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Spartina anglica: a review of its status, dynamics and management

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Spartina anglica: a review of its status, dynamics and management

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Feedback request

The following report was commissioned in 2000. Research into *Spartina anglica* is ongoing with new findings and theories being continually published and may therefore not be taken fully into account in this report.

The *Atlas of the British & Irish Flora* (Preston *et al* 2002) has been recently reclassified *S. anglica* as an endemic 'native'. This report was commissioned before the reclassification of *S. anglica* and uses the former categorisation of 'alien' or 'non-native' species. English Nature does not, however, view this reclassification as a need to change its approach to the management of *S. anglica.*

In order that English Nature may continue to expand it's knowledge and understanding of the status, dynamics and management options for *S. anglica* the organisation welcomes any feedback on new research, findings and in particular management techniques.

Executive summary

The colonisation and expansion of *Spartina anglica* worldwide (except to some extent in the UK) is largely the result of introduction of an exotic organism into an area. At some sites, such as in Tasmania and the San Francisco Estuary, there are clear examples of the threat to biological diversity caused by this introduction (Lee & Partridge, 1983). According to Cohen (1997), more attention and funds have been applied to controlling non-indigenous coastal organisms after they have been introduced, than to preventing their introduction in the first place. Most introductions are accidental (ie via ships' ballast water, aquaculture and mariculture, aquarium and ornamental plant trade and the importation of live seafood and bait) but *S. anglica* has also been introduced deliberately for the control of coastal erosion and land claim.

The situation in the British Isles differs from elsewhere since *S. anglica* can be considered an endemic species that has managed to successfully compete for a niche and displace other species occupying the same habitat. As a result, there is no general consensus regarding its management. For some managers it is a threat to biodiversity especially for wintering birds that feed on invertebrate species of intertidal mudflats and other habitats displaced by *S. anglica*; whereas for others, it is the product of evolution and therefore remains unmanaged. Despite this, *S. anglica* remains a controversial species both in the UK and around the world. In China it remains an accepted component of the ecosystem, whilst in Australia and New Zealand, management plans for its control are being developed. The general consensus is that *S. anglica* can be acceptable in the right environment, but attempts to manage, control or disperse it should be in accord with the management objectives for the area and must take account of coastal processes and hydrodynamic conditions.

Efforts to control its expansion in the UK have not been particularly successful. It was first recorded on the south coast (Southampton), during the late 1800s and early 1900s, from where it has expanded through introduction. After *S.anglica* had developed through hybridisation with the native species *Spartina maritima*, there followed a quiescent period until the mid 1900s, after which there was a period of massive expansion. In the British Isles, it has been artificially introduced for land claim for coastal defence purpose. *S. anglica* has managed to colonise a much greater area than the native *S.maritima* which along with *S. townsendii* and *S. alterniflora* are declining. Currently some populations of *S. anglica* have ceased expanding, and appear to be experiencing dieback, particularly along the south coast but this is not the case in the north-east or north-west coasts where species still seems to be expanding. The surveys carried out for the present study were on sites exhibiting both conditions. At Bridgwater Bay NNR (Somerset) *S. anglica* had a period of expansion between around 1954 and 1984, but at the time of this study appears to be stable (and may be dying back along the estuary) without the application of any control technique. In contrast, at Lindisfarne NNR (Northumberland), the other surveyed site, *S. anglica* seems to be spreading, despite several control methods having been employed for its control since 1970. Even though both areas have different environmental and hydrodynamic conditions, the reasons for the contrary behaviour of *S. anglica* at the sites or other areas of expansion, have not been totally explained.

Various techniques have been applied throughout the UK with the aim of controlling or eradicating *S. anglica*, including hand digging, herbicides, burning, biological control and rotoburying. Despite providing some evidence of achieving an element of control of *S. anglica*, at the moment there is no evidence to prove that anyone of these techniques is better than the others: their effects in the environment are poorly known or they are relatively new

techniques that need to be tried under different conditions. However, this review concludes that the hydrodynamic regimes and the sediment conditions of the area are an essential factor to consider in order to make the most appropriate decision for managing *S. anglica.*

Historical information (maps, papers, reports, aerial photographs) of the coverage of *S. anglica* in the two study areas was collated with the aim of establishing the status of the population in both Lindisfarne NNR and Bridgwater Bay NNR. This information was compared with the data obtained during the fieldwork phase, which used Differential Global Position System (DGPS) devices. Despite being a very recent technique and with the inherent errors with technology, it has been concluded that use of DGPS is a rapid, safe and objective technique for measuring and monitoring *S. anglica*.

The comparison of historical data with the data obtained in the 1999 survey at Lindisfarne and Bridgwater Bay NNRs leads to the conclusion that despite the control and management that has been carried out at Lindisfarne, *S. anglica* appears to be continually expanding rather than stabilising or dying-back. In contrast, at Bridgwater NNR it seems to have died-back in the last decade after a period of expansion during the 1950s and 1960s and without the introduction of any controlling technique.

S. anglica is perceived as a potential conservation problem in areas where it has successfully out-competed native *Spartina* species (*S. maritima*) or other species of the intertidal area such as *Zostera* and *Salicornia*. Colonisation by *S. anglica* of large areas of unvegetated mudflats (ie at Lindisfarne NNR), which are feeding grounds for birds and are highly abundant in invertebrates, is another problem that has been considered a consequence of its expansion. Declines in bird numbers on intertidal habitats are not completely attributable to an increase in *S. anglica*. Large-scale attempts at eradication or control however may result in even greater negative changes to sediment distribution. The colonisation of *S. anglica* in intertidal areas may be a precursor to saltmarsh development.

The Conservation (Natural Habitats, &c.) Regulations 1994, resulting from the European Habitats Directive, place new and stronger responsibilities on relevant and competent authorities and agencies to work closely together to safeguard the nature conservation interests of designated sites. The Habitats Regulations also enable relevant authorities to establish a management scheme for European marine sites[1] in order to deliver conservation measures and take appropriate steps to avoid deterioration of the natural habitats and species for which the sites have been designated.

S. anglica is still a relatively new species in evolutionary terms and there is still much research to be conducted for understanding its distribution and behaviour. Objectives for management plans should be derived on a site-specific basis, taking into account human requirements as well as the natural habitats and species affected, the prevalent hydrological regime, the likely long-term coastal dynamics, sediment transport and the potential effects to other species resulting from its spread or control.

[1] A European marine site is defined in the Conservation (Natural Habitats & c.) Regulations 1994 as a Special Area of Conservation (SAC) or Special Protection Area (SPA) or Ramsar or part of one, which is covered (continuously or intermittently) by tidal waters. The landward boundary is highest astronomical tide. The seaward boundary is that of the constituent SAC, SPA or Ramsar.

Contents

1. Introduction

1.1 Overview

In the late nineteenth century an American species of *Spartina* (*S. alterniflora*) was introduced into Southampton Water, in southern England, from shipping. This hybridised with the native species *S. maritima* to form the sterile species which was named *Spartina x. townsendii*. This reproduced vegetatively until a doubling of its chromosomes formed the new fertile species known as *Spartina anglica* which has spread throughout most of the UK, the North Sea margin and around the world. Hubbard (1968) identified *Spartina anglica* as a separate species to *S. townsendii,* able to reproduce both clonally and by seeds. *S. anglica* has since been identified as being responsible for saltmarsh expansion in many sites, and in some places it has even displaced *S. townsendii* (Martin, 1990). Its rapid rate of growth, high fecundity and aggressive colonisation made it very successful, displacing in some places the natural vegetation and occupying and creating new habitats (Benham, 1990).

The natural distribution of *S. anglica* is believed to be between Poole in Dorset and Pagham in Sussex (Goodman *et al,* 1969, quoted in Raybould *et al*, 1991). It may also have reached northern France by natural means (Oliver, 1926, quoted in Raybould *et al, op. cit.*). All other populations represent spread of the species following deliberate introductions. Between 1928 and 1932, 85,000 plants were translocated from Poole Harbour to 12 sites in Northern Ireland, 26 in the UK and to Denmark. Since then, it has spread successfully in temperate countries, but not in the tropics (Chung, 1993).

The extensive rhizome and root networks and upright stems have made it an ideal agent for trapping and stabilising unconsolidated estuarine muds and balancing the erosion of muddy coastal shores (Martin, 1990). It has been widely employed for these uses along coastal regions of the UK, Europe and other countries, where in some coastal areas its spread has been or is still encouraged. However, even within this region there are areas undergoing active control of *Spartina*. In Britain, it has been regarded as an important species for facilitating effective coastal defence, land-claim and even for the provision of grazing land. However, although originally considered useful and planted for coastal protection and land-claim projects around the world, views on its use and management began to change when *S. anglica* began to spread successfully into areas of conservation value, covering large areas of mudflats with extensive mono-specific swards. As a result, *S. anglica* is now possibly one of the most controversial species worldwide. Due to its evolution, its biology, the habitat that it occupies, its uses and management, opinions of scientists and managers are diverse, varying almost as much as the regional uses that are made of the plant. The views of research and management practitioners on the species continue to vary in respect of its value and management.

1.2 Approach

Of the cord-grass species found in England, the common cord-grass, *Spartina anglica*, is most frequently encountered and it is clear that this species is now a permanent feature of saltmarsh ecosystems. There is extensive literature on the subject of the evolution and spread of this non-native species, particularly in relation to its implications for the nature conservation interest of estuaries in England. Management therefore needs to take into account the population dynamics of this species, which are not as yet fully understood.

There is also concern about the status of the UK populations of *S. maritima* and *S. alterniflora*, which have undergone rapid declines recently, and are scarce in Europe. Both of these communities are listed in Annex I of the Habitats Directive (92/43/EEC) which require the designation of Special Areas of Conservation (SACs) by member states. Within many of the Special Protected Areas (SPAs) and in other candidate SACs with coastal saltmarsh and mudflats there are populations of *S. anglica*. The ecological consequences of expansion of *S. anglica* for coastal habitats and species has been recognised in the three Habitat Action Plans (HAPs) for Coastal Saltmarsh, Mudflats and Seagrass Beds produced as part of the UK Biodiversity Action Plan (UK Biodiversity Group 1999).

English Nature require an assessment of the current status of *S. anglica* in the UK in order to establish best practice approaches to the management of the species where appropriate, and develop habitat management guidelines, particularly for sites designated as Special Areas of Conservation (SAC) under the Habitats Directive 92/43/EEC (McLeod *et al,* 2002). The assessment presented thus includes:

- an extensive review of published research material, both from academic papers, management reports and grey sources;
- consultation with key practitioners and researchers both in the UK and from academic institutions at sites around the world;
- two detailed case studies, involving field surveys of several areas subject to differing environmental conditions, including the mapping of the current extent of *S. anglica*, together with an analysis of historical data in order to demonstrate *S. anglica* status and trends in key areas;
- summarised results of the review to be incorporated into a series of guidelines for assessment, management and monitoring of *S. anglica.*

2. Literature review

2.1 Biology

S. anglica is a vigorous perennial grass that occupies the lower intertidal zone of many coastal and estuarine areas around the temperate regions of the world. Its success has been attributed to its hybrid origin and to the fact that it is able to reproduce by seeds and also spread extensively by clonal growth (Thompson, 1991; Henderson, 1999). Other features of its biology have allowed it to colonise, adapt and in some cases successfully compete with other species and dominate the saltmarshes where it has been introduced.

As an invasive plant, *S. anglica* has colonised a wide geographical range of localised environmental conditions, becoming a dominant component of the habitat where it spreads (Thompson, 1991). It appears to have colonised a largely vacant niche habitat where competition is reduced because of the physical and chemical conditions produced by tidal conditions.

2.1.1 Origins, genetics and evolution

In Europe, *S. alterniflora* was introduced accidentally by shipping into Southampton (England) *c.*1816. This hybridised with the relatively uncommon native *S. maritima* to produce the sterile *S. x townsendii* (thought to have occurred at Hythe in Hampshire *c.*1870), which then underwent a doubling of its chromosomes to produce the fertile amphidiploid *S. anglica* shortly afterwards.

Despite its relatively recent appearance, *S. anglica* has been able to create a niche for itself, spread widely and displace other species in the same habitat. Since the time of its introduction there has been a marked reduction in the distribution of both *S. maritima* and *S. alterniflora* in the UK, largely due to the destruction of much of the saltmarsh in which the species are found. The sole remaining site of *S. alterniflora* in Britain is at Marchwood, 7km from Hythe, where a significant population is located along the edges of channels (Raybould *et al,* 1991). The closest remaining site of *S. maritima* is at Hayling Island in Langstone Harbour, approximately 25km away, with the main populations of this species being found in estuaries around Suffolk and Essex. A population of *S. x townsendii* still remains at Hythe, presumably representing the original hybridisation.

An extensive investigation of the genetic material from populations of *S. alterniflora, S. maritima, S. anglica* and *S. x townsendii* (Raybould *et al,* 1991), found that the remaining population of *S. alterniflora* at Marchwood, although large, appears to consist of only a single isozyme genotype, and only three distinct identifiable isozyme genotypes were found throughout the larger geographic range of *S. maritima*. Further evidence proved that *S. x townsendii* was a hybrid of these two parent species, and that *S. anglica* is the result of chromosome doubling of *S. x townsendii*. However, it was not possible to recreate these events by artificial means, suggesting that both events may have been extremely rare in nature. *S. anglica* was found to be almost totally lacking in genetic variation, probably due to a narrow genetic base from only one origin, or multiple origin from its two highly uniform parents. The success of *S. anglica* is probably due to its ability to exploit an ecological niche which is largely unoccupied by its parent species. However, its long-term survival will depend on its ability to expand its limited available genetic resources by either mutation or recombination of the genes.

Ferris *et al,* (1997), investigated the possible sources of pollen and seed in order to determine which species of *Spartina* constituted the maternal parent of *S. anglica*. They found that the introduced *S. alterniflora*, being wind-pollinated, was most likely to encounter pollen from the more abundant *S. maritima* and therefore the *S. alterniflora* was most likely to be the maternal parent. The hybrid seed which produced the sterile *S. x townsendii* had intermediate characters to its parents, finding a suitable niche and persisting clonally until the natural chromosome doubling occurred to produce the allopolyploid *S. anglica*.

Examination of a wide range of morphological characteristics by Thompson *et al* (1991a) showed that morphological variation seems to be dominated by phenotypic plasticity with a limited number of genetic differences defining the different morphological forms. There also appears to be an age-related decline in vigour of clones with poor survival and clonal growth in successionally older populations, reflecting the results of Marks & Truscott (1985) (see section 2.1.2). These results may contribute to the observation of widespread dieback in which previously healthy swards experience degeneration by rotting of the rhizomes. In the USA similar experiences in *S. alterniflora* swards were previously thought to be due to anaerobiosis and build up of toxic elements, or through infection by saprophytic fungi, but may in fact be due to the decline in clonal vigour with age.

There were also differences in the survival and clonal growth of different populations (Thompson *et al*, 1991b), suggesting that there may be a genetic basis for such differences. Two forms of *S. anglica* are commonly found: 'stocky' forms, which are short plants with wide but short leaves occurring primarily in pioneer populations and 'graceful' forms with tall clumps with a small number of spikes and long, narrow leaves resembling the original *S. x townsendii* (Thompson, 1990). This variation is found across a wide range of natural environments and provides some evidence for a genetic basis for the differences.

The lack of isozyme variation in *S. anglica* (eg Raybould, 1991) raises the question of what may be the cause of the morphological variation observed by Thompson (1990) and Thompson *et al* (1991 a, b, c). The presence of different morphological forms suggests that there is a degree of genetic variation within populations. However, a lesser degree of variability in successionally mature populations, and their decline in clonal vigour with age suggests that population differences may be influenced by age-related somatic variation rather than genetically determined phenotypic differences (Thompson *et al,* 1991c).

2.1.2 Physiology

S. anglica, unlike most plants, is a C_4 photosynthesis strategy plant (Matsuba *et al*, 1997). Desert plants and those found in adverse environments are common in this group, where photosynthetic efficiency has to be exploited as much as possible, and physiological adaptations have evolved to tolerate the high levels of stress. Generally plants with C_4 photosynthesis strategy are sensitive to low temperatures, C_4 grasses being generally more vigorous and productive in warm regions. *S. anglica* is an exception to this in being a cold-tolerant species found in cold temperate habitats, with net photosynthetic rates comparable to those of C_3 plants, and able to maintain competitive growth rates at low temperatures (Matsuba *et al,* 1997, Dyke, 1998).

The presence of cell glands in both leaf surfaces, the increased outflow of ions, the restriction in the entry of excess quantities of toxic ions into the roots, the evolution of root tissues with well developed aerenchyma, and a high water use efficiency, have permitted the adaptation and tolerance of the species to rigorous environmental conditions. Such characteristics have allowed the species the ability to colonise low lying estuarine habitats, to remain immersed in water for at least 6-9 hours a day (and are reported to tolerate immersion for months) and to adjust to extremely high external concentrations of Na^+ and Cl^- (Thompson, 1991).

Other important physical characteristics of *S. anglica* also allow it to be successful in saltmarsh environments. For example, the leaves have a thick cuticle and stomata in grooves which reduce the uptake of salt by reducing the rate of transpiration; waterlogging is counteracted by the presence of numerous roots in the surface layer of mud, the cells of which contain large air spaces allowing oxygen to diffuse out and aerate the surrounding soil; and the deep dense root systems allow resistance to mechanical damage from waves (unattributed internet article).

A wide range of studies have indicated that growth and aerial productivity of the plants depend on a number of environmental factors, such as tidal inundation frequency, salinity, nutrient availability, sediment oxidation and levels of sediment sulphide (quoted in Hemminga, *et al,* 1998). This latter study, however, showed that it was the physical deposition of sediment particles which affected productivity to a large extent, with positive feedback effects of "canopy-enhanced sedimentation". Biomass production in the centre of colonising patches was shown to be nitrogen and phosphorous limited, but other factors were of importance in limiting growth at the edges of the patches.

When investigating the relationship between nutrient availability and competition between *S. alterniflora* and *S. patens*, Levine *et al* (1998) found that in fertilised plots the competitive ability of each species was the reverse of that found in natural marsh conditions, suggesting that under conditions of nutrient limitation, competitive dominance may result from efficient competition for nutrients. In addition, Levine *et al* (1998), hypothesise that when nutrients are not limiting, competition for light dictates the relative competitive outcome.

In order to investigate the growth patterns of *S. anglica*, saltmarshes at Southport, Merseyside, were studied by Marks & Truscott (1985). They found that distinct zones could be recognised in the *S. anglica* sward by their shoot density and vegetative vigour. In the pioneer zone (consisting of first-year seedlings and circular clumps up to 2m in diameter), the mean density of inflorescences was almost $4m^{-2}$, ranging up to more than $112m^{-2}$ in the adjacent transitional zone (where the clumps had merged to form a continuous sward). Two upper marsh zones were also recognised: a mature zone where the *S. anglica* formed a single-species sward with a continuous canopy up to 1.3m tall, and an invaded zone in which additional species, notably *Puccinellia maritima* were also found. In these latter two zones the inflorescences were large and bore at least twice as many spikelets as the lower zones, but the proportion of mature filled seed per inflorescence was inversely related to the number of spikelets. This resulted in a marked difference in the production of viable seed in the upper and lower zones, with the zone of most vigorous vegetative growth and largest inflorescences producing the smallest proportion of viable seed. It is postulated that this represents an inability to sustain a viable population across the range of environments for a species which is approaching its northern limit of distribution on Merseyside. In such areas, the reduced day-length and temperature in autumn may reduce carbon assimilation and prevent adequate filling of late-formed seed in the upper zones.

When investigating the effects of plant density on populations of *S. anglica* in the Dee Estuary, Cheshire, Thompson *et al* (1990) found that natural sward populations were composed of a very small number of interconnected clones which appeared to maintain a persistent rhizome network with a low degree of fragmentation. It is even possible that large areas of the sward may be comprised of a single clone.

Within the sward and mature populations of *Spartina* the dense, rhizomatous base often connects young developing tillers with a large number of older tillers, and although this may provide adequate resources for survival and growth of the young tillers, such advantages may be offset by a risk of dependency and possibly viral accumulation (Thompson *et al*, 1991b).

2.1.3 Expansion

The natural spread of *S. anglica* is either by seeding, or by dispersal of plant or turf fragments which have been torn from vegetation (Ranwell, 1964) with a range of natural dispersal mechanisms such as tidal currents, wind, shipping and birds. Failure for the species to establish in an area has been attributed to inappropriate site conditions such as soil instability and sand and frost conditions. Seedlings or isolated plants, once established, develop into peripherally extending patches, and ultimately into extensive stretches of vegetation by outgrowth of rhizomes, with clumps of *S. anglica* gradually coalescing to form large monospecific swards (Doody, 1984; Groenendijk, 1986). The first spread period (two years) seems to be slow followed by a rapid spread of prolific clonal expansion (Thompson, 1991). Rhizomes develop during the winter season followed by a rapid shoot production during the spring. Doody (1984) has also reported that seeds remain dormant for several years followed by rapid expansion in a relatively short time, apparently related to early seed development and extensive seedling establishment. This phenomenon has been referred to as 'lurking' by Gray *et al,* (1990), and may result from introduction to areas which were not initially suitable for colonisation until mudflat elevations had risen to appropriate levels.

According to Groenendijk (1986) seed viability is affected by the buried depth of the seed, with both deep and superficial positions inhibiting the seed's survival and development. The author also pointed out that seeds which do not germinate within 3 to 6 months deteriorate, and that seed growth decreases at lower levels of the marsh. Another limitation for seed development is temperature, which appears to reduce development if higher than 5ºC. Lower germination rates have also been related to submergence time and anaerobiosis. The development of young tillers and/or flowering plants is subsidised by other parts of the plant. Being protected during their development, spread tillers have more chance of survival than seeds which are independent (Thompson, 1990). As a result of clonal reproduction however, the genetic variability is limited and vulnerability to epidemic disease is increased, thus frequently reported occurrences of natural dieback could be related to its clonal nature (Henderson, 1999).

Spread is highly dependent on sediment deposition (Lee & Partridge, 1983; Chung, 1993) but also depends on settling, compaction and the area available for spread (Lee & Partridge, 1983). The presence of the plants enhances sediment accumulation, which leads to gradual elevation of the marsh surface due to the plant's ability to trap and retain waterborne particles (Hemminga *et al,* 1998).

Wolfenden & Jones (1987) found that expansion of the sward does not appear to depend on sedimentary nitrogen fixation, but nitrogen fixation increases with *S. anglica* colonisation. In the upper marsh, higher rates of N_2 fixation may enhance plant growth.

2.1.4 Sedimentation processes

It is generally believed that the presence of *Spartina* on mudflats enhances the rates of sediment deposition and increases mudflat elevation though the reduction of current energy at the sediment-water interface, thus producing low-energy, depositional conditions (Elliott *et al,* 1998). For this reason *Spartina* has often been planted in order to facilitate these processes and potentially assist with shoreline stabilisation. However, recent research on *Spartina* marshes in the Humber Estuary (Brown, 1998) suggests that the situation may be more complex. It was found that measurements of sedimentation in *Spartina* patches compared to bare areas at the marsh front showed no consistent differences, with either no significant difference between the two areas or greater deposition in the vegetation over some periods and on the mudflats at others. In the continuous sward behind the marsh front, *Spartina* stem density had no effect on net deposition over 2, 4 or 10 tides. In longer-term studies there was found to be greater deposition on the bare mud than within the vegetation, and initially healthy *Spartina* clumps developed waterlogged hollows. The physical presence of the plant stems caused eddying of the incoming tidal waters which eroded channels around the vegetation. In some environments, therefore, the swards may be of more importance in stabilising sediment during periods of erosion than in promoting enhanced accretion.

At many other sites in the same study (Brown, 1998) continuous swards of more mixed vegetation often including species such as *Salicornia sp.*, *Puccinellia sp., Aster tripolium* and *Suaeda maritima,* showed a more expected pattern of accretion with higher rates occurring within the vegetated areas compared with the unvegetated mudflats (Brown & Gray, 1997).

2.1.5 Natural dieback

After a period of saltmarsh expansion, a dieback of some swards has been observed, notably along the south coast, in South Wales, and along much of the east coast as far north as Norfolk, as well as northern France and southwest Netherlands (Gray *et al,* 1997; Gray &

Raybould, 1997). The potential reasons for this pattern vary with the site and conditions but, under natural conditions, have been reported as the result of high mortality from diseases, or due to the presence of phytotoxins produced under anaerobic soil conditions created by poor drainage. It has also been reported that continuous water inundation softens the tissues allowing it to be attacked by *Claviceps purpurea*, a fungus which infects all the embryos by softening the rhizome. It is also possible that the *Spartina* has exploited a vacant niche below the normal elevational range of saltmarsh species, and is therefore highly susceptible to changes in the physical conditions. Also, since the species is relatively genetically uniform the ability to adapt to new conditions is reduced (Gray & Raybould, 1997).

Following the dieback of *Spartina,* the mudflats seem to be more extensively covered in free-living algal species such as *Enteromorpha spp.* and *Ulva lactuca*, possibly resulting from increased nutrients levels and even eutrophication. The presence of such species continues to make the mudflats unsuitable for invertebrates which birds feed upon and which may account for the early observations of bird numbers failing to increase within estuaries after *Spartina* died-back (Goss-Custard & Moser, 1988). Later observations, however, seem to suggest that this may have represented a time-lag between reduction in *Spartina* and re-colonisation of the mudflats by invertebrate populations, as species such as black-tailed godwit (*Limosa limosa*) were found to recover significantly in areas such as Poole Harbour (Gray *et al*, 1997).

2.1.6 Population dynamics

Natural populations are composed of a very small number of interconnected clones, and large areas of *S. anglica* could be a single clone, thus each individual is difficult to identify within the rhizome network (Thompson, 1991). Thompson (1990) pointed out that density within the sward negatively affects the survival of the young, tiller number, flowering tillers and the below-ground biomass. In the same study a cyclic relationship was reported between mean tiller weight and *Spartina* crop density.

2.1.7 Effects on communities

Changes in sediment composition following *Spartina* colonisation may result in a decline in the distribution of invertebrate prey for birds and fishes, and the tall dense structure of a *Spartina* sward reduces visibility for feeding species resulting in reduction of communication throughout feeding flocks and increased risk of predation (Millard & Evans, 1984). Native intertidal vegetation may also be out-competed by the *Spartina*, notably *Zostera* species, the main food source of the light-bellied brent goose (*Branta bernicla hrota*) and wigeon (*Anas penelope*) in sites such as Lindisfarne NNR (Percival *et al,*1998). However, several other factors have also been identified as possible causes of *Zostera* decline, notably sea level rise, an increase in storm frequency and severity, the effects of disease on *Zostera* in the past, and even avifaunal disturbance. Percival *et al,* (1998) carried out a study using a spatial depletion model to test the relative impacts of the various factors. It was found that the spatial location of *Zostera* habitat loss was an important component in determining the impacts, with loss from the upper shore having the greatest effect on wildfowl. This is generally the main area for *Zostera noltii* colonisation and is also the zone where *S. anglica* encroaches. It was therefore considered by site managers that *S. anglica* control would be beneficial to the waterfowl population, particularly if carried out in such a way as to promote *Zostera* recolonisation at the same time. In the United States it has been suggested that the presence of *S. anglica* can suppress native algae growing on the mud surface as well as the native eelgrass (pers. comm. Wu, 1999, Washington State University).

A possible impact of *S. anglica* colonisation on wigeon populations may have been observed in the Ribble Estuary (NW England), where the north side of Warton Marsh rapidly increased in extent through *S. anglica* colonising a zone previously dominated by *Salicornia*, a significant food source for the wigeon on the site (Robinson, 1984). It was also found that in the same area, the extension of the seaward edge of *S. anglica* coincided with the incursion of *Puccinellia maritima* into the upper edges of the *S. anglica*, suggesting the occurrence of saltmarsh succession (Robinson, 1984; Marks & Mullins, 1984). This zone was also found to be particularly susceptible to cattle grazing, with up to 40% loss of *S. anglica* shoots (Marks & Mullins, 1984). Ranwell (1961) also showed that *S. anglica* is vulnerable to sheep grazing with subsequent increase in growth of *P. maritima*.

It has been suggested by Goss-Custard & Moser (1988) that the decline in dunlin (*Calidris alpina*) numbers was greatest in estuaries where *S. anglica* expansion across intertidal mudflats had been greatest, thus reducing the available feeding resources. In estuaries where the extent of *S. anglica* remained unchanged, the numbers of dunlin had not declined. However, dieback of *S. anglica* did not appear to result in a subsequent increase in dunlin numbers, possibly due to the sediment being left in an unsuitable condition for the food-source invertebrates, together with the growth of green algae, which can physically inhibit feeding. This theory was tested by Tubbs *et al* (1992) who found that the spread of *S. anglica* was unlikely to have caused the national decline in dunlin numbers this century. The dominant influence was considered instead to have been through wildfowling-induced mortality, with an increase in numbers identified in the Solent since the 1950s when wildfowling pressure was reduced. The recent decline in the dunlin population may therefore be a short-term oscillation within a long-term trend, with the population index for dunlin increasing substantially in the 1990s after the decline in the 1980s (Cranswick *et al*, 1999).

Davis & Moss (1984, reported in Rhind, 1995) found a temporal relationship between the spread of *S. anglica* in the Dyfi Estuary, Wales and declines in the numbers of oystercatcher (*Haematopus ostralegus*), ringed plover (*Charadrius hiaticula*) and sanderling (*Calidris alba*), although there was also a corresponding increase in numbers of other wildfowl. Millard & Evans (1984) also made similar observations at Lindisfarne. Furthermore, in New Zealand preliminary observations on a 50 year old *Spartina* marsh suggested that the areas of *Spartina* sward support waterfowl in abundances comparable to those of the replaced mudflats, although with changes in species composition (Campbell *et al,* 1990).

Research has shown that dieback of *S. anglica* results in slumped mud platforms, which are exposed for longer than the adjacent mudflats and may provide additional feeding or roosting areas. Although in the early stages of marsh dieback, the consolidation of the platforms by *S. anglica* roots may provide only poor feeding sites, there appears to be no reason why these should not be suitable in later stages (Tubbs *et al,* 1992). Indeed, it was found by Gray *et al* (1997) that after an initial period of low abundance in waterfowl following dieback in Poole Harbour, there was eventually an increase in wader numbers to a density greater than expected.

Spartina is in itself a food reserve for invertebrates. It adds to the large detritus pool within areas although in general, C_4 plants are relatively indigestible and therefore make an unattractive food source for wetland invertebrate species when alive. Of the canopy species, only the sap-feeder *Philaenus spumarius* appears to favour *S. anglica* (Jackson *et al*, 1986). However in China the habitat created by *S. anglica* is considered to be rich in macronutrients, giving a good basis for future agricultural soils (Chung, 1993) and has been harvested for animal feed.

An investigation by Luiting *et al* (1997) into the impacts of *S. alterniflora* on benthic invertebrate assemblages in Willapa Bay found that although both mudflats and areas of *S. alterniflora* sward had dense and diverse invertebrate populations, the character of these assemblages was different. Large swards of *Spartina* had a rich variety of invertebrate taxa and greater densities of predatory species, possibly as a result of protection from tidal conditions afforded by the *Spartina* stems. Settlement, movement, predation and growth of clams were also found to be influenced by the presence of *Spartina* in Willapa Bay, although the actual effects varied depending on the clam species (Dumbauld *et al*, 1997).

Gray *et al* (1997) consider that there are limited data on the impact of *Spartina* presence on other plant or animal communities, and it remains difficult to determine the extent of any impacts on other species. It is possible that the presence of a new species in the environment, with its own inherent faunal population may increase the overall biodiversity of the saltmarsh as long as other species are not displaced.

Since this report was commissioned, an important survey has been completed in the Dee and Clwyd estuaries (Dargie, 2001). This documents pioneer *Spartina* saltmarsh succeeding to saltmarsh that corresponds to the Habitats Directive Annex I habitat type Atlantic saltmeadow:

"There has clearly been enormous change in the Dee Estuary. Total extent excluding transitions has increased from 2103 ha in 1983 to 2832 ha in 2000, a 35% rise in area which greatly exceeds the larger area of survey in 2000. The decline in *S. anglica* stands out (a 90% loss), along with marked declines in the area of all other pioneer saltmarsh habitats (*Salicornia/Suaeda, Aster*). This collapse of *S. anglica* has also been documented recently by Potter, Huckle & Marrs (2000). This reduction in pioneer habitats is balanced by major gains in the area of *Puccinellia maritima* and *Atriplex portulacoides*…….there has been a major increase in these middle - upper saltmarsh zones since 1983. All the above trends point strongly to conversion of pioneer habitats to middle and upper marsh conditions. The remaining pioneer vegetation in 2000 is further west in the estuary compared to maps produced by Charman and the Dee saltmarsh overall is clearly still extending its area. It is likely that succession on the outer edges advances in phases, with a relatively slow stage of establishment by pioneer types and then a sudden conversion to middle marsh conditions with *Puccinellia maritima* and *Atriplex portulacoides* once a certain elevation level is reached………"

2.2 Management of Spartina

There are many opinions regarding *Spartina* management. These are summarised in the table below.

Table 1. Summary of the advantages and disadvantages of *Spartina anglica* (extracted from Doody (1990)

Advantages	Disadvantages
• Prevents coastal erosion and stabilises mudflats • Role in land reclamation and agricultural uses	• Invades intertidal flats rich in invertebrates and feeding grounds for over-wintering waders and wildfowl.
• High productivity	• Decrease in diversity
• Creation of grazing marsh	• Replacement of richer communities
• Value for research	• Promoting reclamation for agriculture that leads to the destruction of high-level salt marsh.

2.2.1 United States

On the Atlantic US coast, climax marsh vegetation types are represented by *S. alterniflora* in the lower zones and *Spartina patens* in the upper zones. Here, *Spartina* on the shoreline is considered to be beneficial as it attenuates wave action, stabilises sediment and enhances accretion rates. There is a great deal of research on the factors affecting growth and productivity of *Spartina*, and the US Army Corps of Engineers has carried out extensive research on planting techniques and the use of *Spartina* to stabilise dredged sediment (Knutson *et al*, 1990).

In San Francisco Bay Pacific USA, *Spartina foliosa* is a natural component of low marsh vegetation, and has been planted for stabilisation of the lower edge of the marsh. However, invasion of the pickleweed (*Salicornia*) zone by *Spartina* species which are not native to this area (notably *S. alterniflora*) may threaten the local survival of the endangered saltmarsh harvest mouse (Harvey *et al,* 1983). The US Army Corps of Engineers recognises this and now recommends that *S. alterniflora* is not used for shoreline stabilisation on the Pacific coast (Knutson *et al*, 1990). Comparative studies of *S. alterniflora* and *S. foliosa* showed that the introduced species is better able to establish itself and spreads more quickly vegetatively than the native plant (Callaway, 1990).

The Pacific Northwest does not have a native *Spartina* species although *S. alterniflora* was introduced on the Washington coast during early 1900s. Since then *Spartina* (including *S. anglica*, *S. alterniflora* and *S. patens*) has colonised 17,000 acres of shoreline, with the single largest area of concern being Willapa Bay (Moore, 1997). The spread of these plants is causing concern, particularly because of the lack on information on the effect on saltmarsh organisms and other species such as the salmonids that feed on them (Landin, 1993). There does, however, appear to be displacement of species such as eelgrasses, Dungeness crabs, clams, juvenile fish of many genera and migratory waterfowl (Sayce, 1990). Trapping of sediment and subsequent raising of mudflat levels also has severe implications for flood defence and watershed drainage (Sayce, 1990).

In Western Washington State, several Native American tribes have traditionally lived from fishing near shore. Bentler (1997) now considers that their sustenance is in danger because of the spread of *Spartina*. The tribes follow a no-spray policy and, due to lack of resources, the control measures have been reduced to digging, excavation and the implementation of a public education programme concerning the awareness of *Spartina* issues.

In Willapa Bay, the spread of *S. alterniflora* is considered to be hampering the oyster harvest and causing serious problems for the birds and fish that depend on the mudflats. Ironically, the species was originally introduced from the East Coast in oysters' packing material. *Spartina* is not naturally found in this area, it has no invertebrate predators to limit its growth and alters the topography through its sediment-trapping ability, causing saltmarsh to rapidly develop from mudflat. A number of methods of control have been used including shading with dark canvas, introducing grazing waterfowl or other animals, smothering the plants with clay or other dredged material and the use of oil, grease or herbicides. There is currently a debate in the region regarding the advantages and disadvantages of control with herbicide.

One of the most important aspects in *Spartina* management, in Willapa Bay, is the influence of chemicals industry and conflicting interests among the community when choosing control techniques (Markham, 1997). In 1995 the WSDA (Washington State Department of Agriculture) created a programme for the control and eradication of *Spartina*. Since its creation, and in co-operation with other programmes, the WSDA has involved communities and local authorities, organised public fora, demonstrated that collective efforts are more efficient and, perhaps most importantly, has allowed simplification of government permit processes for private landowners (Moore, 1997). However, Cohen (1997) considers that there has been much 'hysteria' over the presence of *Spartina* in Washington State, insisting that there are numerous benefits which may be gained from using the plant in a variety of ways. Indeed, in the same conference proceedings Bertolotto (1997) urges that the community as a whole should "Hunt It!, Kill It!", and "Talk About It!", demonstrating the strength of feeling which has been generated by this species.

Cohen (1997) states that control of such species should be treated with caution since methods are generally expensive and have involved some harmful side effects, including the effects of biocides on the ecosystem and human populations, and the ecological risk from introduction of additional non-indigenous organisms when biocontrol is used. Many such attempts have also been highly controversial, involving protracted lawsuits, and as yet no attempts have completely removed the species from the ecosystem.

2.2.2 Australia

Spartina anglica was introduced into Australia during the 1920's although early attempts at establishment were unsuccessful and efforts continued throughout the 1940's and 50's. Eventually colonisation occurred and the species is now still spreading in three major sites: Tasmania, Victoria and South Australia (Hedge *et al*, 1997; Dyke, 1998). Lee (1983) suggests that if the species is uncontrolled local biodiversity in Tasmania could be threatened, and in the River Tamar the amenity value of the coastal reserves and boat ramps has been reduced. Until 1998 it was not considered a serious problem so little attention was paid to its spread. Degradation of Tasmanian estuaries has been reported by Dyke (1998) who describes the plant as a monoculture that spreads altering the resident fauna and flora, changing the habitats of the fish species, water flows and nutrients which feed the aquaculture species, as well as birds and wildlife species inhabiting the area. In 1998 a Strategic Management Plan was created for the management of *S. anglica* in Tasmania involving several government and non-governmental organisations (Dyke, 1998).

The Tasmanian government has been primarily concerned about the effects on aquaculture, mainly shellfish, (*Crassostrea gigas*) which are affected by the changes in hydrodynamics and estuarine nutrient cycling. Other commercial and non-commercial fisheries are also affected due to damage to juveniles' habitats (Dyke, 1998; Hedge and Kriwoken, 1997). Tourism and recreational activities have also been affected by the restriction of public access to the coast, whilst boat ramps and jetties are non-functional due to increased accretion. Furthermore, some sandy beaches have been colonised by extensive *Spartina* swards.

However Dyke (1998) considers that some benefits have also resulted from its introduction in Tasmania: *Spartina* mitigates erosion, stabilises mudflats and reclaims intertidal land. Its dense growth promotes sediment accretion, the build up and broadening of the shoreline, and narrows and deepens channels. These characteristics have led to improvements in the navigability of the shipping channel and a reduction in the rate of erosion of channel banks in the Tamar.

In the same river, *S. anglica* has colonised mudflats and for some members of the community the aesthetic value has increased since the introduction of the plant. In the same region it has been reported that *Spartina* ameliorates bad odours from anaerobic sediments.

There have been a number of proposals for the control of *S. anglica* during the past 20 years but, until 1998, when the Rice Grass Advisory Group (RGAG) was created, those attempts were sporadic, under-resourced or lacked integration between the government, agencies and the general public. Among the controlling techniques that the Group and volunteers have utilised since then, are physical removal, smothering, steam and infrared heat treatment, grazing, burning and herbicides. In addition to the plant's tendency to spread rapidly, other problems have emerged while trying to control it, including the role of agencies, access to the saltmarshes, tides, time, working conditions, and human activity enhancing dispersion (by transporting seeds on boots or in the equipment).

It is of note that the RGAG has set a general strategy for the management of *Spartina*. Each area has its own objectives reflecting its unique characteristics of each area, size of expansion, land use and stakeholders and the resources available for each programme. With the implementation of this plan, it is expected that *S. anglica* will be eradicated within 3-5 years. After that period, 5 years of monitoring are expected to be sufficient to ensure its control. Until now the most effective treatment, in the area, appears to be the herbicide Fusilade® (Dyke, 1998).

The control and management of *S. anglica* in Tasmania, once the strategy plan has been implemented, will be divided according to the roles played by the industry, government agencies and the community. The government responsibility is to protect migratory bird species and their habitats, which are threatened by *S. anglica* swards. Agencies involved in coastal management, natural areas conservation and water and environment management bodies have an integrated responsibility for *Spartina* management. Aquaculture is the main industry affected by saltmarsh accretion in Tasmania so has a role in fund-raising for research studies into control and impacts. Finally the community's responsibility is to support monitoring and control programs and to raise general awareness of the issues (Dyke, 1998).

Three objectives were set in Tasmania involving control methods to reduce the area of expansion or eradication of all known seedlings, clumps, tussocks and swards. The selected management objective should reflect the magnitude of the sward, the land use and ecosystems in areas adjacent to the infestation, the attitude of stakeholders and the resources available for the programme (Dyke, 1998).

The state of Victoria is another area affected by *Spartina* spread. Since 1991 the Australian Department of Natural Resources and Environment has been involved in its control, together with conservation groups and local communities. The approach to its management in Victoria follows a common pattern: mapping its distribution in the area, workshops with the community to raise public awareness and collaboration with other projects such as those as on migratory birds and on assessment of methods (Hedge & Kriwoken, 1997).

2.2.3 China

Background

S. anglica was introduced into China in 1963 for the purpose of land claim, the prevention of coastal erosion and to reduce the effects of sea level rise. Although still being used for these purposes, other uses have also been implemented in different regions over time. Originally 14 individual stems were imported from Essex in the early 1960s. Following its introduction a slow expansion period between 1966-73 took place, with subsequent cultivation in polders (1975-1978) and a climax development between 1978 and 1980. At the Xinyang Agricultural Experiment Station, 21 individuals were planted and used for growth and soil experiments, 16 months after their introduction the number of individuals had increased to 435,000 (Chung, 1993).

The rate of growth was similar to that reported in the UK, and although there was a general increase in extent, the results varied depending on the rate of erosion, winds, planting period and competition. Chung (1993) in his review of 30 years of *Spartina* in China concluded:

- *S. anglica* outgrew the native grass;
- survival of the plants was affected by the planting period (higher survival during the first period), and the number of individuals planted (higher survival with fewer clumps).

The species was not successful in all the intended areas of introduction, but in some areas *Spartina* was able to expand under rigorous conditions, for instance specimens were reported to survive 24 days of 50-80cm continuous flooding. Its uses have multiplied with the years, and it has been demonstrated to protect Chinese coasts from sea level rise and coastal erosion. As a result, *S. anglica* is considered a very efficient tool for environmental engineering by coastal managers and engineers in China, as it is low-cost, uses solar energy, accelerates biochemical cycling and, where it has shown signs of becoming a weed, several additional uses have been found for it.

Effects on coastal morphology

Apart from places where the wave energy and erosion were high, the introduction of *S. anglica* to ameliorate the effects of sea level rise or for land-claim purposes has been proved to be successful. Coasts with strong wave energy and highly erosive conditions showed only minor results from *S. anglica* introduction, but in slightly erosive and stable coasts *S. anglica* accelerated the rate of accretion. It was observed that wave energy, height, and rate of sediment accretion influenced the sizes of the plants. In Qidong and Typhoon, test sections of *S. anglica* were planted. *S. anglica* was found to protect the sea wall where planted, whereas at locations where it had not been planted, the sea wall was destroyed by wave energy. As a tool for land-claim, over 2000ha in Qidong and 967ha in the Yangtze rivers were claimed for agriculture through the use of *S. anglica* between 1975 and 1980 (Chung, 1993).

Effects on soil

Land claimed for agriculture through *S. anglica* cultivation has been found to be rich in organic matter, available nutrients and salt content (the latter not always unfavourable). The porosity and pH also increased and there was a need of less fertiliser. As a result, wheat seedlings, harvesting and crop yield was multiplied and a stable agricultural production has evolved. Furthermore, *S. anglica* has also been applied as a green manure producing yields exceeding those where pig manure or chemical fertilisers were applied.

Effects on animals

S. anglica has been used for feeding cattle, pigs, sheep, rabbits, fish and grey geese. According to the available statistics, goat milk production increased 60% and until 1993 more animals were being fed with it, including mules, horses, water buffalo, goats and hogs. Apart from being used for feeding animals, where it has been planted it provides additional nesting and feeding grounds for migratory birds, which contradicts the general UK views, and the productivity of the sites has increased, leading to an increase in marine fauna. As a consequence it is also used in aquaculture, resulting in bigger fishes which are more resilient to diseases, and thus higher profits at lower costs. Higher production by the ragworm *Nereis* has also been formed in *S. anglica* plantations.

China is one of several countries including USA, France, Britain and Holland, where *Spartina* has been used for cattle grazing; indeed it has been reported by Ranwell (1961) and later by Chung (1993) that it is very nutritious and enhances growth in animals.

Effects on humans

According to Chung (1993), 9.6 x 10^5 Yuans (actual exchange rate is 0.0808£) were invested in the introduction, monitoring and settlement of *S. anglica*, with an economic return of 2.5 millions Yuans, excluding the value of the claimed land. *S. anglica* is also used as fuel, as a raw material in paper making, as a biomedical liquid added to milk, beer, wine and cardiotonic beverages and has shown positive results in treatment of kidney, liver and excretory organ diseases. Other authors, Bull & Bergen (1999) and Dyke (1998) have quoted the possibility of using *S. anglica* for similar purposes.

2.2.4 Netherlands

S. anglica is widely distributed in the Dutch and German Wadden Sea areas. *S. anglica* has become very common in the Netherlands, often replacing *Puccinellia maritima, Triglochin maritima, Aster tripolium* and *Limonium vulgare*. The first spread commenced in the 1900s ceasing in the 1950s. *S. anglica* seems to grow faster over newly constructed coastal engineering works, which increases the possibilities of natural dispersion (Groenendijk, 1986). The experimental work carried out by Groenendijk aimed to assess the possibility of spread in relation to site elevations, the depth of seeds as well as with sedimentation and erosion processes.

Favourable conditions for its establishment featured low current velocity and wave action whilst it was found that in the Oosterschelde estuary, *S. anglica* distribution was controlled by hydrodynamic conditions causing seed transport and uprooting of seedlings. It was concluded that there was not a risk of invasion of *S. anglica* at this site, and that the planting of *S. anglica* would not be a good strategy for preventing erosion of the cliffs in that estuary (Groenendijk, 1986).

2.2.5 New Zealand

Spartina was first introduced into New Zealand in 1913, initially as *S. townsendii* but additional plants of *S. anglica* were sent from the Essex marshes in 1955. Subsequent widespread and indiscriminate planting in estuaries around New Zealand has caused concern, particularly as native saltmarsh is a sparse and valuable resource and encroachment of *Spartina* poses potential problems in relation to wildfowl feeding areas (Hubbard & Partridge, 1981). At the landward edge the extent of *Spartina* is limited by the presence of *Leptocarpus similis*, at the lower limit, and therefore extent of seaward spread, by tidal inundations. Tidal inundation conditions vary at *Spartina* sites throughout the world. For example in New Zealand it was found that *Spartina* is emergent for only 887hr per annum, compared to 1440hr/yr in Poole Harbour and 2000 hours in Bridgwater Bay.

In 1963, concern about the impacts of *Spartina* on New Zealand estuaries resulted in the introduction of legislation prohibiting further planting of *Spartina*. Areas of value for recreation and food collection, and as sanctuaries for resident and migratory birds, were thought to be at risk from the spread of *Spartina*. In particular, concerns were raised over the impacts of *Spartina* spread on the extensive tidal flats, *Zostera* beds and macro-algal beds bordering the existing saltmarsh, together with the impacts of accretion raising muddy land elevation and restricting navigation (Asher, 1990).

Despite the populations remaining small, the control of populations of *Spartina* (*anglica, alterniflora and x townsendii*) is a matter of importance for the New Zealand government (Shaw and Gosling, 1997). Its control until 1997 was accomplished mainly with the herbicide Gallant™, due to "acceptable environmental impacts", which was applied from helicopters, airboats and amphibious vehicles. The success of the control depends largely on proper planning, funding, contingency plans and co-operation between all the different agencies in coastal protection and management (Shaw & Gosling, 1997). In addition the long-term impacts of the removal of *Spartina* are also not yet fully understood, although the long period over which decay of the roots occurs means that the impact of further organic and sediment releases may be minimised (Asher, 1990).

2.2.6 Ireland

At Bull Island Nature Reserve in Dublin Bay, the Dublin Corporation has been attempting to control *S. anglica* since it became prominent in the 1970s, covering large areas of the mudflats which were important as feeding grounds for wader and wildfowl populations. In 1996 a project by the University College Dublin was established to determine whether the *S. anglica* should be controlled, and if so, to determine the most appropriate methods (McCorry, 1999). However, McCorry considers that the recent timescale of the *S. anglica* invasion requires the species to be viewed differently than if it had been longer established within saltmarsh communities, where other monospecific swards such as *Phragmites* or *Typha* are considered to be more acceptable.

2.3 Spartina anglica in the UK

As already indicated above, *S. anglica* spread rapidly around the UK during the last century. Along the west coast the rapid initial spread was followed by a quiescent period for 30-40 years and then a further sudden increase of population (Gray *et al,* 1990; Doody, 1994). According to Way (1990), in the late 1980s, *S. anglica* dominated 6,950ha of tidal flats, 16% of the British saltmarsh habitat and 2% of the estuarine intertidal zone. Although the early spread was due to natural processes, a high proportion of the present distribution is a result of artificial introductions, largely carried out in the 1920s and 1930s. Gray *et al,* (1997) suggested that there were more than 10,000ha of *S. anglica* in the 44,000ha of saltmarsh around the British coast. Despite the rapid spread and the area of land colonised by *Spartina*, evidence of its impact on intertidal communities is largely indirect or circumstantial. There is very little quantified evidence, except at very local scales, to prove that other species have been displaced as a result of *S. anglica* spread.

Mudflats occupied by benthic invertebrates and eelgrass beds (*Zostera* sp.) have been displaced by *S. anglica* at a local scale. As these are often feeding grounds for migratory and resident birds, concern from conservation agencies has increased. Local indirect evidence has been given for dunlin although it has not been possible to directly attribute any decrease in the numbers of other birds to the expansion of *S. anglica* marshes (Gray *et al*, 1997).

Although there is no consensus about the management of *S. anglica* in the UK, there are 3 main strategies:

- in some areas of England it has been reported as a problem and controlling measures have been applied, eg Lindisfarne and Morecambe Bay;
- in other areas, *S. anglica* is not considered a problem and is not controlled or protected eg Bridgwater Bay;
- other areas still use *S. anglica* for combating coastal erosion and thus its spread is encouraged: eg west Sussex.

In the UK overall, *S. anglica* has been managed in 28 locations within 20 estuaries since the 1960s but complete removal has only been successful where there is only a small sward of young plants, and even then continuous monitoring and further management has been necessary (Way, 1990).

Despite its rapid spread, *S. anglica* is now experiencing natural dieback in some places without any management or controlling measures. Gray (1997) reported that *S. anglica* has continuously died-back along the south coast, in South Wales and on most of the East Coast as far north as Norfolk. North of this region, some populations have remained stable and others are still spreading. In comparative studies by Gray (1990 & 1997) with Hubbard and Stebbings (survey conducted in 1967), S. *anglica* increased 40% in area between 1967 and 1990 on the West Coast, whilst on the south coast it decreased by more than 11% and on the East Coast it has shown a large decline of 44% (although according to Gray *et al* (1997 & 1990), there could be errors in the 1967 surveys as a result of survey methods.)

The reasons for the decrease/dieback of *S. anglica* are not fully understood (Raybould, Gray, Brown, pers. comm. and see section 2.5.1). *S. anglica* regression has been attributed in some stands to a spread of the fungal pathogen *Claviceps purpurea* that first appeared in Poole Harbour (Gray *et al*, 1997) and which affects patterns of seed set. However, the infection appears to have little effect on the population dynamics within the estuary, as dispersal and colonisation occurs by vegetative reproduction and therefore is unlikely to be a major cause of the overall dieback (Raybould *et al,* 1998).

Conservation practitioners are concerned that the presence of *S. anglica* has deleterious effects on the diversity and function of intertidal habitats. However, Harwood (1999), working on the Northwest coast of England, and more specifically in Morecambe Bay, considered that *S. anglica* is largely established in a continuously changing environment where it is the only species able to survive and therefore does not lead to a decrease in the overall diversity or the displacement of any other species. The following examples summarise the experience of *S. anglica* spread and its management.

2.3.1 South Coast

S. townsendii spread to every estuary between Poole Harbour and Pagham Harbour from 1870 to 1923, its maximum extent was found to be during the late 1940s and 1950s when it occupied 3326ha of the south coast (Doody, 1984). The most extensive stands were reported in Poole Harbour, West Solent, Southampton Water, Portsmouth, Langstone and Chichester Harbours.

Poole Harbour appears to have the best-documented recording showing the evolution of *S. anglica.* It has also been the source of plants to many other national and overseas areas for land-claim and coastal defence purposes. The plant began to spread around the harbour during the 1890's and by 1924 it had covered 800ha (63% of coverage in this period).

Currently the species only covers 400ha (Raybould, 1997). According to Oliver (1925 in Raybould, 1997) once the plant was established in the area, it spread several feet per year but only formed sward extensions in the upper reaches of the Harbour from Fitzworth Point to Hamworthy.

After reaching its maximum extent in 1924, erosion commenced in the following years at the edges of the marshes. Between 1924 and 1952 *S. anglica* decreased at some sites but continued to increase in others although in general, there was a recession in sward extent in most areas. Between 1981 and 1994 marshes were lost because of land-claim for the Holes Bay road (Raybould, 1997; Gray *et al,* 1991).

S. anglica has not only died-back in the fringes of the marsh but also in the main body of the sward, a condition not very well understood but which seems to be associated with badly drained, highly anaerobic soils with high concentrations of sulphide ions. The latter, together with the lack of oxygen, are toxic to the *S. anglica* rhizomes (Gray, 1991 and Raybould, 1997). Moreover, such a chemical environment can also increase the potential uptake of pollutants. The changes in the extent of *S. anglica* have also been implicated in changes in the mobility of sediments in Poole Harbour (Raybould, 1997)

Another reason for the decrease in *S. anglica* extent is the invasion/colonisation by other species for example in Poole Harbour it has been replaced by *Phragmites communis, Bolboschoenus maritimus,* particularly in areas of low salinity. *Elymus pycanthus, Elytrigia atherica, Agrostis stolonifera, Festuca rubra, Puccinellia maritima,* and *Atriplex portulacoides* are further species known to have replaced *S. anglica* in this manner (Raybould, 1997). It could be therefore inferred that *S. anglica* could be creating conditions leading to a succession to higher marsh.

2.3.2 East Coast

According to Doody (1984) despite a paucity of information regarding *S. anglica* spread on the East Coast, it was not considered a significant component of the saltmarsh community except in some local areas. It appeared that land-claim for agricultural purposes together with sea level rise relative to the land, had affected the development of *S. anglica* before 1984. A survey regarding saltmarsh changes in the Wash over a period of 14 years conducted by Hill (1988), reported a decrease of 83ha of saltmarsh since 1975 but a general increase of 864ha since 1973.

S. anglica in the Wash is present mainly on the seaward saltmarsh edge, but it is also found in poorly drained areas and pans throughout the marsh. There is a sharp boundary between *S. anglica* and other communities and it occurs in grazed and ungrazed habitats but is generally avoided by grazing animals. A rapid expansion was reported during the 1950's, and although *S. anglica* dominates the pioneer community zone, the area around the River Ouse is the only place where it forms a continuous sward and at all the other sites of the Wash the zone is shared with *Salicornia sp.* (Hill, 1988).

2.3.3 North-West coast and Wales

S. anglica was first reported on the North West coast in 1932 in the Ribble Estuary where it was introduced and apparently spread naturally to the Wyre Estuary (1942), and was first recorded in Morecambe Bay in 1949 (Harwood, 1999; Doody, 1984). It has been present on the Grange-Kents bank in Morecambe Bay since 1960s and complaints by local residents have led to control programmes being developed in conjunction with local authorities. Since

1990 it seems to have expanded further and complaints relating to the loss of visual amenity have also increased. During 1998 and 1999 the South Lakeland District Council funded an experimental rotoburying project (Harwood, 1999) (see section 2.4.2), monitored by English Nature and the Institute of Terrestrial Ecology with plots comparing rotoburying techniques together with control trials plots and hand-pulled trial plots. As Harwood (1999) points out, *S. anglica* control is often regarded as an inefficient use of resources in the area, requiring yearly work effort with, in some cases, sward extent continuing to increase despite control efforts. Harwood (1999) suggested that in the absence of control, some sites will undergo a succession process and develop into a more species rich habitat attractive to insects and birds and with a high visual amenity as well as conservation interest. However, for this to take place, *S. anglica* has to be allowed to develop and accrete sufficient sediment for further saltmarsh to establish.

S. anglica was introduced into the Severn Estuary in 1913 as a mud-binder, and subsequently to the Dyfi Estuary in 1920. The species has now spread to almost every estuary in Wales, although rates of spread seemed to be reduced in the period between 1960-1982, than during the previous 40 years (Rhind, 1995). Both anecdotal and documentary evidence suggest, that *S. anglica* is now in a degenerative phase, either as a result of dieback or through natural succession and replacement.

At Blackpill SSSI in Swansea Bay, the importance of the site for ringed plover and sanderling led to some control attempts being implemented, including a programme of spraying, initially using dalapon, and subsequently glyphosate, in conjunction with mechanical removal by excavators. However, it has not been possible to audit the success of this operation, as recent geomorphological changes in the estuary have made the area naturally unsuitable for *S. anglica*.

In North Wales various attempts have been made to control *S. anglica*, including a long-term programme of spraying and digging in the Cefni Estuary, herbicide use in Red Wharf Bay (Anglesey), Conwy Bay, (Aberconwy), Mawddach Estuary and Borth-y-Gest Harbour near Porthmadog. Sheep grazing may also have been used in the lower reaches of the Afon Dwyryd (Rhind, 1995).

2.3.4 Northern Ireland

A management strategy is being developed for *S. anglica* in Northern Ireland (McKeown, pers comm..2004). The Environment and Heritage Service (EHS) held an experimental licence to use the herbicide Dalapon to control *S. anglica,* but this expired in 2002 and has not been renewed. The Pesticides Safety Directorate, who issues the licence, considered that the work was no longer experimental. For this reason, Dalapon was taken off the approved herbicide list and all remaining stocks had to be destroyed. No further herbicide control has taken place and *S. anglica* is starting to spread into previously treated areas.

The development of the strategy includes the assessment of the current distribution of *S. anglica* using GPS, aerial photography and ground truthing. This will help to target the areas most in need of control. Some research has been carried out to investigate the influence of wave-related processes on the spread of *S. anglica* onto mudflats in Strangford Lough (Hammond *et al* 2002). This found that S. anglica did not establish in conditions associated with long waves, which are more likely to disrupt sediment surfaces and uproot seedlings. This may help to predict patterns of establishment and thus help with a management strategy.

Control techniques since 2002 have included trials of strimming to below sediment level, but rotoburying is not considered a suitable option in Strangford Lough (the main area of concern) due to the topography. EHS are currently looking into the possibility of obtaining a licence for the use of Fusilade®, due to the relative success of its use in Tasmania.

2.4 Control techniques

Saltmarsh production is not constant during the whole year and is influenced by sediment salinity, sea level cycles and variability, flooding frequencies and tidal range and wave energy (Elliott *et al,* 1998). A typical characteristic of *S. anglica* is its ability to accrete large amounts of sediment around the base of the plants binding them together with a rhizome network, a process termed biostabilisation (Mazik & Elliott, in press). The morphology of the stems and leaves reduce the ebb and flow velocity of tidal waters and trap the sediments (Thompson, 1990; Elliott *et al,* 1998). Accretion rates may vary on a site-specific basis, for example Thompson (1990) reported accretion rates from 0.2cm to 10cm per year in different regions of Europe.

In order to understand *Spartina* dynamics and associated processes, it is important to monitor rates of expansion and productivity. Being in the pioneer zone, *S. anglica* is sensitive to sea level alteration, changes in sedimentation, erosion rates, sea-borne pollution and other perturbations. However it can also be used as a biological indicator of these phenomena, being a good indicator for habitat succession and changes in productivity and biomass (Gross *et al*, 1986).

As indicated above, in some areas *S. anglica* spread has become a problem, replacing native species and reducing the biological diversity of the area. Different control techniques have been used including hand digging, rotary machines, pesticides and biological controls. Control methods with associated monitoring are carried out frequently, almost annually, in areas with severe rates of increase. However, as noted by Norman and Patten (1997) the cost effectiveness of the methods needs to be considered in management plans for *Spartina* control.

2.4.1 Physical removal

Physical removal is perhaps the cheapest way of controlling *S. anglica*, and has been used in most of the places where management has been implemented. However, it is a very labour-intensive process that appears only to be effective for single plants and small clones, and according to Dyke (1998) it is unlikely that all rhizomes are removed when clones are bigger than 15cm in diameter.

Mechanical excavation has proved to be a more efficient tool, where access across the mudflat is possible, such as in Tasmania, but problems can arise from the liberation of sediment and rhizome material (Dyke, 1998). Poorly controlled techniques will allow further colonisation by the species as well as disturbance to associated habitats. Despite this, mechanical removal techniques are often effective and generally accepted by the public particularly as they remove the need for pesticide use (Harwood, 1999).

An experimental combination of clipping shoots and burying them beneath 10cm of sand was attempted in Willapa Bay, USA with the aim of killing plants by removal of oxygen sources to the rhizome. This was found to be effective with little regrowth occurring, although clipping alone was less effective.

2.4.2 Rotoburying

This technique has been used in limited areas on the Lindisfarne National Nature Reserve since 1995. It is considered to be a successful tool that does not require as much labour as digging, does not add any chemicals to the environment and does not lead to *Spartina* spread (pers. comm. P. Davey, NNR Site Manager).

At Lindisfarne, the rotoburying technique consists of a tractor-mounted device that buries the *S. anglica* to a depth that does not allow recovery or regeneration, a similar technique having been employed to bury stones in areas used for turf cultivation. There have been concerns about its use in relation to the potential impacts on the invertebrate community of the saltmarsh and in particular impacts on birds and fish feeding on them (Harwood, 1999) although Harwood (1999) notes that there was no apparent damage to invertebrate community from the activity. After the initial disturbance which led to some individuals being lost, a new niche was created that was colonised rapidly and the sites returned to conditions similar to those before the disturbance. However the speed and extent of recovery by invertebrates may depend on the timing of the rotoburying in relation to seasonal recruitment cycles.

Rotoburying appears to be effective in eradicating *Spartina* marshes but, as noted by Harwood (1999), its efficiency and the period between each rotoburying session will depend not only on the technique employed but also on the amount of seeds produced following the activities. The rotoburying technique macerates and buries plants but not necessarily seeds that can germinate leading to the regeneration of the sward. Another limitation identified by Denny and Anderson (1998) in a study at Lindisfarne NNR is that rotoburying cannot be used in soft sediments where *Spartina* is usually more extensive.

The decomposition of buried *Spartina* should also be taken into account before carrying out rotoburying in large areas. For example, large amounts of organic material decaying within the sediment soft and poorly aerated sediments will create anaerobic conditions and thus the production of phytotoxins such as hydrogen sulphide (H_2S) and methane (CH_4).

2.4.3 Smothering techniques

In Australia field experiments have been conducted into the effectiveness of smothering the plant, involving the inhibition of photosynthesis and elevation of temperature by the covering of the sward under black plastic or weed melting (Bishop, 1995). Despite the technique proving successful, Dyke (1998) encountered some inherent problems in the application, as it is a labour-intensive technique requiring treatment over extended periods of time (6 months). The technique is non-selective and the cover can be damaged by storms or vandalism creating navigation and conservation problems. As with the decomposition of buried *Spartina*, smothering may also produce organically enriched sediments and associated problems.

2.4.4 Grazing

Grazing by cattle and sheep is another very common technique for managing *Spartina,* and has been used in the United States, China, New Zealand, Australia and even the UK (Bridgwater Bay), where, although it was not applied for control purposes, it is believed to have helped to stop the spread of the plant. Despite being an efficient technique not all sites are suitable for grazing (Chung, 1993; Dyke, 1998). Shaw & Gosling (1995) reported that grazing in wetlands causes environmental degradation by damage to native saltmarsh through trampling, increasing soil erosion and compaction from hooves, together with the increase in nutrients levels from urine and faeces. However, as mentioned earlier, it has been the most commonly used technique for controlling *Spartina* spread in China (Chung, 1993).

Ranwell (1961 in Hill, 1988) reported how different regimes of grazing can affect saltmarsh development. In Bridgwater Bay, *Spartina* was replaced by *Atriplex hastata* in places where sheep grazing had occurred, whereas in places without grazing, it was replaced by *Phragmites australis* and *Bolboschoenus maritimus.*

2.4.5 Burning

Burning techniques have been used in Tasmania without success. It is a non-selective technique and does not appear to be efficient (Dyke, 1998).

2.4.6 Herbicides

In the UK, the main legal instruments covering pesticide use are the Food and Environment Protection Act 1985 (FEPA) and control of Pesticides Regulations (COPR) 1986, and subsequently the Plant Protection Product Regulations 1995 as amended by the Plant Protection Products (Fees) Regulations 1997. FEPA introduced statutory powers to control pesticides with the aim of protecting human beings, creatures and plants, safeguarding the environment, ensuring safe, effective and humane methods of controlling pests and making information available to the public. Only approved products (including adjuvants) may be sold, stored, advertised, or used. The information that follows does not imply any approval for the use of products listed for the control of *S. anglica*, and further advice must be sought, preferably from a holder of a recognised Certificate of Competence; required for anyone giving advice when selling or supplying pesticides approved for agricultural use.

In particular, proposal for the use of herbicides for *S. anglica* control in sites covered by statutory designations must be accompanied by information on non-target species and consent for their use must comply with label recommendations (Cooke, 1986). Updated English Nature guidance on the use of herbicides in nature conservation sites was published in 2003 (Britt *et al* 2003).

Prior to 1940, copper sulphate was sprayed as an herbicide for controlling the spread of S. anglica (Hardy, 1968 in Doody 1984). It was then replaced by Dalapon® (sodium dichloropropionate) and Feneron®, and currently the most frequently used herbicides are based on glyphosate, sprayed from the air as well as manually on the mudflat. Moreover, they are more successful when placed directly onto the plants, with an aerial application used as a support (Kilbride, 1995).

Dalapon was used successfully to control the spread of *Spartina* on the amenity beaches of Southport in the Ribble Estuary, where two applications at concentrations of 57kg/ha were found to be the most cost effective method resulting in 91% mortality. After a third application the mortality was 99% in mature populations (100% in young plants) with slow subsequent recolonisation resulting in only 1 plant per 100m^2 in the sprayed areas (Truscott, 1984). It was concluded that the effectiveness of this method depends on the correct timing, matching the plant's growth cycle to the prevailing tidal and weather conditions, and repeated applications at 3 or 4 yearly intervals may be required.

At Lindisfarne National Nature Reserve, the herbicide Roundup® PRO, based on glyphosate, has been used as this herbicide translocates down into the *Spartina* rhizomes, has low toxicity and degrades into non-harmful by-products. Its application is therefore considered not to affect the estuarine ecosystem (Monsanto, 1992). Data from early trial plots showed *Spartina* to have been replaced by *Salicornia*, with evidence of an increase in the invertebrate population, and the use of Roundup® PRO has been approved.

In Wales a combination of Dalapon and Roundup® was found to be more successful than the individual application of either herbicide. Furthermore, the use of herbicides was combined with mechanical disturbance by excavators in order to increase success rates (Rhind, 1995).

The efficiency of any treatment depends much on the position on the shore of *S. anglica* swards, the periodicity of the treatment between treatments and subsequent tidal inundation. According to Kilbride (1995) Rodeo® (another glyphosate based herbicide) should be applied around spring tides in order to maximise the exposure time. Rodeo® is the only herbicide that until 1997 was permitted in Washington State for *Spartina* control, but it has been reported that it can cause non target plant injury through drift. Because of this, the need for awareness of potential problems regarding its use has been pointed out by Kubena *et al,* (1997).

Dyke (1998) found Fusilade® (Fluazifop-butyl) to be the most suitable herbicide for controlling *Spartina* in Victoria (Australia), due to its 99% mortality efficiency, particularly as it does not affect native vegetation. Fusilade® is a highly selective post-emergence grass killer, is rapidly degraded in the soil and mortality rates in nearshore fauna, even though still reported, were found to be low.

The efficiency of glyphosate-based herbicides was compared to the slash and smother technique in Port Sorell (Australia) resulting in 100% more efficient results, with the area remaining clear for one year.

Specht (1997) and Felsot (1997) state that in order to minimise any risk on controlling *Spartina* with herbicides, there is a need for a Comparative Risk Assessment (CRA) or Ecological Risk Assessment (ERA) of the chemical technologies that might be involved. Such an assessment should include the effects on *Spartina* and other biota, the period of exposure, the data from toxicity tests and effects on non-target vegetation.

2.4.7 Biological control

Research by the University of Washington (Wecker, 1998) attempted to determine the most appropriate methods of control in Willapa Bay, with biological control considered to be the most promising new option. Greenhouse experimental studies found that *S. alterniflora* clones were severely stressed or killed by moderate populations of *Prokelisia marginata*, a leafhopper common to the home range of *S. alterniflora* (Daehler & Strong, 1997).

Further work on the possibilities of *Prokelisia* spp as biological control agents was carried out by Wu *et al* (1999) who found that a greenhouse population of *S. anglica* introduced to Puget Sound in Washington was highly vulnerable to these planthoppers from California. No apparent harm was caused to the native strains of *S. alterniflora* and *S. foliosa* even by the highest densities of planthoppers, although the alien *S. alterniflora* introduced to Willapa Bay in Washington was found to be vulnerable. It was postulated that this was the result of both *S. anglica* and the alien *S. alterniflora* not normally being found in areas of *Prokelisia* spp, with no defensive adaptation evolved to reduce the potential harm caused by the planthoppers. The stenophagous nature of *Prokelisia* means that they should not pose a threat to other plant genera, particularly as no close relatives of *Spartina* are found in coastal areas of Washington State.

Other species proposed by Daehler and Strong (1997) for biological control of *Spartina* could include the oyster scale shell and stem-boring gnats.

2.4.8 Steam and infra-heat treatment

This relatively new technique for combating weeds was developed in New Zealand and has been used for combating road weeds in Australia (Dyke, 1998). Steam at approximately 100°C, causes extensive tissue damage to aerial parts of the plant and extends to below ground parts. From observations in New Zealand it seems to be an effective control technique but is not selective and thus affects other plants and animals in the sward. The size and weight of the equipment means that it is not suitable for use on mudflats as it requires considerable quantities of hot water, is time consuming and the results depend on the extent of the sward. There may be also health and safety issues involved with the use of steam.

Heat treatment is an alternative technique involving a propane gas flame used to heat a grill, at approximately 850°C. This new technique emits infra-red heat which kills the plant cells and was planned to commence in 1999 in Australia. Results from this technique have yet to be published.

2.4.9 Natural dieback

Greenhouse experiments and observations on *S. alterniflora* saltmarshes in Massachusetts, carried out by Portnoy (1999), showed that alterations to salinity, depth and duration of flooding can degrade estuarine habitats by affecting saltmarsh biogeographical cycling. In dyked marshes where waterlogging was constant, *S. alterniflora* production declined due to sulphide toxicity. Drainage also, apparently slowed the decline of *S. alterniflora* in Massachusetts, with greater aeration accelerating decomposition and iron enrichment that produced acidification.

Restoration of *Spartina* areas can also be practised. Portnoy (1999) recommends saltmarsh restoration programmes to be planned with caution for both the seasonally waterlogged and drained systems. Tidal reintroduction should be carried out on small areas and continuous monitoring of pH and sulphide levels should be carried out on pore water and surface water as well as dissolved nutrients, iron and dissolved oxygen.

3. Case studies

3.1 Introduction

In order to quantify the recent population dynamics of *S. anglica* in England, two case studies were undertaken in 1999; Lindisfarne National Nature Reserve (NNR) on the Northumberland coast and Bridgwater Bay NNR on the Somerset coast. Those sites were chosen for their location, representing an area undergoing relative sea level rise and one with more stable conditions. In addition, these sites have considerable historical data on the extent of *S.anglica*, and represent two different management strategies which have been initiated in order to control it. At Lindisfarne, control of *S. anglica* is considered a priority management issue, whilst at Bridgwater Bay it is not.

Techniques for mapping the extent of large areas of coastal vegetation such as saltmarsh require simple yet precise survey methods that are both non-destructive to the habitat and safe for the surveyors. Field surveys of saltmarsh, as with other intertidal areas, require rigorous health and safety precautions to be taken, with regard to tidal streams, inundation, soft substrata etc. A further aim of the fieldwork was to compare the advantages and disadvantages of using Differential Global Positioning Systems (DGPS) logging devices in conjunction with aerial photographs together with historical data in order to map and monitor *S. anglica* extent in the intertidal zone.

For extensive areas of saltmarsh, remote sensing methods (eg by aerial photography and associated photogrammetric techniques) are useful because they provide a rapid, non-destructive means of mapping vegetation. Such techniques allow analysis of temporal change when aerial photographs from previous years are available, but may give reduced accuracy in areas where sward boundaries are not well defined or where there are patches of vegetation (Gross *et al*, 1986). For field studies the DGPS is considered a useful tool either to map boundaries or define positions of spot samples or ground control points to an accuracy of within 1-2m. The use of DGPS has been considerably more accurate than standard GPS which may have an error of up to 100m, although fully portable DGPS equipment is not widely available.

Following the recent discontinuation of selective availability (SA), GPS equipment has become more accurate, perhaps to an accuracy level <10m. However, this level of accuracy will depend upon equipment, satellite coverage and atmospheric conditions and therefore maybe unsuitable depending on survey requirements. It is considered that DGPS continues to provide more accurate position fixing but this technique has cost implications which may be prohibitive. New methods of satellite position fixing will come on to the market over the next couple of years and it is therefore suggested that the applicability of any position fixing and logging system be reviewed regularly.

Extremely accurate position fixing may be achieved by real time kinematic GPS and full topographic surveys, either by levelling with theodolite or EDM (Electromagnetic Distance Measurement). However, such equipment may be prohibitively expensive and labour intensive over large areas such that the derivation of Digital Elevation Models (DEM) from aerial photographs may be more practicable if required. It is important to emphasise that the level of accuracy possible with modern equipment may be redundant in areas where boundaries of saltmarsh are not clearly defined. Protocols for the mapping of such diffuse boundaries need to be established prior to any survey and the methodology used to be clearly described in order to allow subsequent survey work to be comparable. A combination of remote sensing techniques with ground truthing by field studies with DGPS generally provides the best compromise between accuracy and time-cost considerations. Other techniques for saltmarsh monitoring to determine abundance, biomass and area measurements, eg by transect/quadrat survey, are not considered in this report but details of such methods are outlined by Hill (1988). In the present study, temporal changes in the extent of *S. anglica* at Bridgwater Bay NNR and Lindisfarne NNR were measured using historical data from aerial photographs and maps combined with current data obtained from a field study utilising DGPS.

Information was gained from two sources as follows:

a. Field survey

A Sercell NR51 DGPS connected to a PSION real time logger was used as a tool for logging the extent of *S. anglica* coverage in the field. At each survey area, two members of Institute of Estuarine and Coastal Studies (ICES) staff followed the boundary of the *S. anglica* swards along a fixed level of abundance, corresponding to the change from dense to sparse *S.*

anglica. Position as well as time and any necessary comments were logged every 10-15 metres. Photographs of the survey area were also taken together with samples of the vegetation and these were cross-referenced to DGPS position. Periodically a position was taken at the extreme extent of the *S. anglica* (defined as <1% coverage). All data were consequently downloaded from the logger to PC and then input into a GIS system for subsequent analysis. The survey technique provided a relatively rapid and accurate estimation of the main boundaries of the saltmarsh, to within 2m in places where clearly defined boundaries existed and allowed some estimation of change in extent within these limits when compared to historical data. However, due to safety reasons, some areas were inaccessible by foot and hence the method may only allow partial coverage of any site depending on substrata.

b. Comparison with historical data

Existing information of the extent of *S. anglica* from aerial photographs for Bridgwater Bay (from 1947, 1971, 1984 and 1994) and Lindisfarne (1996) were also input into GIS following orthorectification. *S. anglcia* boundaries for Lindisfarne in 1975 were digitised from maps and input onto GIS. The data derived from the field survey were compared to present and historical aerial photographs as well as other graphical data, in order to give an idea of the change in extent (spread or dieback) of the *S. anglica* marsh.

3.2 Measurement techniques

i. Aerial photographs

Aerial photographs provide valuable data for the monitoring of *Spartina* presence and distribution, both spatially and temporally. Inter-annual and intra-annual comparisons can be made and give a general picture of the dynamics of the system. As well as a source of historical data, aerial photographs are a quick, safe and non-invasive technique. There is little risk for the surveyor and data obtained are less liable to subjective assessment of distance, allowing the entire saltmarsh to be recorded with the same standard error. Moreover, digitised information from aerial photographs has a major use in mapping techniques. However, there is an inherent subjectivity in the assessment of the delineation of sward edge, particularly in conditions of gradual succession or colonisation. The date of photography may be dictated by aircraft availability and thus not be standardised for tidal state. Furthermore seasonal variation in sward cover and weather conditions may also affect the quality of the results.

As with any other technique, interpretation of aerial photographs is subject to errors linked with the resolution of the equipment and those introduced by analysis software. At least four control ground points (CGP) have to be established for the orthorectification. CGP have to be easy to identify, permanent in time and space and sufficiently large to be recognised in photos and in maps. In estuarine and coastal conditions where the majority of *Spartina* swards will occur, CGP may be difficult to identify from aerial photographs, even where they are on the main land. Furthermore, the seaward side of the marsh often lacks any potential CGP and consequently errors may occur during the rectification process. The accuracy of the orthorectified photographs in the current study varied from 5 to 50m, although errors within the areas of saltmarsh being analysed were generally <20m. Consequently, this error must be taken into account when interpreting any perceived changes in the change in *Spartina,* particularly with regard small-scale changes, which may not necessarily be attributable to *Spartina* regression or expansion.

Wilton and Saintilan (2000) found that errors introduced during the georectification process and from the analysis of the image are cumulative. Although the final accuracy is very difficult to measure because individual errors can work for and against each other, Meehan (1997 in Wilton and Saintilan, 2000) calculated an estimated value of $100m^2$.

ii. Historical maps

Historical maps are useful for comparison with recently derived distribution maps, although the accuracy of the information given in historical maps may be open to question. Maps may have been drawn from field sketches and distances estimated by eye, hence unless changes have been extensive conclusions should be treated with some caution.

iii. DGPS

The accuracy of the fixing of the spatial extent and feature of a saltmarsh can be increased through the use of DGPS, which allows rapid and accurate measurements. However, for safety reasons part of some sites cannot be covered, which may lead to an incomplete survey of a site. Despite this, it is considered to be a viable mapping technique, which can provide an indication of the change in extent of *Spartina* sward.

The technique is potentially subject to operator error in terms of measuring the edges of dynamic swards, particularly if different personnel are used for different areas or surveys. Because of this, standardisation of field recording techniques is necessary and a detailed mapping methodology developed on a site/surveyor basis.

3.3 Study sites

3.3.1 Bridgwater Bay NNR – Somerset

Background and historical data

Bridgwater Bay is a coastal area in Somerset on the southern shore of the Severn Estuary. The Bridgwater Bay National Nature Reserve (NNR), which compromises 2564ha, is designated as a SSSI, and is included within the Severn Estuary European Marine Site (SPA, Ramsar and pSAC). Mudflats with saltmarsh, sandflats and shingle ridges largely dominate the ecosystem, connected by a complex network of fresh and brackish ditches. Several wintering waterfowl species are present in numbers of international and national importance (English Nature, 1998, 1999). Bridgwater Bay SSSI covers 3574.1ha (8831.6 ac), including Bridgwater Bay NNR. In addition to the wintering birds, the water bodies are highly diverse and include six nationally rare and eighteen nationally sparse species of invertebrates. The hydrodynamic regime, geology and morphology of the area have led to the deposition and creation of extensive and highly mobile mudflats. Strong westerly winds have also influenced the vegetation and ecosystem development.

Dargie (1999) reported a total area of 1521ha of saltmarsh in the Severn Estuary and 390ha along the Somerset coast, which included an area of 193.1ha of *S. anglica* coverage. Table 2 lists the results from different surveys including Bridgwater Bay.

Table 2. *Spartina anglica* coverage for the Severn Estuary, County of Somerset and Bridgwater Bay 1967-1999 (from Dargie, 1999; Smith, 1979; Martin 1990; Burd, 1989)

Region Area	**Severn Estuary ha**	**Somerset ha**	**Bridgwater Bay ha**
1967 (Martin, 1990)	350		
1979 (Smith, 1979; Burd 1989)	774	340.29	334.24
1998 (Dargie, 1999 - 1521ha saltmarsh area)	193.1	87	
1999			Aprox. 55

The most extensive area of saltmarsh within Somerset is at Bridgwater Bay and includes one of the largest *S. anglica* beds within the estuary. It occupies a wide coastal band from Wall Common to Steart Island and fringes the mouth of the Brue (Figure 1.). *S. anglica* dominates much of the seaward edge of the marsh, and has invaded and consolidated the fronting mudflats. Higher up the shore, *S. anglica* has been displaced by *Puccinellia maritima* and *Aster tripolium*.

Spartina coverage in Bridgwater Bay was reported in 1954 (Mr. Thomson *pers. comm*. File Bridgwater Reserve Scientific Records, English Nature Taunton Office Somerset), expanding in Steart Island from the North-west corner towards the south although these was not noted to be of concern. According to Hubbard & Stebbings (1967 in Martin, 1990), in 1967, *S. anglica* covered approximately 350ha on the Severn Estuary, with 226.4ha between Lilstock to River Avon and from the River Avon northwards (129ha.).

Smith (1979) calculated an area of 488.3ha between Bridgwater Bay and Aust, 62.7ha north of the Severn road bridge (both shores) and 223.1ha on the north shore between Beahley and Cardiff giving a total of 774.1ha (Smith, 1979 and Martin, 1990). Smith (1979) calculated 334.24ha of *Spartina* cover at Bridgwater Bay divided into four areas: Steart Island, Steart Point, Steart Flats and Stockland Marsh. Some sites covering Steart Point and Steart Flats were recorded as being sheep-grazed during the April-October season.

In 1983 *P. maritima* was reported as the dominant species of the saltmarsh at Bridgwater with a pioneer zone of *S. anglica* spreading at the north of Fennin Island (Dr. P. Doody, *pers. comm*. JNCC). There are no data on the extent of coverage by *S. anglica* at this time, so comparisons between the original and more recent data cannot be carried out. Burd (1989) reported 340.29ha of *S. anglica* coverage in Somerset, with 334.24ha at Bridgwater Bay, although these figures were based on Smith's survey in 1979, thus restricting the potential for comparison of data.

Dargie (1999) surveyed approximately 87ha of *S. anglica* at Bridgwater Bay, although this may be an under-estimation, as some sites were not surveyed due to safety reasons. Although the measurements were not exact, it was found that the Bridgwater NNR had some of the larger *S. anglica* swards within the Estuary.

S. x. townsendii was first reported in the Severn Estuary in 1919 even though its introduction had already been mentioned in the records of the Watson Botanical Exchange Club in 1915 (Martin, 1990). It is not clear whether it was introduced from Poole Harbour or Hayling Island, but the first introduction seems to have been in Kingston Seymour in 1913 and it was reported to have been introduced to Bridgwater Bay in 1930 (Holland, 1982). Plants from

Bridgwater were subsequently exported to Canada, USA, China, Tasmania, Philippines and New Zealand from 1959 to 1970 (Borley *pers. comm*. 1980 - Bridgwater Reserve Scientific Records, English Nature Taunton Office Somerset).

Ranwell (1961) investigated the effects of sheep grazing on *S. anglica* saltmarshes within the site and this activity, as well as cattle and rabbit grazing have been reported since 1907 (Stapf, 1907 in Ranwell, 1961). Moreover, prior to Ranwells study, the effects of grazing on *S. anglica* had not been researched. Other mammals (rats) on the site appeared to feed only on *S. anglica* during certain times of the year.

According to Dargie (1999) *S. anglica* was found to dominate 69% of the marsh vegetation, although higher up the marsh it is mixed with *Puccinellia, Elymus* and *Bolboschoenus.* In the non-grazed area *S. anglica* is replaced by *Aster*, *Phragmites* and occasional *Elymus* and *Bolboschoenus*. It also forms parts of sub-communities dominated by *Puccinella maritima, Limonium vulgare*, *Plantago maritima*, *Armenia maritima* and *Triglochin maritima.*

Current status and development of *S. anglica*

It would appear from the fieldwork carried out in 1999 that *S. anglica* is dying back (Figure 1) and although the sward has never been actively managed, sheep grazing may have controlled its spread. Part of the *S. anglica* bed is fenced, in order to contain the sheep, rather than to protect the saltmarsh.

During the fieldwork in 1999, it was noted that *S. anglica* did not form a dense marsh (*cf.* Lindisfarne NNR), but that there were bare sand patches in the main body of the marsh. Within a distance of approximately 30m from the main body of the marsh and towards the estuary, patches of *S. anglica* less than 1m in diameter were recorded. Parallel creeks divided the sward and isolated clumps of *S. anglica* were found across the survey area.

The Steart flats complex was surveyed but Stockland Roach was excluded from the fieldwork for safety reasons, whilst part of the Common Wall and Steart Island were assessed from a distance. The *S. anglica* distribution for 1999 and for previous years has been mapped in Figure 1. The historical extend of *S. anglica* was derived from aerial photographs taken in 1947, 1971, 1982, and 1994. Table 3 defines by categories the *S. anglica* changes with time (5 = large extension, 3 = medium extension, and 1 = short extension). In order to compare the information from the photographs from different years with the recently surveyed data, the area has been divided following the divisions given by Smith (1979).

Following comparisons with Table 2, *S. anglica* was present during the 1940s but had not spread. There followed an expansion during the 1960s and 1970s, with a subsequent decrease in area during the 1980s and 1990s. However due to potential mapping errors from previous surveys and during the present analysis, an exact value for the change in *S. anglica* cannot be calculated with any certainty. Despite this, analysis of the data from the 1999 IECS survey of Steart flats suggests an area of *S. anglica* coverage of around 270ha. If this is compared with the *S. anglica* area calculated by Smith in 1979, (1014.5 ha) it can be concluded that *S. anglica* has died-back since that time and may now represent only 25% of the maximum extent this century.

Table 3. Comparison in the extent of *S. anglica* between the 1940 and 1999

	Dense *S. anglica*				**Sparse *S. anglica***			
	CW	SF	SI	SR	CW	SF	SI	SR
1947	1	1	1	None	1	1	1	
1971		5	5	5		5	4	
1982	5	4	2-3-4	5		5	5	
1994		3 - 2	3-2-4	5-4	5	4	3	
1999		2 - 3	4-3-2	no data	4	4	3	

CW = Common Wall; SF= Steart flats; SI = Steart Island; SR = Stockland Roach. The values are equivalent to the area of spread, with 5 indicating rapid *S. anglica* expansion in the area and 1 for areas which have undergone negligible expansion or where *S. anglica* has died back.

Historical comparison suggests that *S. anglica* expanded from 1947 to the 1980s but has undergone dieback in the past 10 years. However, this conclusion should be qualified as the original surveyors questioned the accuracy of the historical data.

Dargie (1999) suggests that the isolated circular clumps of *S. anglica* found in the outer margin of the saltmarsh shown as sparse *S. anglica* in Table 3 and Figure 1 indicate the remnants of a former continuous sward. However, the abundance of those sparse clumps varies over time and there are also difficulties identifying boundaries from aerial photographs.

Dargie (1999) suggests the long-term trend in the Severn Estuary being a net loss of *Spartina* marsh in the outer parts of the estuary as a consequence of erosion; with Gwent and Gloucestershire as the only place in the Severn Estuary where *S. anglica* expansion could be occurring. Dargie cites a modest expansion in the middle and upper estuary and a conversion to other mixed communities on higher ground. As a general trend, Dargie (1999) suggested that, combined with other factors, the Severn Estuary saltmarsh is undergoing a transgression in response to sea level rise.

3.3.2 Lindisfarne NNR – Northumberland

Background and historical data

Lindisfarne NNR covers 3451ha of mudflats, saltmarsh and dune. Part of the Berwickshire and North Northumberland Coast SAC, it also lies within the Lindisfarne SPA. Its mudflats with areas of *Zostera* and *Enteromorpha* cover provide feeding habitats for national and internationally important numbers of wintering waterfowl (English Nature 1998,1999, English Nature/SNH, 2001).

A local farmer introduced 500 specimens of *S. anglica* from Poole Harbour into the southern part of the reserve in 1929, in order to prevent coastal erosion. Since then it has spread significantly and is only prevented from further expansion by unfavourable conditions (deep water, channels etc.). Tides have dispersed the seeds around the embayment and colonisation has also been encouraged through transplanting to other parts of the reserve (Mr P. Davy *pers. comm*. Lindisfarne NNR site manager & Doody, 1984). *S. anglica* colonisation further progressed after the construction of the causeway (1966), which modified the sediment fluxes and processes (Davey, 1993 & Doody, 1984). The species has been managed across the majority of the reserve due to concerns that if uncontrolled, *S. anglica* could displace food resources for bird populations, and thus alter the ecological function of the area (Doody, 1982).

During the 1930s and 1940s, the colonisation process was slow although by 1957 it was reported that the plant had spread and clumps had appeared at sites some distance from the original source, such as Ross Point and Goswick. By 1963 it was predicted that *S. anglica* covered 33ha and by 1982 400ha (Doody, 1984). At Corkhill it was noted that, if uncontrolled, *S. anglica* could cover half of the mudflat exposed on a low water spring tide, displacing most of the *Zostera* and *Enteromorpha* beds (Doody, 1984).

The first available map of *S. anglica* distribution at Lindisfarne was produced in 1975. The aims of that project were to create a qualitative evaluation of the wildfowl resources at that time, to establish a baseline for future studies of change in vegetation distribution in the area and to describe the reserve's floral communities (Unknown, 1969).

Control of *S. anglica* at the site commenced in 1970 with hand-pulling and digging. In 1977 chemical control with dalapon was introduced resulting in logistical problems (volume of chemical required to achieve the expected outcome). In 1989 chemical control was reintroduced but with the Monsanto agricultural group introducing a mixture of glyphosate. The technique appeared to work but had a deleterious effect on some of the invertebrate fauna. In 1993 backpack spraying with Roundup ®PRO and Mixture B® proved to be 90% effective. In 1994 it was not possible to repeat the spraying because Mixture B® was no longer approved for use in intertidal areas. Another chemical was used instead (Ethoken c/12) but was not successful and consequently volunteers attempted that year's control by digging and hand-pulling the plant.

In 1995 the new technique of rotoburying was introduced, involving the destruction and burial of the *S. anglica* sward (Davey, 1993 and Davey, *et al,* non-dated paper). This technique inverts the upper 25cm of sediment, burying all the above ground vegetation (see section 2.4.2). According to Denny and Anderson (1998), rotoburying had a significant effect on *S. anglica* biomass, but regrowth appeared two years later. During the time *S. anglica* was absent, *Z. noltii, Z. angustifolia* and *Ruppia maritima* increased in biomass in places where rotoburying had been practised, compared to adjacent control areas.

S. anglica **expansion and current status at Lindisfarne NNR**

Figure 3 shows *S. anglica* distribution and its changes from 1969 onwards including the two sites within the Lindisfarne NNR that were surveyed during the 1999 fieldwork. The southern area of saltmarsh, on private land where it was originally introduced, was chosen as the first study area (Study Area 1), the other area being located south of the causeway (Study Area 2). The latter site has been subject to various management/control practices, and some of the effects of this control are visible by eye (eg post markers showing the controlled or managed sites).

The unmanaged study area (Study Area 1) features a very dense *S. anglica* sward. However, despite the apparent good health of the sward, a number of patches of open mud/water were identified within the main body of the marsh during the IECS field survey, an occurrence which may suggest dieback (Dr. A. Gray, ITE *pers. comm*.). These areas had not been reported from previous studies at the site, perhaps having been missed, unrecorded, or possibly suggesting the trend is a recent phenomenon. Given the absence of previous detailed *in situ* studies in this area, it is difficult to draw conclusions from this observation.

Figure 3 shows the changes in distribution of *S. anglica* in the study area at Lindisfarne since the mid 1970s. The red line represents *S. anglica* distribution from the first map available dated 1975. The green line represents its distribution in 1996 and the blue line, the data obtained from the IECS survey in 1999. The differences between 1975 and the other years could be as a consequence of different mapping techniques, and it is considered that the latest survey used a more accurate method despite inherent inaccuracies (section 3.1 and 3.2). The distribution of *S. anglica* on the baseline map from 1975 was recorded by direct observation from walking around the area. The information was mapped, with sketches of transects and notes also made; the points that were not accessible were analysed by aerial photographs. The data suggesting sward expansion in 1996 were derived from aerial photographs of that year and the 1999 situation was derived from the data obtained using the methodology described in the previous section.

It is evident from Figure 3 that at Lindisfarne, *S. anglica* does not exhibit the same pattern of advance and retreat as at Bridgewater Bay. If extent lines from the present survey and 1996 aerial photographs are compared with the extent shown on the 1975 map, the extent of dense *S. anglica* has remained stable over the past 25 years. The differences in the pattern of *S. anglica* dynamics between the two study sites could be partially a consequence of different mapping techniques used over time. However, the broad results are in accordance with documentary data showing differences in the dynamics between the north and south of England. It is clear that there has been an expansion of *S. anglica* on the Holy Island side of the causeway, as although it was present during the 1960-70s it has increased in extent since then as shown by the present study. However, the extent of the sparse coverage shows that in some areas, sward has been maintained or may even have died-back in the unmanaged areas. In areas close to the causeway it appears to be spreading despite these areas having undergone control.

4. Conclusions

4.1 Literature review

S. anglica is a relatively new (in evolutionary terms), vigorous and invasive plant species, which has been artificially spread from its point of evolution in the UK, to a large number of estuarine ecosystems throughout the world.

Its vigorous growth form allows it to outcompete the native *Spartina* species, and exploit a specific habitat niche where it colonises large areas of unvegetated mudflats, or displaces the natural colonisers such as *Zostera* and *Salicornia.*

S. alterniflora (one of the parent species of *S. anglica*) has been transplanted from the Atlantic coast of the US to the Pacific North-west, where there are no native *Spartina* species, and to San Francisco Bay where it outcompetes the native *S. foliosa*. This species therefore presents similar problems to *S. anglica* elsewhere.

The vigorous nature of these species makes them suitable for shoreline stabilisation, land-claim and flood defence purposes, and has resulted in their introduction to many of their present locations, a situation which is now viewed with concern by a number of agencies.

Moreover, this vigorous nature has further contributed to the concerns expressed regarding its colonisation and impacts on habitats conservation importance.

There is also some recent evidence that under certain tidal conditions, the presence of *S. anglica* stands may actually cause scouring and lowering of mudflat surfaces within the stands.

Moreover, *S. anglica* stands have a role in sediment trapping following periods of erosion.

There is now widespread concern about the impact of large monospecific swards of *S. anglica* on the balance of ecosystems. However, the majority of these concerns seem to be based on anecdotal evidence or feelings expressed by local stakeholders rather than scientific evidence. Despite this, as concerns are so widespread, they should be taken seriously in considering control and management initiation.

Environmental concern has led to a reduced acceptability of planting (with the possible exception of China), to the extent that in some areas that legislation has been introduced to prevent further planting (New Zealand).

Although natural dieback has frequently been observed, particularly in some of the older populations such as those of Poole Harbour, the causes and processes are insufficiently understood as to be able to rely on this as a long-term solution.

The unusual genetic uniformity of *S. anglica* may ultimately reduce its ability to adapt to changing coastal conditions and result in the overall decline and loss of the species in long-term evolutionary timescales.

4.2 Field survey

4.2.1 Bridgwater Bay NNR

At Bridgwater NNR *S. anglica* has been present since the early 1900s, expanding during the 1960s and 1970s and currently appears to be in a dieback phase without the need for the application of a control technique.

Analysis of the data (Figure 1) indicates the expansion in the main *S. anglica* sward in Bridgwater Bay, between the periods of 1947 and 1971, with a contraction in range between 1971 and 1982. Thereafter, a further range contraction occurred to 1994, although at a slower rate, with the 1999 survey showing a boundary similar to that of 1994.

Figure 2 suggests the sparse stands of *S. anglica* to have contracted from 1982-1999 although the pattern before this period is less clear. The figures suggest an extensive expansion in the extent of the main *S. anglica* sward from 1947 to 1971, with a contraction in extent until the 1990s. For the sparse areas this contraction many have continued through to the present survey. Such a pattern of movement has been noted at other sites (Sections 2.1 and 2.2).

4.2.2 Lindisfarne NNR

At Lindisfarne NNR the dynamics of *S. anglica* expansion appear different to those at Bridgwater NNR, with the boundaries of dense *S. anglica* swards having remained stable. Patches of sparse *S. anglica* seem to have spread in some parts of the reserve (Holy Island) whilst in other parts there has been some dieback. Efforts to control *S. anglica* have not led to its eradication in those areas since it still present in the site, and has colonised other parts of the reserve.

Figure 3 shows the *S. anglica* extent at Lindisfarne from studies in 1975, 1996 and 1999, with the sward in the south of the site unmanaged, and the northern area subjected to management by rotoburying and previous spraying. The southern sward, which has been unmanaged over the last 25 years, shows a broadly similar extent of dense coverage between surveys, but the extent of sparse sward appears to have possibly contracted over recent years. This may suggest that the colonisation phase has ceased, with the dieback process commencing.

However, the sward area in the northwest of the site immediately south of the causeway may have increased during the last 25 years. It is for this reason that trials to control the expansion through spraying and rotoburying have been introduced, with some success noted in test plots.

4.2.3 Monitoring methods

Changes in density and extent of *S. anglica* can be difficult to quantify on a large scale with a high level of accuracy, although improvements in survey techniques and position fixing accuracy will make future comparisons more accurate.

Measurements of *S. anglica* extent have often been made by skilled-eye survey in past studies and some observations of *S. anglica* distribution in the current study were also measured by eye from a distance, in areas where tidal conditions and substratum did not permit safe direct measurement.

Measurements made using DGPS allow a highly accurate (<2m) assessment of the extent of *S. anglica* in areas where clear boundaries exist and tidal conditions and substratum allow monitoring by foot.

Aerial photographs allow a more objective assessment of coverage and, if a series of historical photographs are available, some indication of temporal change is possible.

The errors inherent in measuring the distribution and extent of *S. anglica* by eye are such that direct comparison of past studies can only be semi-quantitative.

The lack of accurate ground control points and digital elevation models for the intertidal zone means that the boundaries derived from aerial photographs following orthorectification may have errors of up to 50m, although it is considered that errors are generally <20m. Such errors should be taken into account when interpreting data derived from aerial photographs.

In areas where *S. anglica* is patchily distributed and boundaries are poorly defined, some subjectivity is inherent in defining extent, and these assumptions may make the increased accuracy of DGPS redundant.

Following the discontinuation of SA (selective availability), standard GPS may in future offer a higher accuracy than in the past (generally about 15 m) although the accuracy of hand-held GPS will still be considerably less than more expensive DGPS/GPS equipment.

Given the variable error inherent in the various techniques, it is recommended that a standard sampling protocol be agreed, which is appropriate for the habitat characteristics and management objectives of a given area. The methodology also should be adopted for all studies such that accurate comparable temporal changes may be quantified.

4.3 Management and control

Management and control of *S. anglica* has been attempted in many areas where it occurs, with a wide variety of methods being adopted, including physical removal or destruction, chemical controls by herbicides and biological controls through an introduction of pest species.

There are, however, concerns about the impact of the control methods themselves on the environment, ie physical removal may result in the release of large quantities of sediment, the use of herbicide could damage the ecosystem or public health and the use of biological control may result in problems for indigenous species.

The approach taken differs between areas, eg at Lindisfarne NNR it is seen as detrimental to birds whilst at Bridgwater NNR it does not seem to be perceived as a problem for the habitat or the communities. This can also be applied to other regions where *S. anglica* is present.

The two case study sites encompass different approaches to control and management of *S. anglica*. At Bridgwater Bay NNR, it is not considered a threat to ecosystems health or function, and has not been the subject of any co-ordinated management practice. However, at Lindisfarne NNR, S. *anglica* expansion has been concluded to be a threat to both intertidal habitats and bird communities, and has therefore been subject to a number of control methods.

5. Recommendations

The present review has been produced following the collation of relevant literature, both in the UK and worldwide, discussion with key practitioners and field survey within the case study sites. It has resulted in a review of the dynamics and management of *S. anglica.* The recommendations given in the following tables and figures are targeted at the specific conditions where *S. anglica* is considered to be of conservation concern and to the techniques for its control and management.

General recommendations

S. anglica has been considered in various areas to be a conservation problem, and research is still needed regarding its function within the habitat and the consequences of its expansion or dieback for fish, birds and invertebrate communities. Its introduction is identified in the UK Habitat Action Plans for coastal saltmarsh, seagrass beds (*Zostera* sp) and mudflats as a factor affecting the habitat (UKBG 1999).

A series of potential conservation problems, outlined in Figure 4, have been attributed to *S. anglica* expansion including the displacement of *Zostera*, competition with indigenous *Spartina* and accretion and colonisation of large areas of mudflats. As shown in Figures 4 and 5, some of the consequences of *S. anglica* expansion in the environment could also be the effects of the techniques used for its control. It is recommended that further research be conducted on the effects of *S. anglica* spread and control on invertebrate community richness, diversity and structure, as well as on fish and bird communities.

S. maritima has been replaced in some areas by *S. anglica*. There is a need to encourage studies on the ecological effects and consequences of the displacement of *S. maritima* and other species of conservation interest such as *Zostera* and *Salicornia*.

S. anglica is often considered a nature conservation problem with potential deleterious effects observed from its spread in an area. These conditions, with recommendations for best control-practice are given within Table 5.

However, areas where *S. anglica* represents a conservation problem will generally feature more than one of the conditions listed in Table 5. Management and monitoring plans developed by local/national authorities should incorporate both conservation and socio-economic considerations (eg land claim), when determining management objectives for intertidal habitats.

Recommendations for monitoring / management techniques and further research

The most commonly employed *S. anglica* control techniques have been summarised in Table 4, together with the consequences and recommendations for use, including relative efficacy, time scale benefits and known effects on the environment. Figure 5 summarises the advantages and disadvantages of each technique.

Most monitoring techniques may be considered complementary, however, the use of aerial photographs together with direct recording by DGPS or GPS is considered to be most effective, offering a quick, safe and relatively accurate technique. Aerial photographs provide the most complete picture of the composition of the saltmarsh but are not particularly good for measuring intra-annual changes. Land surveys using DGPS can provide accurate data on the change in saltmarsh extent, and in combination with aerial photographs provide an indication of saltmarsh dynamics. Comparison of historical spread using maps and survey data can be applied at a broad level, but cannot provide the accuracy required to measure change with any degree of certainty.

Therefore a combination of field monitoring utilising DGPS in conjunction with aerial photographs using DGPS fixed ground control point positions (from field survey) provides the best compromise of accuracy and coverage. It can be used in combination with historical information, although the accuracy in quantifying change over time must be treated with caution.

Grazing appears to be an effective technique for controlling *S. anglica* but not for eradication. However, grazing is non-specific and will affect other species in the sward.

Manual cutting of *S. anglica* provides a short-term management solution in areas where the rate of expansion is low, or where accretion is starting to occur. In places where other control techniques cannot be used, manual cutting will also become a necessary tool.

Rotoburying appears to be an effective control technique. However, there is little information available describing the effects of rotoburying on invertebrate communities. It is recommended that more trial plots be initiated within a number of sites where *S. anglica* is considered an environmental problem. Trials should include the investigation into the effects of the technique on the invertebrate community of the saltmarsh, as well as on the marsh structure itself.

Research into the survivability of seeds in relation to smothering as a control technique for *S. anglica*, and the long-term application of them would be valuable.

There appears to have been little research into the levels of bioaccumulation and potential side-effects from herbicide usage, and the implication for changes in the trophic chain.

Although herbicides have been used as a *Spartina* control technique, it is recommended that further research is carried out on potential effects of the chemicals, components or derivatives in the surrounding fauna and flora be carried out.

Biological control is a technique that has not yet been tried in Britain and would be subject to strict controls. If it is to be considered, there is a need for extensive research into the species to be used for control and the potential effects on the ecosystem. Further research is also needed in manpower levels, relative costs and long-term effectiveness.

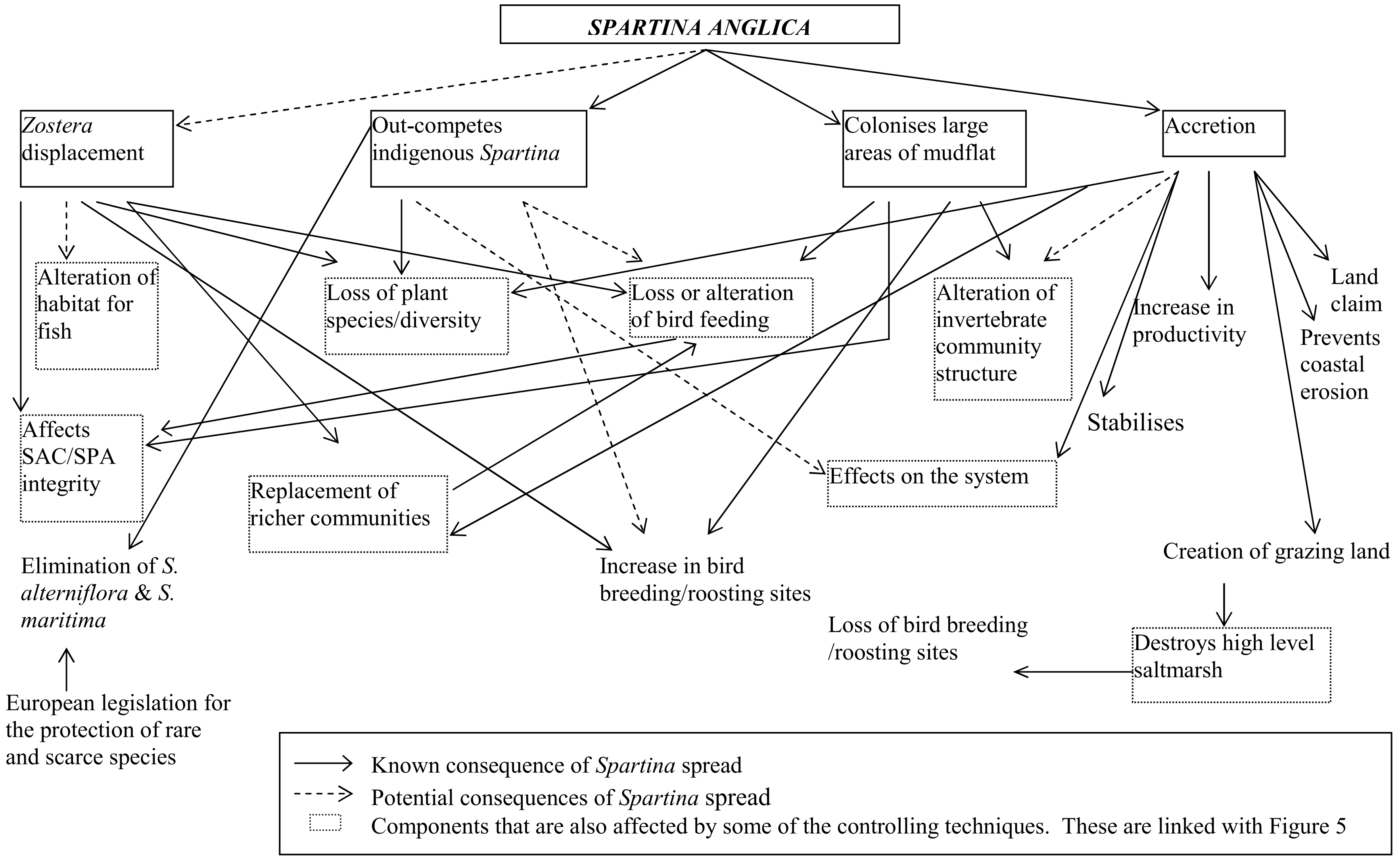

Figure 4. Consequences of *S. anglica* expansion

Table 4. Summary of techniques commonly used for the control or eradication of *S. anglica* swards

Techniques	**Consequences**	**Recommendations**
Manual cutting	• Short-term solution. • Very selective technique. • Cheap if volunteers are used. • Health and safety implications. • Seeds can be dispersed by workers and in their equipment. • Has to be repeated annually. • Labour-intensive technique. • Appears only to be effective for single plants and small clones. • There is no need for pesticides so there is little ecological damage. • However, some damage to habitats and disturbance to birds.	Manual cutting can be a short-term solution in places where *S. anglica* is starting to spread or colonise. It can also be used in swards where the accretion rate is not accelerated and one or two days a year can be dedicated to cut the new swards. Can also be used as a complementary technique to any other control methods when, for various reasons, parts of the marsh cannot be reached. With machinery
Rotoburying	• Does not add any chemicals/pesticides. • Successful tool that does not require a large labour force but large capital investment because of the machinery cost. • Effective in eradicating *Spartina* marshes. • Sites have returned to conditions similar to those before the disturbance. • Colonisation of other species begins after a short period of time. • Enables creation or re-colonisation of *Zostera* beds if conditions are suitable. • A treatment is effective for more than 4 years. • Evidence of birds being attracted by the sediment displacement but consequent impacts on the birds that feed on the invertebrates. • Its efficiency and the period between each rotoburying session will depend not only in the technique but also in the amount of seeds produced following the process. • Site limitation, it cannot be used in soft sediments where *S. anglica* is usually more extensive. • It cannot guarantee that seeds have been destroyed or that *S. anglica* is not going to appear again. • Major change to sediments. • There is no apparent damage to invertebrate communities but there is a possible redistribution of invertebrate populations living in the sediments. • Problems can arise from the liberation of sediments and rhizome material. • Organic enrichment processes could result as a consequence of large amounts of organic material trapped within the sediment. • Suitable conditions for production of phytotoxins such as H_2S and CH_4.	Useful in solid compacted sediment, where the rotoburying machine can safely operate. There is a need for further research regarding the effects of this technique on invertebrate communities, as well as the long-term effects in the ecosystem.

Techniques	**Consequences**	**Recommendations**
Smothering techniques	Appears to be effective. Experimental technique with limited data. Labour-intensive technique. Health and safety implications. Invasive technique. Relatively expensive. Requires treatment over extended periods of time (6 months). It is a non-selective technique. Long period of time before *S. anglica* dies. As with the decomposition of buried *Spartina*, smothering will also produce organically enriched sediments and associated problems. Problems related to methane and sulphide production. Storms or vandalism can damage covers leading to visual, navigation and ecological problems.	Being still an experimental technique, there are a number of unresolved issues regarding its effectiveness over time, effects on the ecosystem, survivability of seeds, consequences of covering the system for 6 months, and succession after the treatment.
Do nothing	Cheap. No chemical inputs. Allows natural succession to occur. Could take 30 years.	Depending on the human community interests and habitat involved, do nothing may not actually alter the natural development of the marsh. It has been reported that *S. anglica* eventually dies-back and other species colonise.

Techniques	Consequences	Recommendations
Herbicides	Effective technique but effectiveness depends on the plant's growth cycle, tidal and weather conditions. It is more successful when placed directly onto the plants, with aerial fumigation work as a support. Non-selective technique. Costs dependent on the method of application (eg Aerial spraying is expensive but covers a larger area). Application equipment can be uncomfortable to carry, heavy, warm and very uncomfortable if sprayed directly. Re-colonisation might occur. Treatments have to be repeated annually for at least for 5 years. Despite its components and/or degradation it involves adding chemicals into the system. Chemicals may leach out and might affect *Zostera* beds. Ecological impacts associated with prolonged and regular use of herbicides in estuaries has not been investigated on a large scale (Dyke, 1998). Efficiency depends on the pesticide used: Dalapon: 99% mortality after the third application. Roundup® PRO: has low toxicity and degrades into non-harmful substances, and is therefore thought not to deleteriously affect the estuary ecology. *Salicornia* has replaced *S. anglica*, with evidence of an increase in invertebrate populations, and the use of Roundup PRO has now been approved by MAFF. Fusilade®: has been the most suitable herbicide for controlling *S. anglica* in Victoria with 99% efficiency and little effects to native vegetation. It is a selective post-emergence grass killer; mortality rates in nearshore fauna are very low and it is rapidly degraded in the sediment. The negative aspect of its use is that, despite it is considerate a selective alternative, it still can kill non-target species. Rodeo® is the only herbicide that until 1997 was permitted in Washington State to control *S. anglica* but it has been reported that it can affect hormones of other non-target species.	Research is needed involving bioaccumulation of herbicides on other organisms and/or the effects of the chemicals, components or derivatives in the surrounding fauna and flora. Research regarding changes in the food chain is needed.

Techniques	**Consequences**	**Recommendations**
Biological control	Macro- grazing Efficient tool. Relatively cheap. Does not add pollutants. Agricultural benefit since it produces good quality animals. Effective for controlling but not for removing *S. anglica*. Not all sites are suitable for grazing. Continuous control. Environmental degradation by damaging native saltmarsh through trampling, increasing soil erosion and compaction from hooves, and increased nutrient levels from urine and faeces. Grazing can affect saltmarsh development. Saltmarsh succession is affected.	Appears to be a good control rather than a removal technique. The effects on the environment would depend on the number of cattle or sheep grazing the marsh.
	Micro eg insects Very effective and selective experimental technique. Newest experimental technique. Site specific. Introduction of an alien species into a habitat. Introduction of parasites and diseases. Requires testing for insects in each biogeographic region. Expensive due to site research required.	This technique has not yet been tried in Britain. If its introduction is to be considered there is a need for research on the species used for control and effects on the ecosystem. Further research is also needed on manpower, relative costs and long-term effectiveness.
Other techniques	Burning Non-selective technique and not effective. Steam and Infra-Heat treatment Relatively new technique. But is not selective so it affects other plants and animals in the area. The efficiency of the treatment is directly related to the amount of equipment. Size and weight of the equipment are not suitable for mudflats as it requires considerable quantities of hot water. It is time consuming and the results depend in the expansion sizes.	Need for research on recovery rates.

Table 5. Potential conservation problems as a result of *S. anglica* expansion

Conditions where *Spartina anglica* is a nature conservation problem	**Potential Consequences**	**Recommendations**	**Control Techniques**
Spread with the displacement of natural colonisers such as *Zostera* and *Salicornia*	• Loss of *Zostera* beds and SAC integrity. • Reduction of feeding grounds for waterfowl. • Alteration of habitats for gobies and pipe fish.	• Further research into the actual or potential threat of *S. anglica* replacing *Zostera* beds is needed, as there is currently no consensus of opinion between scientists and managers. • It might reduce the extent of feeding grounds but can improve roosting and nesting habitat. There is a need of further research involving the function of the habitat. • Further studies into the effects of *S. anglica* in fish communities. Research should include an assessment of direct influences (detrimental or advantageous) to fish populations and habitats.	• There is a need for a technique that does not damage *Zostera* beds or S*alicorni*a. • Herbicides and rotoburying should not be considered in places where protection of species is required. • The same applies to any other technique that involves sediment disturbance.
Competition with the native *Spartina* species	Loss of species. Loss of diversity.	• *S. alterniflora* is an alien species in UK but still is classified as a rare species. *S. maritima* original marsh of the UK is a rare habitat. There is little information regarding the ecological effect of their disappearance. Further research on the ecology of these two species and their habitats is required. • According to the European Directive on conservation, sites for conservation should be selected giving preference to those areas supporting local *Spartina* (even though *alterniflora* is not local, it is included under this classification). But there is a need for consensus in this matter.	• Non-selective techniques should not be considered if protection of other *Spartina* species is required. • Depending on the distribution of each species, grazing or rotoburying could be considered with the opportunity of future restoration.
Colonises large areas of unvegetated mudflats	Loss of mudflat area. Reduction in feeding grounds for wildfowl and waders. Alteration in roost availability. Increase in breeding habitat for waders, wildfowl and passerine birds. Invades mudflats rich in invertebrate abundance.	• There is a need for further research regarding changes in invertebrate communities (richness, abundance and diversity) as a result of changes in colonisation. • Identification of other potential causes of the reduction of mudflat area.	• Manual cutting and herbicides could be considered if the protection of mudflats is the main aim. • If the sediments are not too soft, rotoburying should be considered.

Conditions where *Spartina anglica* is a nature conservation problem	**Potential Consequences**	**Recommendations**	**Control Techniques**
Accretion	Changes in habitats – loss of intertidal. Affects community diversity. Prevents coastal erosion and stabilises mudflats. Promotes land-claim for agricultural uses that may destroy high level saltmarsh. High productivity. Replacement of richer communities.	• It is necessary to create a management plan with aims and objectives for the uses and control of *S. anglica* for each area. • The complications of coastal squeeze and changes in mudflat morphology and function should also be incorporated into any management plan.	• Depending, on the stakeholders' uses and views of *S. anglica,* various measures for elimination could be considered (ie rotoburying). • If it is being used primarily for coastal defence its accretion could be induced using grazing as a control technique.

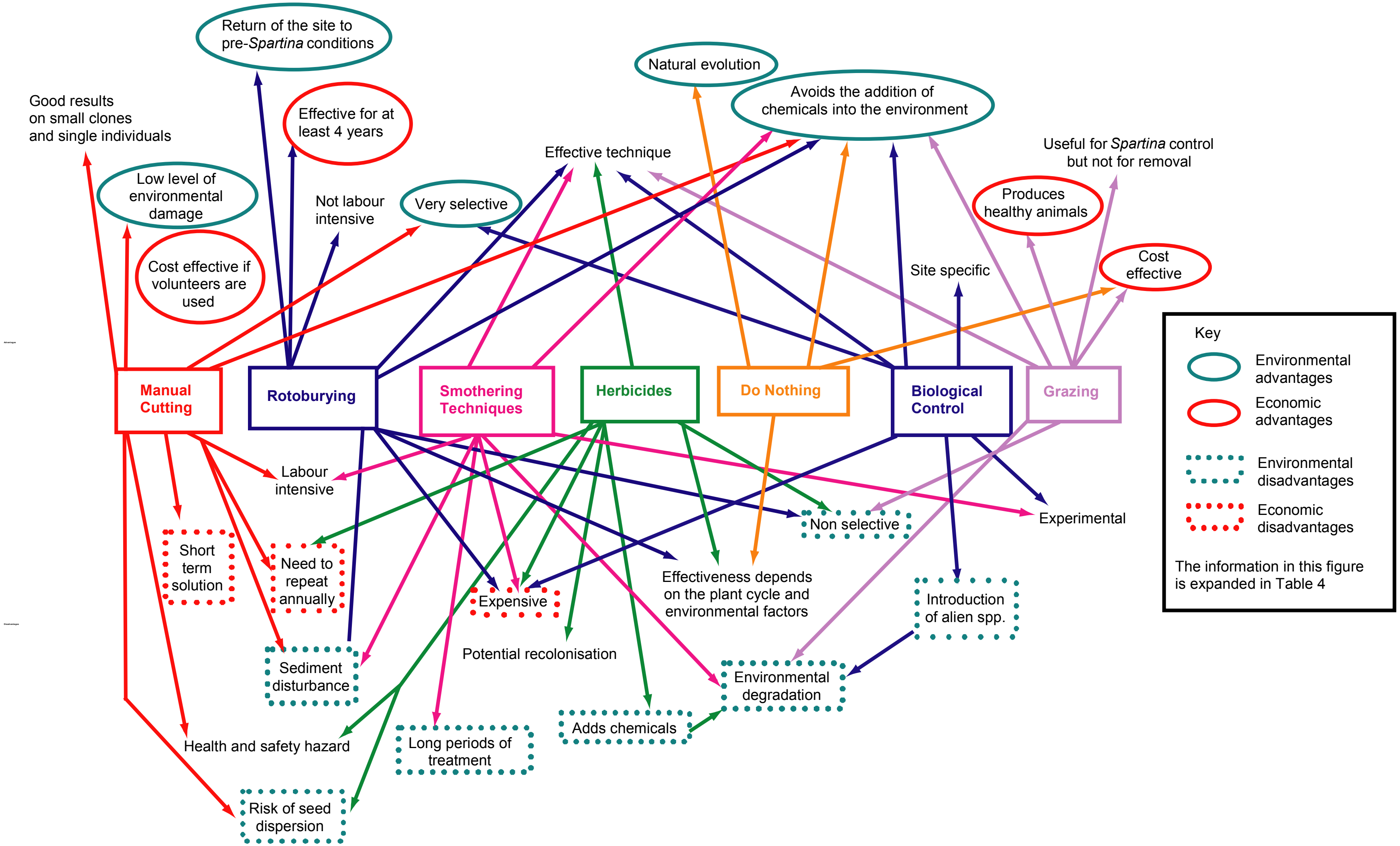

Figure 5. Advantages and disadvantages of *Spartina* control techniques

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Appendices

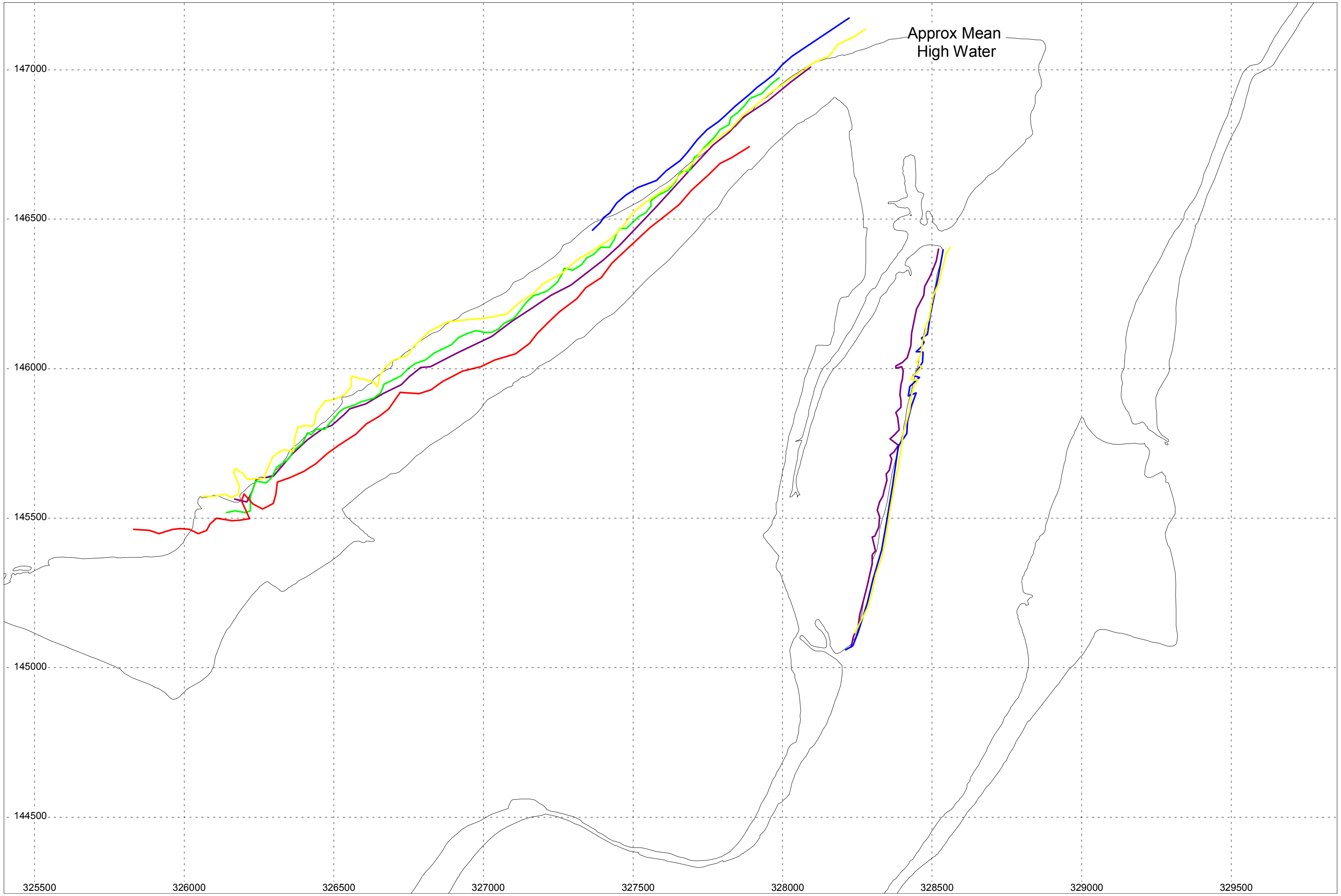

Figure 1 Seaward limits of dense *Spartina* at Bridgewater Bay between 1947 and 1999.

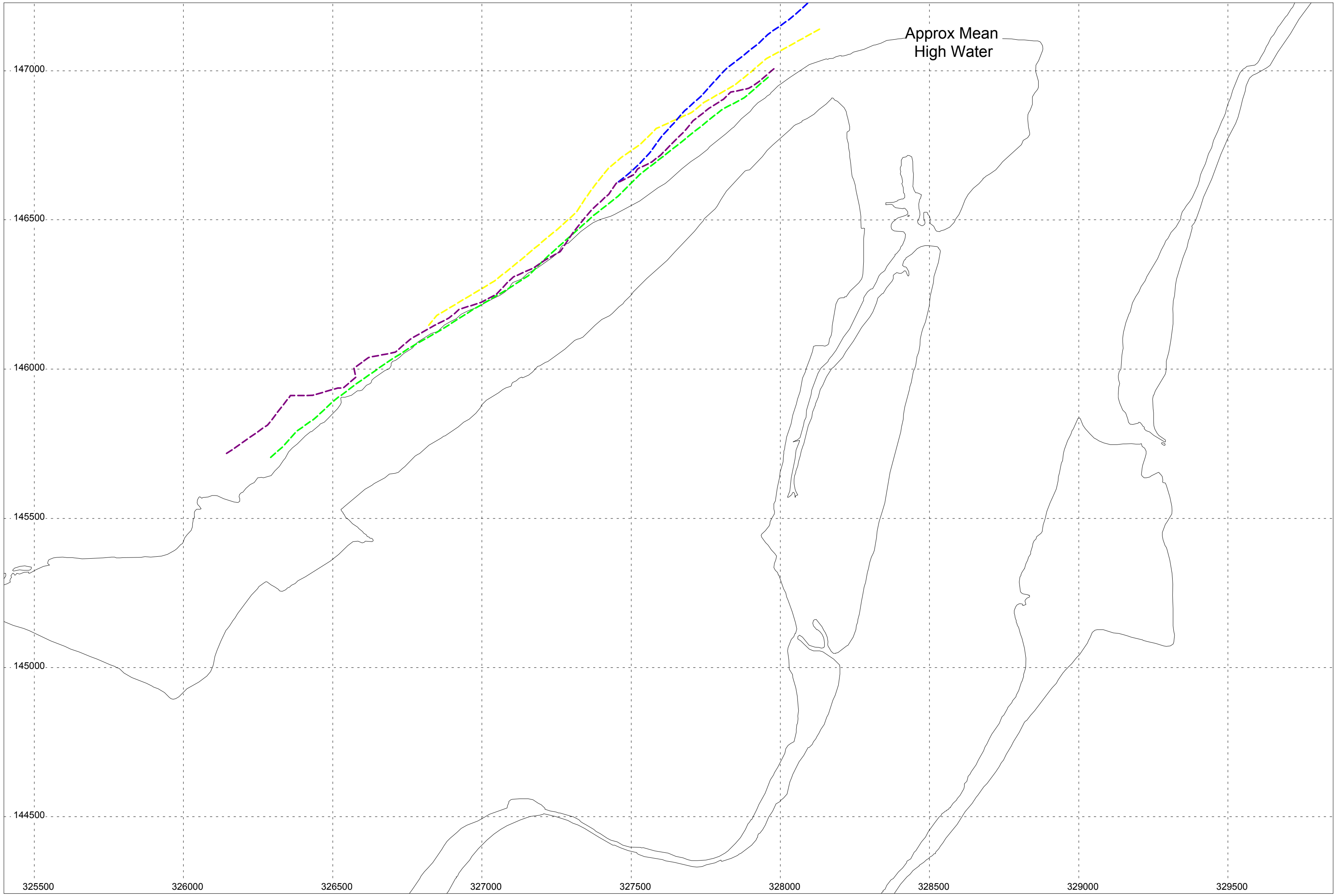

Figure 2 Seaward limits of sparse *Spartina* between 1971 and 1999

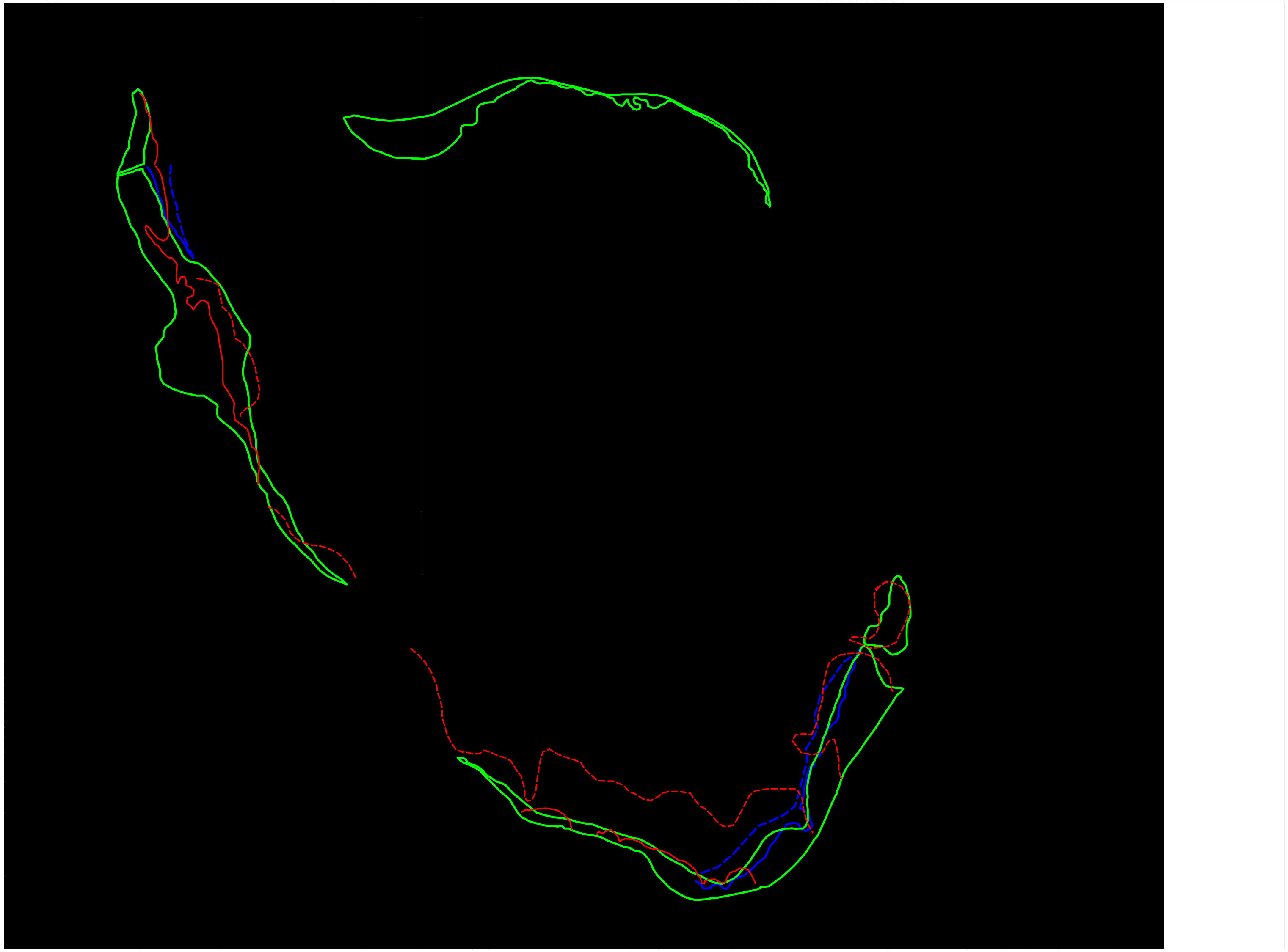

Figure 3 Seaward extent of *Spartina* at Lindisfarne NNR between 1975 and 1999.

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Front cover photographs:
Top left: Using a home-made moth trap.
Peter Wakely/English Nature 17,396
Middle left: Co_2 experiment at Roudsea Wood and Mosses NNR, Lancashire.
Peter Wakely/English Nature 21,792
Bottom left: Radio tracking a hare on Pawlett Hams, Somerset.
Paul Glendell/English Nature 23,020
Main: Identifying moths caught in a moth trap at Ham Wall NNR, Somerset.
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