsh in this way. It is likely, however, that within an estuary as a whole it can be significant, at least in some estuaries (Nedwell *et al*., 1999). As far as the salt marshes themselves are concerned it is more difficult to assess. Particulate nitrogen as a whole has been referred to in the section on tidal flow (3.2.2) but it remains unclear what proportion of this is particulate and how much of the particulate is of plant origin. Floating plant material is generally regarded as, more or less, equating to coarse organic matter (COM) with the finer material in suspension. In studies in England, France, and Portugal it was clear that while COM was present at all stages of the tide there was generally a net export of floating plant material (Boorman *et al*., 1994).

The impact of floating plant material and its nitrogen content appear to be limited to local areas of the marsh. This happens particularly along the drift line at the upper tidal limit where much of the total load of plant material was sometimes deposited in layers thick enough to smother plant growth (the vigour of subsequent plant growth clearly showed that there must have been a significant nitrogen content to the plant material). However, it was clear that this resulted in the concentration of plant material deposited rather that any raised nitrogen content overall. A related occurrence was observed, from time to time, on the marshes of the Blackwater estuary (UK). When algal mats, produced in particularly eutrophic parts of the estuary, were left by the tide on the lower edge of the marsh this also resulted in the death of the vegetation beneath (in this case seedlings of the pioneer salt marsh plants *Salicornia* spp.).

3.2.7 Deposition of animal products.

This basically refers to the circumstances resulting from the grazing of animals on the marsh vegetation. Generally salt marshes are only lightly grazed if at all but there are at least in some localities cases where marsh grazing has a significant effect on the vegetation of the marsh. In some localities particularly in the north and west of the British Isles salt marshes are grazed more or less regularly by sheep as they are in France to produce the prized local lamb. The net effect of grazing is that the production of urine and faeces enhances the internal stocks of organic nitrogen and thus reduces nitrogen export. This is likely to be true for other grazed salt marsh sites. The enhancement of the soil nutrient status through the impact of grazing for short periods will occur when well-fed animals from elsewhere are on the marsh. This may occasionally be the case when the marshes are winter-grazed by wild geese but generally the effects are local and small. Studies on the effects of goose grazing in The Netherlands showed that grazing had a negative effect on mineralization which outweighed the possible positive effects of nitrogen from the goose droppings (Van Wijnen, 1999).

3.2.8 Rainfall and rain-flow over the marsh surface

The effects of rain on the salt marsh are often dismissed except by ecologists who happened to be working on the marsh at the time. However, a closer examination shows, that while the tide is covering the marsh, the effects of rain on the marsh will be negligible, this is not true during periods of marsh emergence. Any sediment deposited recently on the marsh surface has the potential for being re-mobilized and washed away from the site of the original deposition if not lost to the marsh completely – turbid sediment laden water running in rills off the marsh surface and into the creek system bear witness to this. During periods of heavy rain the impact of raindrops on the mud surface visibly break up the surface and sediment is mobilized. The same tends also to be true of plant or animal material on the marsh surface. In no case is there any effect of facilitating nitrogen inputs to the marsh except for the possibility of the rain carrying nitrogen loading (see next section 3.2.9).

Rainfall can also affect nitrogen deposition directly. In studies in both Europe and the United States it was shown that wet deposition fluxes were broadly correlated with precipitation (Holland *et al.*, 2005). Thus given that the average rainfall in Wales is around twice that in lowland England this would imply that assessments and interpretations relative to the critical load setting in Wales should take account of this.

In studies in a wide range of Scottish salt marshes consideration was given to the ways in which nitrogen contributions to a salt marsh through rainfall could vary in relation to the size of the catchment of that marsh (Boorman, 2002b). In many cases studied marshes received from their watershed runoff equivalent to 5 to 30 m of rainfall to the marsh (against a regional average of 2000 mm yr^{-1}). This precipitation with the load of nitrogen deposition would all be running seawards through the marsh thus increasing the potential nitrogen by an order of magnitude or more. Thus while nitrogen inputs from fresh water flows via (terrestrial sources) are already being taken into account in the report it does seem that we also need to make allowances for whole catchment inputs from N-deposition to be taken adequately into consideration. From the Scottish studies it was clear that this could be done relatively easily but this would have to be on an estuary or even individual marsh basis.

3.2.9 Atmospheric deposition

Atmospheric deposition of nitrogen is typically dominated by nitrates and by forms of dissolved organic nitrogen but it can also occur as ammonium-nitrogen, nitrate-nitrogen and also particulate nitrogen (Russell *et al*., 1998, Paerl *et al*., 2002). Recent work in the UK indicated that the total nitrogen deposition was evenly distributed between the oxidised and reduced form (Anon, 2009). These authors indicated that the nitrogen levels contributed as dissolved inorganic nitrogen through rainfall were comparable to those in coastal tidal waters. However, it has also been pointed out that precipitation is only a small part of a marsh water budget and atmospheric deposition rates will therefore form only a small part of the marsh nitrogen budget (Morris, 1991, Lent *et al*., 1997). However, studies in the New Jersey coastal areas suggest that atmospheric deposition contributed around 39% of the total nitrogen load (Gao *et al*., 2007) and that atmospheric deposition is an important pathway for nitrogen inputs and thus a potentially significant nitrogen enrichment source for biotic production. It has been suggested that generally nitrogen deposition rates are higher in Western European marshes than in the United States (Rozema *et al*., 2000). More recent comparative studies on nitrogen deposition in Europe and the United States also showed that while dry deposition rates of particulate nitrogen were similar in the two areas wet nitrogen deposition rates in Europe were much higher than in the United States (Holland *et al*., 2005). Deposition rates of nitrate nitrogen were double in Europe while ammonium nitrogen was more than three times higher. When wet and dry deposition rates were combined the total figures for Europe were two to three times higher than for the United States. Depositions in Europe were more or less evenly divided between nitrate and ammonium nitrogen. It is important to note that the authors of this study concluded that the data was limited by irregular and incomplete spatial sampling.

Atmospheric inputs of the order of 30 to 80 kg N ha^{-1} y^{-1} have been reported in the UK (Goulding 1990) and The Netherlands (Van Breemen & Van Dijk 1988; Koerselman &

Verhoeven 1992) and elsewhere in north-west Europe by Rozema *et al*. (2000). The total deposition of nitrogen including both forms has changed little over the period 1987 – 2006 (Anon, 2009). It was also found that large atmospheric inputs of N increased the amount of extractable N in the soil but did not influence process rates such as mineralization. Smaller rates of input (5 to 12 kg N ha^{-1} y^{-1}) have been reported for the Atlantic coast of the USA (Tobias & Neubauer, 2009).

3.2.10 Salt marsh nitrogen fixation

As with some plant communities salt marshes are able to fix atmospheric nitrogen. In the case of salt marshes, however, the nitrogen fixation mainly occurs on the marsh surface through the activities of cyanobacteria. In mature marshes, however, the rates are quite low (<0.5 to 6.8 g N m^{-2} y^{-1}) and only form a small part of the total nitrogen inputs (circa 10%) and it is estimated to be an order of magnitude lower than internal nitrogen cycling rates (Rozema *et al*., 2000). In young or newly restored marshes the rates are considerably higher (they can exceed 35 g N m^{-2} y^{-1}) and are considered to be sufficient for macrophytes demand (Currin *et al*., 1996, Tyler *et al*., 2003). It would seem reasonable to suggest that the key factor in the effective functioning of the cyanobacteria is the extent of bare ground remaining exposed to the light. As the marsh matures and the plant cover closes the canopy the nitrogen fixation rates will decrease. Nitrogen fixation has also been shown to occur in the pioneer salt marsh plant *Spartina anglica* through acetylene reduction associated with root bacteria (Wolfenden & Jones, 1987). It was shown that nitrogen fixation was highest in dense, well established stands of *Spartina* where it could contribute significantly to plant growth rather than in the pioneer zones where there was a shortage of nitrogen. In this zone, however, fixation of nitrogen was lower and could only contribute up to 2-3 % of the plant's nitrogen requirements.

3.2.11 Tidal flat nitrogen fixation

The tidal flats are at too low a level in relation to the tide to support higher plants, however, they are often densely colonized by cyanobacteria which can often form mats completely covering the sediment surface (Nedwell *et al*., 1999). These authors also note that as the nitrogen loading of an estuary rises then the contribution through nitrogen fixation can be inhibited by the levels of ammonium nitrogen in the pore waters of the sediment. While the status of the tidal flats is outside the scope of this report it is likely that at least some of the nitrogen fixation occurring on the tidal flats will be re-circulated in the tidal flow and thus could become available to the salt marsh.

3.2.12 Salt marsh mycorrhiza

While only about 3% of the roots of the world's terrestrial plant species which have been examined, about 95% of the species belong to families that have some form of mycorrhizal association (Reed, 1999). Mycorrhizae have been described as a symbiosis in which a fungus supplies soil-derived nutrients to plant roots. When mycorrhizal and non-mycorrhizal plants of a particular species are grown under similar conditions the plants with the fungal association are able to accumulate greater amounts of nutrients, particularly nitrogen and phosphorus, and grow to a larger size (Reed, 1999).

The first record of a mycorrhizal association in a salt marsh plant species was in a Welsh salt marsh (Mason, 1928). Since then mycorrhizal associations have been recorded in a wide range of different salt marsh plant species including *Salicornia europaea*, *Juncus gerardii* and *Triglochin maritima*, three species in which Mason had failed to find mycorrhizae (Adam, 1990).

Probably the best studied salt marsh mycorrhizal association is that of *Aster tripolium* (Rozema *et al*., 1986). These studies showed that the growth of *Aster* at high salinities was significantly improved in plants with mycorrhiza but this could not be related to specific mineral nutrients or mineral nutrition. *Salicornia europaea* shows a positive growth response to raised levels of mineral nutrients particularly to nitrogen (both the nitrate and ammonium forms) in field experiments with increase in shoot numbers, biomass and seed production (Davy *et al*., 2001). These authors also noted that *Salicornia* also showed mycorrhizal associations but these were not specifically linked with the growth responses described above.

3.3 Nitrogen outputs (exports).

This section will describe the pathways by which nitrogen is exported out of the salt marsh and the forms of nitrogen involved. Its layout will correspond to that of the previous section (3.2) but there will be differences in that not all the routes described in section 3.3 are relevant to this section.

3.3.1 Tidal flow (sea water).

Tidal fluxes usually dominate the exports of nitrogen from salt marshes just as it was reported in the previous section on nitrogen imports (Tobias & Neubauer, 2009). The direction of exchanges can be reversed on a short timescale even within a single marsh (Dankers *et al*., 1984, Anderson *et al*., 1997). It thus remains very difficult to predict whether a particular marsh will export or import particular nitrogen forms at any given time (*e.g*. Childers *et al*., 2000). There are some generalizations which can be made both in terms of the question of import *versus* export and with regard to the question of the form of nitrogen involved. Generally speaking the older marshes tended towards exports particularly of organic matter and sediment but nutrients appeared to be better integrated in the system and thus rather less mobile (Boorman, 2000). Nevertheless there are also reports of older marshes exporting soluble nitrogen both in organic and inorganic forms (Tobias & Neubauer, 2009). It has also been shown that tidal amplitude can result in changes in nitrogen fluxes. At tidal amplitudes of greater than 1.2 m marshes tend to switch to exports of nitrate nitrogen (Childers *et al*., 2000). This switch is consistent with higher tidal ranges giving more direct drainage of ammonium rich pore water that can rapidly be oxidized and exported as nitrate nitrogen. When the various forms of nitrogen are compared it can be seen that mean net exports are higher than the imports for all forms of nitrogen except dissolved organic nitrogen (Tobias & Neubauer, 2009). Their data show that the highest of the nitrogen exports, by a considerable margin, is for particulate nitrogen of biological origin. The quantities exported are equal to or greater than the sum of the other forms of nitrogen.

In the British studies on salt marsh nutrient fluxes (Boorman *et al.*, 1994) a number of visible particulate organic nitrogen export events occurred when a tide high enough to cover the whole marsh coincided with a strong wind with an off-shore component brought a mass export of floating plant material which was lost to the marsh. These were only occasional events and the actual quantities observed, although large, were not measured but the effects on the nitrogen status of the marsh must have been considerable. Sometimes the deposits were washed up along the drift line and they had accumulated to depths in excess of 200 mm over a width of several metres. This all represented material lost to the marsh; material which would have decayed on the marsh surface and the nitrogen content recycled to the marsh system.

3.3.2 Tidal flow (fresh water)

The nitrogen fluxes resulting from the tidal movements of fresh water are generally associated with imports, providing nitrogen to the salt marshes, rather than exports (see section 3.2.2). Any export though the tidal movements of freshwater are likely to be small and do not merit further consideration.

3.3.3 Stream flow

The stream flow involves the flow of fresh water into the marsh and the associated nutrient fluxes are invariably associated with imports to the marsh. High tides and tidal surges could occasionally reverse the direction of stream flow but this would then involve sea water and this has already been considered (Section 3.3.1.).

3.3.4 Groundwater flow

The remarks made in the previous section on stream flow are equally applicable to groundwater flow which is unlikely to have any major effects on salt marsh nutrient exports. However, particularly for marshes on coarse and more porous substrates the possibility would exist for nitrogen and for that matter other nutrients to percolate downwards through the marsh sediment (soil) and subsequent to be integrated with the movement of groundwater seawards. It has been pointed out that it is difficult to separate these ground water movements from the much larger contribution though stream flow and these are not considered to be of great significance with reference to nutrient exports particularly when compared with the magnitude of tidal exchanges (Boorman, 2009).

3.3.5 Sediment transport

The role of sediment transport in the development of salt marshes has already been described (Section 3.2.5). It has been estimated from a range of marshes that about 52 % of the net exports of nitrogen occur as particulate nitrogen, associated with the sediment flux, amounting to between 45 and 420 kg ha^{-1} yr^{-1} (Tobias & Neubauer, 2009). The same provisos and cautions mentioned with regard to the sediment nitrogen imports (Section 3.2.5.) equally apply here particularly with regard both to the mobility of inter-conversions between the various forms of nitrogen and the total nitrogen levels in the soil estimated as being of the order of 4000-6000 kg ha^{-1} yr^{-1} (Hazelden & Boorman, 1999). The overall picture seems to be that nitrogen associated with the sediment has to be regarded as less easily lost than the soluble forms of nitrogen both inorganic and organic. Particulate nitrogen can certainly be exported but the loss of sediment is still likely to have a greater effect on the future of the salt marsh overall.

3.3.6 Floating plant material

The export of floating plant material can be a very visible form of nitrogen export but it is more difficult to assess its full significance in terms of nitrogen fluxes. However, in studies in England, France and Portugal it was clear that while COM was present at all stages of the tide there was generally a net export of this form of floating plant material (Boorman *et al*., 1994). The effects of the import of floating plant material have already been considered to be limited and local (Section 3.2.6). There is little reason to conclude that the exports will be any more significant than on the site of deposition. The main processing of dead plant material generally takes place *in situ* and the associated fluxes are considered under the heading of the relevant transport mechanism(s).

3.3.7 Breakdown of plant material

The vegetation on the salt marsh is partly composed of annual species and partly of perennial ones but in either case there is only limited green vegetation cover in the winter although climatic variations in the area are such that some growth occurs during milder winters. Each spring growth recommences and builds up to a peak value of about 500 g m^{-2} by July but perennial plant species tend to go on growing longer.

The decomposition of salt marsh vegetation, during the litter stage, was studied as part of the joint European salt marsh study (Boorman *et al*., 1996). In two British salt marshes the processes involved were studied by the use of litter bags. There was some standing dead plant material and plant litter present all round the year. In a pioneer marsh the proportion of standing dead plant material was at its highest during the winter and through to late spring while the quantity of plant litter peaked during the summer. In a high marsh this was relatively constant through the year although falling somewhat during the winter. The amounts of litter remained relatively high for longer but dropping during the winter. There were difficulties in determining the rates of decay on the pioneer marsh because of the occurrence of considerable algal growth on the decaying litter which obscured the losses. Nevertheless it appeared that 50% of the litter decayed in 59 days even with quite low winter temperatures. In the high marsh rates of decomposition were considerably higher with losses of 60% over 10 days. There was no significant reduction in the rates of decay when the mesofauna were excluded suggesting that most of the decay was through bacterial and fungal action. The greatest rates of breakdown of plant material occur during the late summer and the autumn while mean temperatures are >10°C. Thus the release of plant nutrients occurs when the nutrient demands are lower. There will, however, be considerable opportunities for nitrogen loss during the winter months.

3.3.8 Grazing by herbivores

The extent to which salt marshes are grazed varies from place to place and from country to country. Two factors which significantly affect the extent of grazing are the size of the marsh and the porosity of the substrate. Generally speaking small marshes are least likely to be grazed either by wild animals or for agricultural purposes as the areas involved are unattractive either to the natural fauna or to farmers. The marshes that have developed on coarse, sandier sediments are more attractive to both natural and domestic grazing animals as they are easier to access than marshes with soft fine sediment often crossed by a network of deep creeks hazardous for both animals and people. The general effect of grazing salt marsh vegetation is to speed up the recycling of nitrogen; it also seems to reduce nitrogen exports (see Section 3.2.7.-8).

3.3.9 Rain flow over the marsh surface

As mentioned in Section 3.2.8 it seemed likely that the biggest effect of rain water flowing over the marsh surface is the remobilization of sediment recently deposited on the marsh which could lead to some exports of nitrogen. However, the levels of nitrogen in the sediment tend to be quite low and often less than in the estuarine water which flows over the marsh. In addition the reworking of sediment is generally on a local scale within the marsh and almost always within the marsh-mudflats estuarine system. Rainfall could also play a small part in washing out mobilized nitrogen but again only small quantities are likely to be involved.

3.3.10 Mineralization and mobilization

Mineralization has been defined as 'the conversion of a nutrient from an organically bound form to a water soluble inorganic form as a result of natural biological processes'. In the case of nitrogen this means the breakdown of amino-acids, amines and amides to ammonia which can be released into the atmosphere or oxidized to nitrate or nitrite both of which are water-soluble and readily released. Mineralization rates vary between 3 to 122 g N m^{-2} y^{-1} (Morris, 1991, Anderson *et al*., 1997, Rozema *et al*., 2000, Thomas & Christian, 2001, Tobias *et al*., 2001b). The supply of new nitrogen to a salt marsh has been estimated to be only of the order of 0.5 to 5% of the nitrogen needed for plant growth and productivity (Tobias & Neubauer, 2009) and the difference is made up through the mineralization of organic reserves into the ammonium pool which has a high rate of turnover. Notwithstanding the mobility of ammonium nitrogen, most of it is utilized by plant metabolism and generally no large exports of nitrogen have been observed (Anderson *et al*., 1997). These authors also noted that microbial immobilization plays an important role in retaining a significant fraction of mineralized nitrogen. A significant proportion of the nitrogen is retained in pore water in the ammonium form (Benner *et al*., 1991). Tracer experiments have shown that nitrogen can remain in salt marsh soils for considerable periods but that the ammonium nitrogen pool does act as the common ground for nitrogen exchanges.

3.3.11 Nitrification

This is the oxidation of NH_4-N to NO_3-N. It is restricted to the soil surface or other well-oxygenated zones (Howes *et al*., 1981; Tobias *et al*., 2001a; Eriksson *et al*., 2003; Dollhopf *et al*., 2005; Costa *et al*., 2007). It is inhibited by high sulphide levels (Joye & Hollibaugh, 1995), high salinities (Seitzinger *et al*., 1991; Rysgaard *et al*., 1999) and by low (<4.5) pH (Portnoy & Giblin, 1997). Marsh pore waters are generally rich in NH_4-N and so nitrification is limited by the availability of O_2.

Annual nitrification rates range from 0.26 to 52 g m^{-2} yr^{-1}, although 80% of reported rates are <10 g N m^{-2} yr^{-1} (Abd Aziz & Nedwell, 1986; Anderson *et al*., 1997; Tobias *et al*., 2001b; Eriksson *et al*., 2003; Hammersley & Howes, 2005; Dollhopf *et al*., 2005; Costa *et al*., 2007). In marsh budgets, nitrification is 4 to 20 fold lower than mineralization.

3.3.12 Denitrification, ANAMMOX and DNRA

Denitrification is the breakdown of nitrogenous compounds to gaseous nitrogen and its release to the air. Although NH_4^+ is abundant in soil pore waters the pHs are usually low enough to prevent significant volatilization of NH_4^+ to NH_3 (Morris, 1991). Denitrification is the primary route for losses of gaseous nitrogen from salt marshes (Tobias & Neubauer, 2009). In addition to nitrogen itself intermediate oxides of nitrogen are also produced and contribute to these exports of nitrogen. The actual rates of denitrification in salt marshes vary from 0 to 60 g N m^{-2} yr^{-1} although two sets of data from the United Kingdom showed lower rates of 0.3 – 0.8 g N m^{-2} yr^{-1} (Tobias & Neubauer, 2009). Generally the rates of denitrification closely followed the concentration of ambient nitrate nitrogen. Where there is plenty of NO_3-N this is denitrified directly. When concentrations are low organic matter is mineralized and then denitrified in what is known as coupled denitrification. There is competition between the uptake of nitrogen for plant growth and its loss though demineralization but generally the majority of nitrogen goes into plant growth. Denitrification is small in relation to internal N cycling in the marsh. In a mature marsh losses through denitrification are balanced by gains through mineralization.

DNRA (Dissimilatory Nitrate Reduction to Ammonium) is largely mediated by anaerobic bacteria. NO_3^+ is reduced to NH_4^+ rather than releasing N to the atmosphere (Tobias & Neubauer, 2009). It is controlled by a variety of environmental factors. Rates of N loss range from 1.2 to 92 g N m^{-2} y^{-1} and are 0.3 to 2 times that for denitrification (Tobias *et al*., 2001a, c). DNRA is an important pathway in high-sulphide, organic-rich sediments and these occur in some salt marshes.

There is also an alternative pathway by which nitrogen can be exported from ecosystems and that is the anaerobic ammonium oxidation (ANAMMOX). ANAMMOX uses ammonium to reduce nitrite to produce gaseous nitrogen. It is a chemoautotrophic process and unlike denitrification it does not require organic carbon. However, salt marshes are high in organic carbon and generally ANAMMOX only accounts for <10% of the gaseous nitrogen production and it is not currently considered an important route for nitrogen loss (Dalsgaard *et al*., 2005).

3.3.13 Uptake by plant roots

The nutrient uptake of nitrogen by plant roots increases in response to the supply level up to a maximum uptake rate where a plateau uptake level is reached. This level is determined by the characteristics of roots of the plant species concerned. There are special mechanisms to facilitate nutrient uptake when soil availability of that nutrient is low (Lambers *et al*., 1998). Nitrogen limitation can increase the capacity to absorb nitrogen but this also decreases the capacity to absorb other non-limiting nutrients. The mechanism appears to be one of the plants reducing the nitrogen concentration at their root surface thus increasing the diffusion gradient from the low nitrogen soil. This compensatory mechanism is greatest for mobile ions such as nitrogen. Most nitrogen is taken up by the plants in the form of inorganic nitrogen. However, although organic material such as amino acids can be utilized directly, it seems that the salt marsh flora in temperate climates will, in preference, use inorganic forms of nitrogen.

3.3.14 Deep burial

Nitrogen can effectively be lost from salt marshes certainly, as far as salt marsh plants are concerned, by deep burial as the marsh accretes. A wide range of studies indicated that the effective depth of the plant root zone is of the order of 300 mm (1 ft). However, the extensive studies into nutrient cycling in the Essex marshes indicated that the active root zone was probably no more than 200 mm (Boorman *et al*., 1996). Estimations of accretion rates in the area suggest that the average rate of salt marsh accretion was of the order of 5 mm yr-1, (Boorman *et al*., 2002). This would indicate that within 40 years the accreted sediment would be beyond the reach of plant roots. In other sites considerably higher rates of accretion occur (up to 30 mm yr^{-1}) with correspondingly higher rates of burial. Long term nitrogen losses by deep burial have been estimated at figures ranging from 1 to 50 g N m^2 yr^{-1}. Considering a range of different examples it would seem reasonable to take a general figure of nitrogen losses in response to accretion necessary to accommodate sea level rise to be of the order of 2 to 6 g N m^2 yr^{-1}. This figure (Tobias & Neubauer, 2009) is given in g N m^{-2} mm^{-1} of sea level rise so total losses may exceed this. However, developing marshes can be expected to have higher accretion rates, in excess of 5 mm yr-1, and for these marshes nitrogen burial rates can be comparable to rates of nitrogen delivery. It is considered that for most marsh systems nitrogen burial is of the order of 50-60% of total nitrogen inputs (Tobias & Neubauer, 2009).

3.4 Nitrogen in salt marshes – reserves and sinks

The previous sections have considered in some detail a wide range of imports and exports of nitrogen associated with salt marshes as well as describing some of the processes involved. In order to consider the overall nitrogen situation and the possible impacts of new inputs on the marshes it is necessary to get the various different processes into some form of perspective. A particular input or export may seem to be large or small often just depending on the units used to express it. What is really important is the input or export in relation to the total amounts of that particular form of nitrogen in the system as well the consideration of possible rates of conversion to other forms. These parameters were determined in detail for a salt marsh in Essex as part of an international study of salt marsh processes (Boorman *et al*., 2000a). One of the problems in making comparisons between the various components is the question of the units used.

Table 3.4.1 gives the amounts of the nitrate-nitrogen, ammonium-nitrogen and the total nitrogen in the marsh at Tollesbury. The marsh in question is an active marsh at the lower end of the main marsh range. As can be seen from the table the mean annual figures for nitrogen levels are given in mg g^{-1} on a dry weight basis for all the components except for the tidal water where results are expressed in g $l^{-1}$of water. However, while some comparisons are possible they become more meaningful when expressed in terms of g m^{-2} but this needs information on the total volume (depths of soil) involved. The estimates given in the last four columns are based on nitrogen levels using a measured active root zone in the soil of 200 mm, the recorded densities of the different forms of plant material and the estimated total nitrogen input from sediment accretion. From this it will be seen that over a year 96.5 % of the nitrogen in the marsh is in the soil with a further 3.4 % in the various categories of plant material. The nitrogen content for soil includes the plant roots but it is probably reasonable to estimate that the weight of roots and their nitrogen content is approximately equal to the living plant material and thus approximately 1.9 % of the soil nitrogen is in plant roots. This would indicate that just less than 95 % of total nitrogen is in the soil and around 5% is in plant material.

The most significant fact is that within this salt marsh system there is an estimated 830 g N m^{-2} at any one time. This fits in with other studies which showed that total nitrogen pools were in the range 200 to 1000 g m^{-2} (Tobias & Neubauer, 2009). This has to be compared with tidal imports and exports of nitrogen, each of the order of 20 to 30 g m^{-2} yr^{-1}, various other sources and fluxes (Sections 3.3.1& 3.3.2). Against these there are the burial losses which are estimated to account for around 50% of the total nitrogen inputs. The amount of nitrogen contributed by the sediment accretion at around 9 g total-N m^{-2} yr^{-1} is relatively small. The nitrogen loading in the water over the marsh is rather higher amounting to around 300 g m^{-2} yr^{-1}. Given the differences in nitrogen levels between flood and ebb tides there is little indication of significant uptakes.

Despite the complex and dynamic nature of the nitrogen system there does seem to be a suggestion that in some cases the system is relatively well buffered at least for the actively growing marshes. It appears that while the younger marshes may show signs of nitrogen shortage there is little evidence of eutrophication except in cases when there is a significant local source of water-borne nitrogen pollution. The diurnal tidal flow through the marsh at least can be seen as a source by which any spare nitrogen remaining, after the salt marsh plants had taken up their immediate needs, could readily be removed enabling the marsh to return to equilibrium. It should be noted from the various flux studies (Boorman *et al*., 1996) that while the marsh nitrogen levels remained relative constant there were major variations in the direction and magnitude of the nitrogen fluxes. It should also be noted that bacterial breakdown of organic matter, using organic nitrogen as a carbon source, can release nitrogen into the air (as N_2) thus providing at least one route for the removal of excess nitrogen.

Table 3.4.1 Salt marsh nitrogen levels at Tollesbury, Essex (adapted from Boorman *et al.*, 2000a).

	mg g^{-1} (mg l^{-1} for water)			g m^{-2}			%
Component	**NO_3**	**NH_4**	**Total N**	**NO_3**	**NH_4**	**Total N**	**Total N**
Sediment [a, b]	0.04 [a]	0.00 [a]	2.95 [a]	0.0001 [b]	0.00 [b]	0.011 [b]	0.001
Marsh Soil	0.08	0.00	6.69	9.60 [c]	0.00 [c]	802.8 [c]	96.54
Tidal Water	0.95	0.20	2.00	0.19 [d]	0.04 [d]	0.40 [d]	0.048
Higher Plants	0.10	0.00	30.6	0.05 [e]	0.00 [e]	15.6 [e]	1.88
Standing Dead	0.11	0.00	29.5	0.006 [e]	0.00 [e]	1.56 [e]	0.19
Litter	0.11	0.00	29.5	0.028 [e]	0.00 [e]	7.60 [e]	0.91
Algae	0.15	0.00	40.8	0.014 [e]	0.00 [e]	3.70 [e]	0.44
Totals	–	–	–	**9.89**	**0.04**	**831.67**	100

Notes: -
(a) Analysis of sediment only
(b) Sediment nutrient load at high water with 200 mm water over the marsh
(c) Assuming an active rooting depth of 200 mm and a bulk density of 0.6 g cm^{-3}
(d) At high water with 200 mm water over the marsh
(e) At the recorded standing crop
(f) Estimated annual total N input from sediment load = 8.85 g m^{-2} y^{-1}, (assuming concentration in water = 17.9 mg l^{-1}, an accretion rate of 5 mm y^{-1} and a density when deposited of 0.6 g cm^{-3})
(g) The nutrient loading in the water over the marsh would give an estimated annual nitrogen availability for NO_3-N of 127 g m^{-2}; for NH^4-N of 27 g m^{-2} and for total-N of 268 g m^{-2}

It will be clear that there are both large reserves of nitrogen in the marsh soil and also considerable quantities of nitrogen in circulation around the marsh and the adjoining estuary. Salt marsh plants will be taking up nitrogen from the soil and to a small extent by direct foliar uptake but, except possibly in the youngest pioneer marshes, the nitrogen removed by plant uptake is likely to be considerably less that the total available. Given that water flows in and out of the marsh and that estuarine nitrogen levels are considerably lower than in the marsh soil this may to some extent act as a mechanism for the removal of nitrogen in excess of plant nutritional requirements. There is thus at least a possibility meriting further investigation as it could affect the interpretation of the impact on salt marshes of raised nitrogen levels.

3.5 Factors affecting functional nitrogen status

One outcome from the European co-operative salt marsh studies was the realization that at least in the lower levels of Dutch and English marshes phosphorus levels were the limiting factor controlling plant growth and only in the higher and (functionally) older marshes were nitrogen levels the limiting factor. Although nitrogen is commonly the primary factor limiting plant growth it is necessary for all the other plant nutrients, both macro- nutrient and micro-nutrients, to be available at adequate levels. Thus when nitrogen levels increase there can only be a plant growth response if phosphorus, and the other nutrients, are also fully available. Either nitrogen or phosphorus can be the factor limiting growth unless the ratio of the available forms of each is in balance. This has been extensively studied in the marine sphere where the ratio between N and P of 16:1 is widely accepted and is referred to as the ‘Redfield ratio’. This ratio defines the nutrient needs of marine algae. For salt marsh plants there is less information but a similar although slightly lower ratio would seem to be applicable. Terrestrial plant species generally have N:P ratios of the order of 10:1 to 14:1 (Tessier & Raynal, 2003). However the authors point out that the optimum ratio varies for different ecosystems and that further work is needed.

Nitrification provides the plants with the readily assimilated nitrate nitrogen, however, this process can be inhibited both by anaerobic conditions and also sulphide levels in a marsh (see Section 3.3.11). This occurs despite pore water in salt marshes normally having a ready supply of ammonium nitrogen although this ammonium can also limit plant available nitrogen by inhibiting nitrogen fixation.

Factors other than plant nutrients can also affect plant growth in salt marshes. The primary colonization of mudflats by pioneer salt marsh plant species can be strongly limited by the sedimentation rates as these plants depend on a high rate of accumulation of fresh sediment in order to secure the growth of plant roots as an anchor for the young plant and for the uptake of nutrients (Boorman *et al*., 2000b).

While several salt marsh species showed limited responses to additional nitrogen in experiments in Norfolk their response was further limited by water shortage and hyper saline conditions in the upper marsh during summer months (Jefferies & Perkins, 1977). The levels of nitrogen added were considerable, of the order of 700 kg ha^{-1} yr^{-1}, and over five years this produced only relatively small changes in the vegetation. The above considerations apply to only two of the plant nutrients and shortage of any one of the macro- or micro-nutrients has the potential to act as a limiting factor for plant growth.

There is a range of other environmental factors which have been shown to have the potential to limit plant growth and thus the impact of rising nitrogen levels; these include the effects of salinity, sediment supply and waterlogging (Huckle *et al*., 2000). Thus to assess fully the impact of a particular nitrogen level it would be necessary to have information on these other environmental factors which could limit the response to raised nitrogen levels.

3.6 The effects of nitrogen on plant diversity

There is plenty of evidence that nitrogen levels can reduce plant species diversity. The problem is that different levels of soil nitrogen have differing effects on specific plant communities growing under particular environmental conditions. We have seen from the previous section (Section 3.5) that specific nitrogen levels can have very different effects under varying environmental conditions and that each case (study site, salt marsh plant community *etc*.) has its own conditions. There are, however, some general points that can be made. Plant species diversity is reduced when a particular plant or group of plants are able to outgrow and thus reduce or exclude other species. Generally an early warning of impending changes (decrease in species diversity) can be seen in the increased growth and vigour of one or more species while other species show no, or only a reduced, response. When a plant community is composed entirely of plants with similar limited stature and when there are areas of bare ground visible then it is reasonable to conclude that there is only limited competition between plant species. Stimulation of plant growth under these conditions by nitrogen or other plant nutrients will have little effect. If, on the other hand, the plant community is composed of tall plants growing close together with no bare ground visible it is probable that the less vigorous species are already decreasing in size and numbers and thus the addition of extra nitrogen will only make the situation worse.

These are general points but they can equally be applied to a range of salt marsh situations. The pioneer salt marsh communities along the lower edges of the marsh are limited by the extreme environmental conditions and generally competitively vigorous species are excluded. Any nitrogen-induced growth response is thus not likely to increase competition and so reduce species diversity. The only possible effect of modest increases in nitrogen levels will be to increase the growth of those few species able to withstand the extreme conditions. In the higher parts of the marsh there is a closed plant canopy suggesting that inter-specific plant competition has become the limiting factor and that nitrogen-stimulated growth will only increase this effect with the corresponding loss of species diversity. However, there are many salt marsh plant communities that fall between these two extremes. It is difficult to define the points at which nitrogen ceases to have a beneficial effect or starts to have a damaging one. It is, however, clear that not all salt marsh plant communities will have the same response to specific increases in nitrogen inputs.

3.7 Salt marsh and transitional plant communities

The vegetation of British salt marshes has been described and classified in detail (Boorman, 1999; Rodwell, 2000), however, the Critical Load studies have all used the newer European Nature Information System (EUNIS). While this certainly has the advantage of being European-wide there do appear to be some anomalies and differences when compared with the NVC system. Salt marshes are described in the EUNIS class ‘A’ as marine habitats whereas the British approach is rather to restrict the term to the sub-tidal *Zostera* communities preferring the term ‘maritime communities’. The preamble to this report specifically included the phrase ‘transitional communities’ for those areas with a maritime influence but occurring landwards of the salt marshes. Transitional communities as recognized in the UK include communities such as the various plant associations along the drift line marking high water spring tides, dune and salt marsh, dune slack and salt marsh communities as well as grass land and fen communities with a brackish influence. These all fall outwith the EUNIS Class A but are included under the NVC classification. There would seem to be a need to examine the range of British ‘maritime’ communities recognized under the NVC and how these would fit into the EUNIS system. A quick examination of the two systems also suggests that some of the generally recognized British (including Welsh) salt marsh communities are difficult to fit into EUNIS (see Section 1.2). This needs to be sorted out particularly for those plant communities which may have special region conservation significance.

3.8 Salt marshes and associated plant communities in Wales

There a considerable body of data on the salt marshes of Wales, for example a recent bibliography of papers on this listed 14 major titles (P. Rhind – *pers. comm.*), and there are also a considerable number of local site descriptions, published and unpublished, with details of the species composition and extent and condition of sites with salt marsh and transitional communities. It could be argued that much of this extra detail is not relevant when it comes to considering the possible impacts on these areas of aerial nitrogen distribution. The evidence presented in this report strongly indicates that the responses to such increases in nitrogen supply can vary greatly for different salt marsh situations and different salt marsh plant communities and that the responses are not necessarily always the same in particular situations. Even a limited reading of the corpus of information on the salt marshes of Wales shows that the principality supports a wide range of the salt marsh species and communities found in the UK including some major salt marsh systems as well as a wide range of small local but none the less important salt marsh areas (Boorman, 2002a). It is important to treat each system on its merits and special characteristics. There are several key factors which need to be taken into consideration when making an impact assessment. These include botanical, geographical and environmental aspects. It is necessary to assess the composition of the plant community(ies) and their state of development, whether pioneer or mature and also the individual plant species making up these stands. The condition of the vegetation is also important as to whether it is essentially open with bare ground or closed with complete ground cover. Then there is question of the physiographic situation of the marshes whether in low lying areas experiencing direct rainfall only or surrounded by high ground thus creating a catchment concentrating rainfall and nitrogen deposition from a much wider area. These matters have been considered in outline but time precluded any detailed considerations. There is additionally the question of determining if there are any particular local sources of aerial nitrogen pollution or of nitrogen-enriched discharges whether agricultural of industrial.

3.9 The effects of nitrogen deposition on salt marshes

Section 2 of this report included a list of four key questions in relation to the aerial deposition of nitrogen and its effects on salt marshes. The general role and effects of nitrogen in relation to salt marshes have been considered in the preceding sections (3.4 to 3.6) and have been quantified as far as possible. It is appropriate now therefore to consider what are likely to be the implication of nitrogen inputs within the defined critical loads of 20-30 kg N ha^{-2} yr^{-1} (2-3 g m^{-2} yr^{-1}). It will be clear from the evidence already presented that salt marshes generally are associated with quite high levels of nitrogen (Section 3.4). There are high levels of total nitrogen within the salt marsh system (e.g. 8300 kg^{-1} ha^{-1}) and there are also big inputs and outputs but with much smaller net changes which can be in either direction depending on the condition of the marsh. These exchanges appear to be considerably larger (often an order of magnitude larger) than the defined critical load. Evidence presented in Section 3.4 shows that even a modest rate of sediment accretion brings with it 3-4 times that of nitrogen equivalent to the critical load level and the water borne nitrogen load is many times that carried through sediment inputs.

It may well be true that salt marshes under a high marine influence may show a lower sensitivity to additional (aerial) nitrogen but this is likely to reflect the adequacy of their nitrogen supplies together with the maximum control through the salinity of the habitat. It is possible that the sites with a lower marine influence may be more responsive to additional nitrogen. It is possible but, by no means certain, that this could lead to reduction in species diversity. The effects of the reduction in salinity in such areas might well be even greater and each case would need to be considered on specific details.

The age of a salt marsh, particularly the individual functional age as defined in Section 3.1., is probably the most significant factor. The vegetation in pioneer and lower marshes are likely to show a positive growth response to increases in nitrogen loading while the higher marshes with closed plant communities are likely to show a decrease in species diversity with any increases in nitrogen inputs. The evidence presently available would indicate that for these responses to occur nitrogen levels would need to be significantly higher than the defined critical loads. The set critical load does appear to be well below the level at which plant species diversity in a salt marsh could be significantly affected, possibly by a factor of x2 or x3. Nitrogen deposition within critical load limits is unlikely to result in any damaging effects to salt marsh vegetation. Any possible effects are most likely to be found in the tall vegetation of the closed upper marsh communities where interspecific competition is at its greatest. Thus it is suggested that the value of 30 kg ha^{-1} yr^{-1} be applied to most of the marsh with the lower level of 20 kg ha^{-1} yr^{-1}

being applied to the more densely vegetated upper marsh and to areas of marsh subjected to direct run-off from adjacent catchments.

The nutrient status of a particular salt marsh is clearly applicable to interpretations of the impact of nitrogen at or above the set critical load. The European salt marsh studies at Tollesbury, Stiffkey and other mainland European marshes clearly indicated this. However, these assessments were only possible after many years of detailed studies. As yet there does not appear to be any easy way of assessing the trophic status except in extreme cases where deleterious changes have already occurred. Further examination of these and other data may give us some clues as to the way forward. It would appear that at the present the best we can do for individual salt marshes is to consider carefully all available information collectively. Decisions based on trophic status, marsh age (actual or functional?), marsh condition and other sources of nitrogen *etc*., provide the best way forward while more sophisticated methods, based on sound science, are being developed.

3.10 The Welsh perspective

Much of the evidence presented in this report has been gathered from salt marsh studies in other countries and even in other continents (there are many important USA-based salt marsh studies). It is pertinent to ask therefore are there any special Welsh perspectives? While this report and the studies referred to represent data gathered over a very wide geographical area there are certain aspects regarding Wales which are different. Nitrogen deposition does show some differences from the rest of the UK The maps presented by Holland *et al*. (2005) clearly suggest that dry fluxes of HNO_3 and the dry particulate deposition of NO_2 are rather lower in Wales than in the rest of the UK. The network of gauging stations does not provide accurate data at the local scale needed. The higher rainfall in Wales than in much of England could well tend to increase the potential for aerial nitrogen to reach significant and possibly damaging levels. This possibility can be enhanced by the way that local topography can concentrate the water flow from a wide area (the local catchment) in an individual salt marsh (see Section 3.2.8).

The report so far has only considered the possible impacts of nitrogen depositions at or exceeding the set critical loads but it is acknowledged that there are also the critical levels of ammonia and oxides of nitrogen to be considered. There appears to be insufficient evidence to make significant comments on this matter but the robustness of the salt marsh nutrient system might suggest that the application of the critical load limits may afford sufficient protection. There was insufficient time within this project to consider in detail the impacts of nitrogen at or above the critical levels, but it seems likely that the cumulative effects of these short term impacts would, in general, be adequately covered by the application of the critical load approach.

4. CONCLUSIONS

There is a considerable amount of data available, both published and unpublished, on nitrogen levels and cycling relating to salt marsh habitats. Within the time frame of this project it has only been possible to make a general assessment of selected data sets. The time frame precluded any detailed mathematical integration and modelling of the various data sets. However, from the data which was considered some clear patterns emerged.

In a wide range of salt marsh studies it has become clear that salt marshes include a range of relatively nitrogen-rich habitats. There are significant nitrogen reserves in the soil and the habitat is characterized by high levels of nutrient cycling including nitrogen in its various forms.

The levels of nitrogen uptake by the various salt marsh plant communities are low compared with the magnitude of nitrogen reserves in the soil and the levels of nitrogen involved in the associated nutrient cycling.

Within the salt marsh system there are only relatively small changes in net balances between nitrogen imports and exports.

From rather limited data from direct field experiments it was clear that quite large nitrogen additions were needed for significant changes to occur to the vegetation.

Studies on nitrogen fluxes and exchanges indicated that any response to changes in nitrogen levels was likely to vary with the developmental status of the salt marsh as indicated by the plant communities concerned and by the interpretation of the functional age of the marsh.

The annual inputs of nitrogen within the prescribed critical loads are small compared with the levels of nitrogen stored in the soil. Nitrogen deposition within critical load limits is unlikely to result in any damaging effects to salt marsh vegetation.

It is suggested that there may well be mechanisms though which excess nitrogen may be removed from the system. Forms of soluble nitrogen within the rooting zone of salt marsh plants can either be taken up by the plants or they would be washed out by the regular tidal inundation.

For lowland marshes the nitrogen input by rainfall and dry deposition was limited to direct deposition within the area of the marsh itself. However, in upland (hilly) situations this could be greatly increased by a whole order of magnitude depending on the extent of the local catchment of an individual marsh.

The conclusions that the authors draw from the data examined are that within the set critical load limits nitrogen deposition is unlikely to have any damaging effect on the salt marshes of Wales (or elsewhere in salt marsh communities).

Any possible effects are most likely to be found in the tall vegetation of the closed upper marsh communities where interspecific competition is at its greatest. Thus it is suggested that the value of 30 kg ha^{-1} yr^{-1} be applied to most of the marsh with the lower level of 20 kg ha^{-1} yr^{-1} being applied to the more densely vegetated upper marsh and to areas of marsh subjected to direct run-off from adjacent catchments.

5 RECOMENDATIONS

From the various studies that went into the production of this report it became clear that the whole question of the setting of critical load limits and the management of vegetation in the coastal sphere and particularly in relation to salt marshes needs further good quality information to improve the reliability of the interpretations and to implement more effectively the findings in practical nature management applied in specific situations. Some of the work can be carried out completely or almost completely through desk studies using available information both published and unpublished. Other work will require some or more extensive field studies and experimental work. For each of the following five items there is a broad outline of what will be required.

5.1 Salt marsh vegetation classification

This report noted that there were still some difficulties over the relation between NVC and EUNIS and in view of the relevance to salt marsh conservation generally, and more specifically to nitrogen impact assessments, some desk studies are needed to integrate pre-NVC and NVC data on British salt marsh plant communities and to relate them accurately to the EUNIS system.

5.2 Welsh salt marshes

While there is extensive information on Welsh salt marshes, the plant communities concerned and their general situation there is a significant effort required to integrate the data. This could largely be through a desk study but a limited amount of field data will also be needed to fill in any gaps found in the data. There needs to be further information gathered on two specific points. Firstly, more detailed information is needed on the nature of the catchment surrounding specific marshes and on the role that the catchment drainage to the marsh might play in enhancing nitrogen inputs. Secondly, any specific point sources of nitrogen within the ambit of particular marsh catchments need to be identified and assessed.

5.3 Nitrogen cycling in salt marshes

This report has made considerable use of nitrogen data from a wide range of sources, however, the data used only represents a fraction of that available at the current time. A wider integration of this data would greatly improve the accuracy and detail of predictions. The study would be primarily a desk study. It would also identify any gaps in available data sources but where possible fill the gaps with specific limited data collection in the field.

5.4 Field verification of effects of low level nitrogen addition

The findings in this report have been based on the interpretation of data gathered from a wide range of sources and while the authors have confidence in their conclusions it would only be prudent for there to be a follow-up process of field experiments to validate the findings and recommendations particularly if these are to be applied on a wide scale.

5.5 Improvement in nitrogen monitoring

The whole of this report and indeed the planning behind it have been based on the finding of a limited number of UK monitoring stations. In view of the habitat and climatic variations within the British Isles it is strongly recommended that further monitoring stations be established to ensure the various different areas of the United Kingdom are adequately covered.

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