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Near-future sea level impacts on coastal dune landscapes

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Abstract

Very little attention has been paid to the impact of global warming, especially sea level rise, on coastal dunescapes, despite the fact that these provide natural protection along many of the world's shorelines. This paper reviews likely responses given the IPCC climate change predictions to 2030AD, which include sea level rise in the order of 0.09 to 0.29m. It is envisaged that coastal dunes will react in a variety of ways dependent both on regional and local factors. Rising water levels will increase susceptibility to erosion, but the fate of released sediment, particularly the onshore/offshore partitioning, must depend on morphodynamic antecedence, and the propensity for periodic domain shifts. The release of material at the shoreline may allow construction of coastal dunes, to the point of progradation in some zones. The response of dune vegetation to a warmer, wetter climate is uncertain. Most of the main temperate dune species are C3 plants which given favourable conditions would respond positively to CO_2 enhancement. However local factors may offset such potential gains.

Introduction

Coastal sand dunes provide extensive protection to many of the world's shorelines. The interaction of dunes with the adjacent beach and nearshore provides the essential basis of a stable shoreline, through the regular exchange of nutrients and minerals. Dunes are often regarded as relatively fragile environments, yet a more pragmatic assessment might focus on their adaptability and responsiveness to environmental change (Nordstrom *et al.* 1990). The exact nature of the response of coastal dunes to the projected rise in sea level is still largely a matter of speculation, and it is probable that adjacent dune systems will react in different ways. The aim of this short paper is to discuss the nature and substance of the response of coastal dunes to sea level rise and global warming.

Coastal dunes and sea level

The role of coastal dunes

Coastal sand dunes are one manifestation of a suite of landforms associated with varying water levels. Given an adequate sediment supply, material may accumulate at various locations within a coastal system. Favoured sites include river or estuary mouths which attract sediment in order to achieve hydraulic equilibrium, within shore caustics (or shadow zones), and at the downdrift ends of transport cells (Fig. 1). Under certain conditions marine sediment may accumulate sub-aerially as coastal dunes. Such developments may be triggered by sealevel fall, or domain shifts within the reflective/dissipative continuum. The latter occur when the beach and shoreface angle alters, becoming flat-

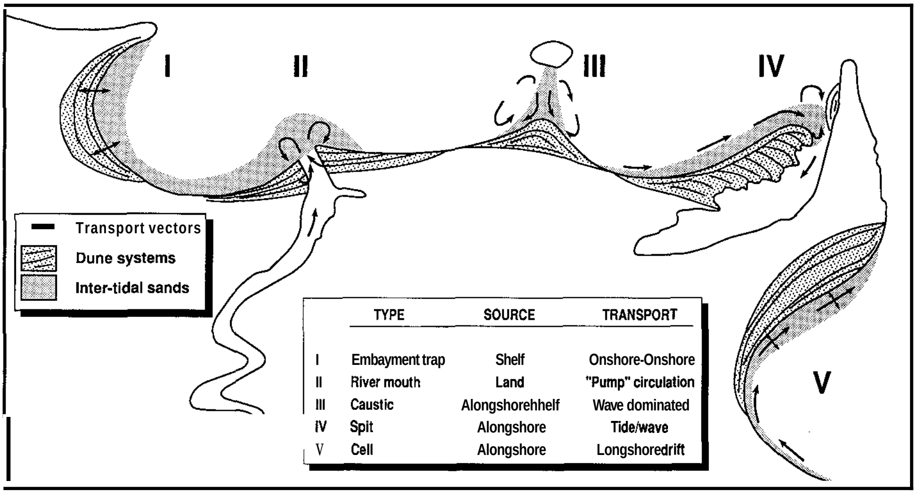

Fig. 1. Five types of coastal deposition zone typically associated with the presence of coastal dunes. In each case excess sediment may be stored sub-aerially. Stabilisation of dunes is strongly dependent on vegetation; in extreme conditions sediment will probably be transferred out of the coastal system precluding widespread formation of marine dunes.

ter or steeper, perhaps due to fluctuations in sediment supply or the opening or closing of a nearby tidal inlet. Such secular variation in beach slope imparts a strong control over the mode (or domain in terms of area) of the form of the breaking waves. Profile steepening leads to more reflective conditions, profile flattening to more dissipative ones, which in turn are associated with types of dune morphology and development (Short and Hesp 1982). On all time scales, sub-aerial storage should be viewed only as a ephemeral process; sediment is constantly exchanged with adjacent environments as energy conditions fluctuate. Thus dunes are eroded during storm surges to replenish the nearshore profile, material is pumped through spit-estuary complexes to retain a hydraulic balance, or overwashed to rebuild barrier islands further inland. The rate of change varies from site to site, but in all cases such processes form part of natural virement within self-compensating coastal systems. The role of vegetation within these episodic but largely cyclic systems is important. Coastal dune vegetation falls into two broad categories, sand-fixing (*e.g.* Atriplex) and sand-building (*e.g.* Ammophila, Elymus, Spinifex). The former is responsible for stabilising surfaces while the latter is involved in accumulating material. The more diverse the ecosystem the more adaptable the dune system will be. The degree of vegetation stabilisation is a primary factor in determining the mobility of the system. The establishment of plants (in terms of both productivity and strategy) is dependent on a variety of stressed ecological gradients (Carter 1988; Crawford 1989). The degree of vegetation stabilisation is also reflected in Short and Hesp's (1982) morphodynamic classification of coastal foredunes. Inland or established dunes often show a wide diversity of both morphology and vegetation. Ecological maturity is often represented by a succession towards terrestrial plant associations, perhaps dominated by heathland, coniferous or deciduous woodland or freshwater wetland.

Dunes also play an important role in regulating coastal groundwater. **A** permeable dune system tends to support a freshwater lens, which provides a barrier to landward salt intrusion. The freshwater lens is recharged both by direct precipitation and allogenic streams, and is discharged under low piezometric pressures into the beach or nearshore zone. The size of the freshwater lens depends on the precipitation regime, possible artificial recharge and the geometry of the dune system, particularly the height of ridges.

Very extensive dune systems have formed at various times in the geological past. Perhaps the most favourable conditions for the development of coastal dunes include an abundance of sediment, a variable climatic and/or wave regime and a slowly falling sea level. However where sediment is abundant, extensive dunes do form under rising sea levels. Reworking and release of shoreline materials may lead to the formation of major dunefields, as for example in The Netherlands (Jelgersma *et al.* 1970). Local factors such as the dominance of onshore winds and a high tidal range may also be significant. Many of the Holocene dunes of Europe are formed of glaciogenic Pleistocene sands which have been reworked and incorporated into the coastal system. The most extensive dune fields are either adjacent to river mouths or estuaries with high sediment loadings (Rhine, Gironde, Tagus) or adjoining shorefaces and shelves strewn with glacial debris. Many dune systems show evidence of reactivation phases between stable and unstable morphologies (*e.g.* Orme 1990; Tooley 1990). Phase transitions may be triggered by numerous causal factors, including human activities, fire, sediment budget fluctuations, vegetation cycles, climatic change or sea level oscillations.

Coastal dunes develop as accumulating systems with very positive sediment budgets (*i.e.* input far exceeds output). Outputs may arise from the returning of sediment to the coastal system, or through landward eolian transfers, or by human activities (sand mining). A negative budget leads to a dissected dune system, characterised by erosional landforms (blowouts, deflation hollows and plains, reactivation dunes, scarping) (Carter *et al.* 1990). Often eroding dune complexes support small areas of accumulation, which develop by 'cannibalisation' of primary landforms. Many European dunes, especially on windward coasts are of this nature.

Near-future climatic changes and sea level rise

The last decade has been one of intense speculation over the impact of global warming. The general prognosis is that likely increases in radiate energy-absorbing gases (CO_2, NH_4, NO_x, water vapour, CFCs) will result in temperature increases in the order of 1.0 to 1.5°C by 2030 (Houghton *et al.* 1990), although there are marked regional differences, some of which suggest rises two or three times the average estimate. Other probable climate changes include small increases in precipitation (10 to 15% is typical) and the frequencies of extreme events, like storms or droughts.

The doubling of atmospheric CO_2 will have a direct effect on the growth rate of plants, through the enhanced accumulation of carbohydrates during photosynthesis. In an enriched CO_2 environment, photosynthetic rates may increase up to 100% (Pearch and Bjorkman, 1983). There are important metabolic differences between species, so that some plants respond more readily to rises in CO_2.

One obvious consequence of global warming will be sea level rise. Over at least the last 150 years and probably for much of the late-Holocene, world sea level has been rising slowly. Estimates vary (Pirazolli 1989), but a consensus figure would be 1.0 to 1.1 mm/year, although this can be substantially different in areas experiencing tectonic subsidence or elevation. As yet, there is very little evidence of an acceleration of sea level due to global warming (Woodworth 1990), although the recent Intergovernmental Panel on Climatic Change (IPCC) estimated range of anticipated rises from 0.09 m (low) to 0.29 m (high), with a best guess of 0.18 m between 1985 and 2030 (Warrick and Oerlemans 1990). All these estimates envisage a dramatic acceleration with rates from 1.9 to 6.4 mm/year, between two and seven times the 1890 to 1990 levels.

Rising sea level will have a direct impact on coastal processes, effectively raising the plane of activity from which waves operate. This may be most evident during storm surges, when the frequency of attack at any level will increase markedly, so that the so-called 1 in 1000 year flood height in 1990 might reduce to the 1 in 30 year flood height by 2030 (Wigley 1989). Such increasing frequencies could lead to amplification of coast erosion, flooding and avulsion, as well as a general enhancement of sediment fluxes. Dunes which have been 'fixed' by ecological and engineering techniques may, at first, be less vulnerable to sea level rise. Erosion will be limited although eventually steep cliffs will form and perhaps fail as semi-cohesive materials (Carter 1980). Thus the pattern

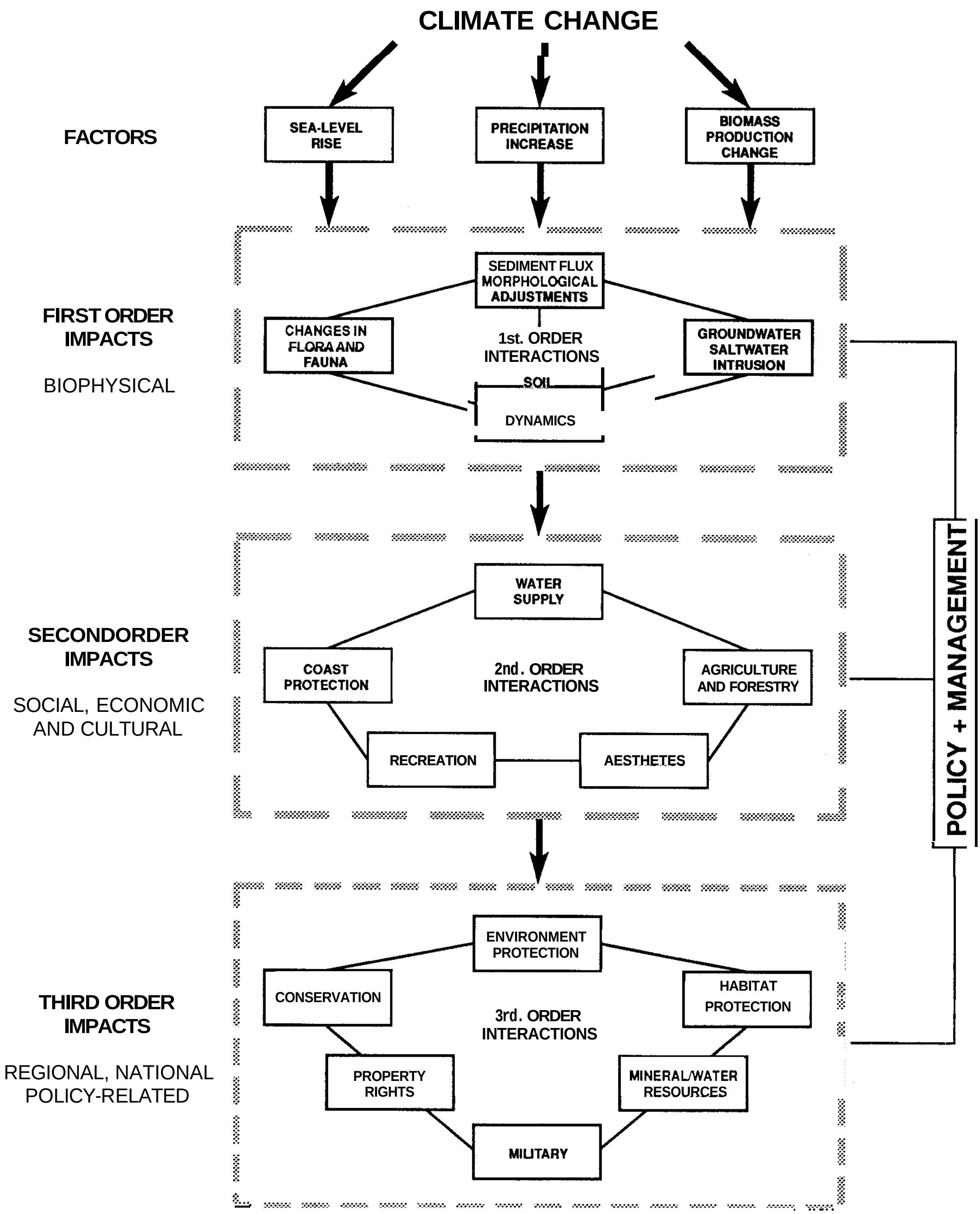

Fig. 2. **A** hierarchical (multi-level) response system for the impact of climate change on coastal dunes. Within each level there are interactions. Management needs to be integrated across all levels.

of erosion may move from near-continuous on unfixed dunes to more episodic on fixed examples. Yet once instability dominates the response of both fixed and unfixed dunes should merge. Coastal aquifers could alter, perhaps through saline intrusion or increased pressure on the freshwater lenses.

Impact of sea level rise on coastal dunes

General considerations

Very few studies have considered the specific problems of sea level rise and coastal dunes although the importance of sea level changes to their evolution is noted by many authors (*e.g.* Jennings 1963; Short 1988). Those that have tackled the subject (*e.g.* Christiansen *et al.* 1985; Christiansen and Bowman 1986; Boorman *et al.* 1989; Meulen 1990) identify a range of likely impacts to the geomorphology, flora and fauna.

Over the last decade there has been an increasing emphasis on understanding the interactions of climate change on the natural environment. Parry (1990) notes the increasing complexity of impact/interaction models, culminating in hierarchical structures, within which biophysical, socio-economic and cultural issues are addressed. Thus with coastal dunes (Fig. 2), it is possible to define first, second and third order impacts, each supporting various interactions. Supplementary to this integrated approach is the adjoint method which identifies the sensitivity of attributes to various impacts, and describes the likely response pattern. For example, foredune erosion under a constantly rising sea level may proceed intermittently rather than progressively. Other processes, perhaps blowout growth and decay, may adopt a more cyclic or hysterytic form. The adjoint method allows exploration of these non-linear behaviours to relatively simple functions.

*The impact of sea level rise **on** foredunes*

The concept that dunes are eroded during storms to replenish beach levels has been known since the mid-nineteenth century (see Carter 1988). Sometimes the beach-dune exchange system is so well-balanced that storm losses equal interstorm gains, and the net shoreline movement is zero (Psuty 1990).

Dune erosion tends to occur during positive surges, when high tides, onshore winds and low barometric pressure coincide. Surges are normally distributed as positive or negative residuals from predicted astronomical tide levels (Flather 1987). As sea level rises, so surge return periods at specific heights will decrease (Fig. 3), suggesting that dunes will be eroded more frequently. Because dunes comprise comparatively low-strength materials with a relatively fast reaction time (time taken to respond to any perturbation) and short relaxation time (time taken to reach a new equilibrium – see Allen 1974), erosion rate will probably remain proportional to the rate of sea level rise. Several site factors will influence erosion, including surge type, sediment texture, hydrostatic and hydrodynamic conditions, although as Van der Graaff (1986) notes, the surge water level height is the most critical, accounting for over 80% of the variance in his studies. Hughes and Chui (1981), in a series of detailed experiments, point out that maximum erosion often occurs in advance of the surge peak, before the beach profile has time to adjust to the increased energy levels.

In the simplest, two-dimensional cross-shore case, adjustment to rising sea level will probably be achieved by dispersal of the eroded-volume across the nearshore and inner shoreface, to depths commensurate with the wave base. This equates to the basic Bruun-type adjustment (Bruun 1962), see figure 4A. All shoreline erosion products are moved seaward to re-establish the equilibrium profile under the new sea level. This, however, is an asymptote, which is unlikely to prevail as some sediment will be transported into deeper water, onshore or alongshore. More realistic is the notion that a proportion of eroded material will move landward, onto the foredune or beyond. Often, sediment released by erosion is returned rapidly to the dunes (within weeks), and some of this will move landward at the crest, either over or through the foredunes (Carter and Wilson 1990; Hesp 1990).

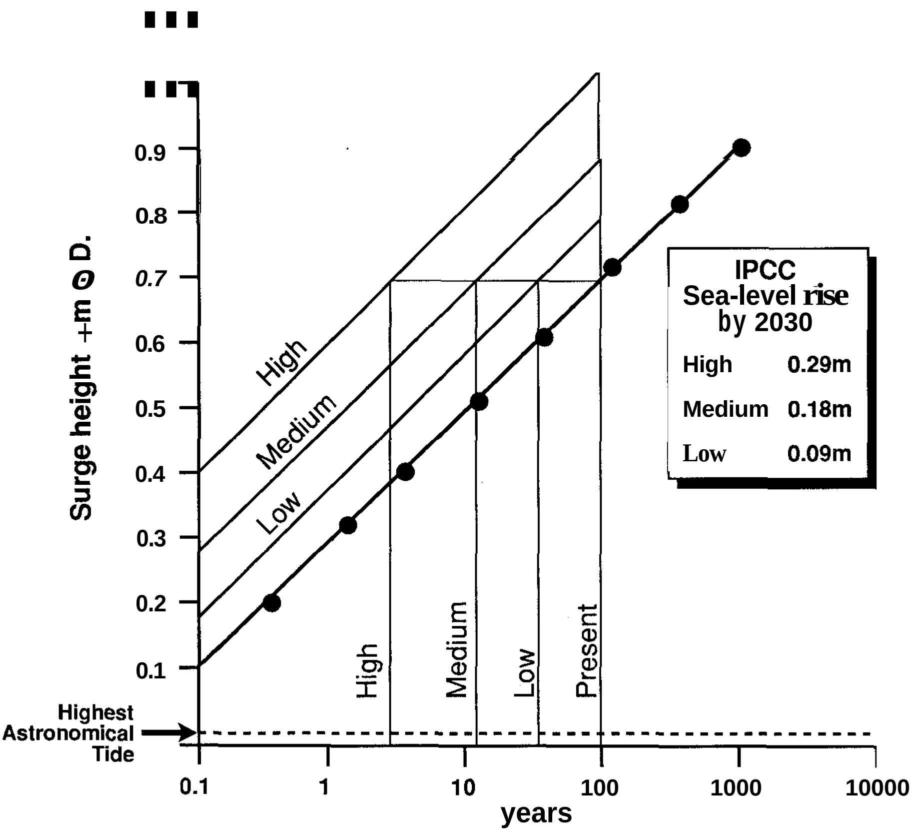

Fig. 3. Rising sea level will reduce the return period of events (notably erosional storms) at specific levels. In this example the 1 in 100 year level (0.7 m) under 'normal' circumstances (1990), **will** become the 1 in **3** year level by 2030, allowing far more frequent wave attack of the shoreline

In Fig. 4B the eroded volume is balanced by that deposited both to landward and seaward. Thus the dune moves up and landward as the sea level rises. An accreting dune under a rising sea level will transform into sharp-crested form, substantially altering the near-ground airstream. Ultimately a dynamic balance will be achieved between the accelerated air flow, the relief and the flux of sediment over the crest, for any degree of vegetation cover. If vegetation is either absent (as in arid settings) or ineffective (through engulfment), then a transgressive dunefield may evolve (Fig. 4C).

Perhaps the most intractable problem in the model of foredune response to rising sea level is what decides the net amount of sediment which will be transported landward and seaward. Such a process must depend at the primary level (dependent on sea level change) on the morphodynamic domain of the nearshore zone (and the frequency and magnitude of storms), the rate of sea level rise and the relative proportions of coarse and fine sediment. The landward return of sediment would be facilitated on a modally dissipative beach that experiences occasional perturbation to reflective or reflective-intermediate states (see Wright and Short **(1984)** for terminology) as shown in I and **II** on Fig. 5. The left hand side of Fig. 5 shows the modal state (shaded) and the various transitions that will occur over a range of dissipative and reflective nearshore morphologies (shown on the right) subjected to sea level rise. A key element appears to be the range of transition trajectories (shown by arrows in the matrices), allowing both the release of sand-sized sediment and a mechanism for moving it landward. In most other modally-dominant settings (III–V) it is possible to envisage a largely offshore movement of

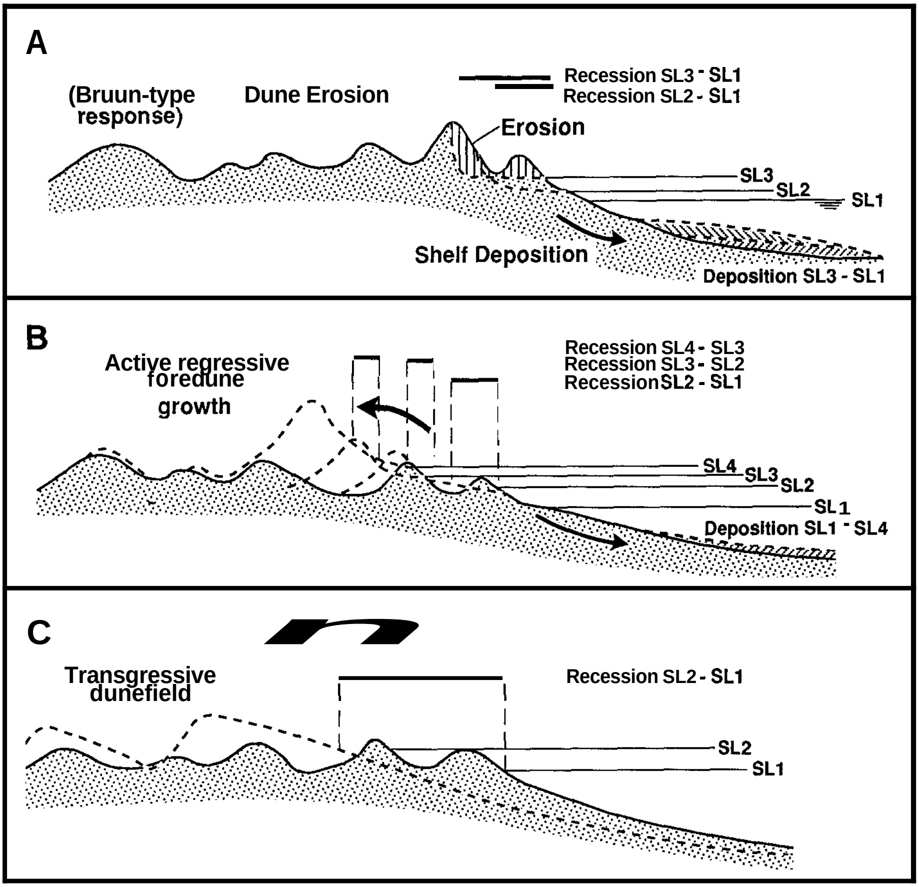

Fig. 4. Three simple models of cross-shore response. In **A**, sediment moves offshore to replenish the shoreface (Bruun-type response), in B, sediment is transferred inland and trapped by vegetation, while in C, vegetation is either absent or becomes ineffective leading to a large-scale transgressive dunefield, most likely with transverse and parabolic dunes.

material. The cross-shore redistribution may be moderated by the presence of significant proportions of coarse, immobile material. At the secondary level (independent of sea level change), factors relating to the beach/dune environment assume more importance. These include local wind regime (especially the proportion of transport-effective winds), the morphology of the beach and the effectiveness of sand trapping vegetation.

Impact of sea level rise on dune systems

In many cases it is not realistic to consider simple cross-shore partitioning of sediment as sea level rises. Far more likely is that a three-dimensional (longshore and cross-shore) redistribution will occur, with material moving within an erosional front (Orford *et al.* 1991). Thus sediment starvation in one area will be countered by sediment accumulation in another. One of the most likely zones of accumulation will occur within re-entrant embayments or at the distal extremities of spits. Here rapid foredune progradation may take place, particularly if the nearshore/beach morphodynamics favour the welding of beach ridges in the upper intertidal zone. The rate of progradation may well increase concomitantly with an accelerating sea level rise as more sediment becomes available. Growth may be limited only by allogenic factors such as topography, the need to maintain cross-shore discharge and the breakdown of the longshore transport system. Ulitmately, these adventitious dunes may themselves be reworked as a rising sea level encounters them.

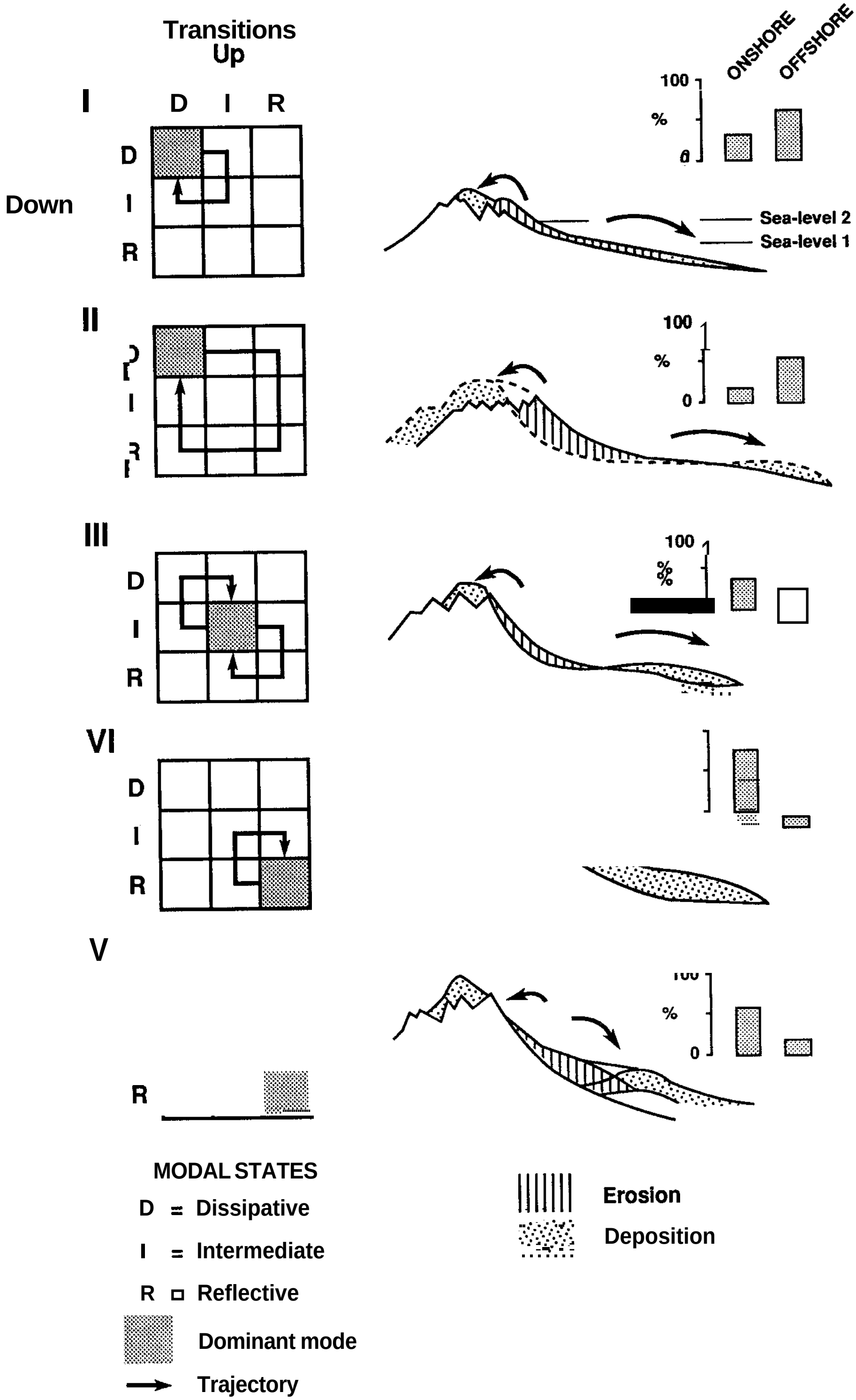

Fig. 5. The ratio of onshore/offshore sediment release partitioning will depend to a large extent on the domain structure/dynamics of the nearshore zone. In I and II a modally-dissipative nearshore is perturbed on occasions, allowing landward dispersal. In III, **IV** and V the tendency for landward dispersal declines and is replaced with seaward movement.

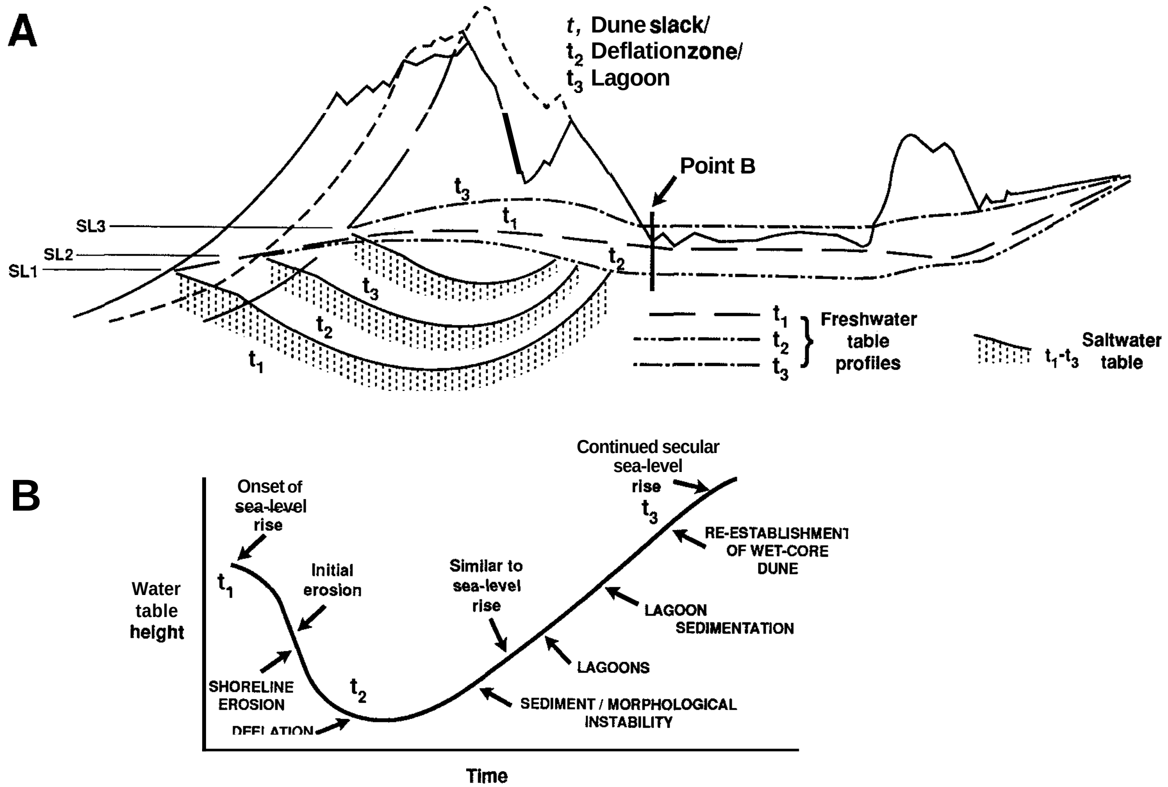

Fig. 6. A. The response of groundwater to long-term shoreline erosion in a dune system. B. A graphic representation **of** water table height over time through a phase of sea level change.

The physical alteration of the dune system under rising sea level is also likely to be reflected in the groundwater hydrology (Meulen 1990; Noest this issue). The rising or falling of the water table, irrespective of changes in precipitation, may trigger internal geomorphic changes (Fig. 6A). For example, a fall in the water table may result in renewed deflation and enhanced mobility in internal sand, which in turn may lead to further physical alterations. As erosion proceeds water tables may fall, so that existing wet-core dunes will become dry. In time, however, rising sea level may offset and reverse this, initial fall. If, in the interim, interdune areas have become deflated then temporary lagoons may form, possibly to be refilled with water-lain sediments. Figure 6B charts these phases of relaxation and reaction through any sea level rise event.

Sand dune vegetation

Although much has been written about the reaction of vegetation to global warming and CO_2-enhancement (*e.g.* Bolin *et al.* 1986; Fantechi and Ghasi 1989), very little has dealt with coastal ecosystems. In the case of dunes there are several interrelated points to consider, namely i) the metabolic response of the plants to CO_2-enrichment, ii) the community response, including competitive plant strategies, iii) the reaction of species to changing physical conditions including increased sand supply to the foredunes and, perhaps, changes in precipitation and groundwater.

Most plants grow better in a CO_2-enriched environment, reaching photosynthetic optima at different saturations. Ammophila and Elymus, the major dune forming grasses, are C3 plants, the most common pathway among higher latitude species (Smith and Brown 1973). In these, CO_2 is used for photorespiration, in which CO, is first fixed as a carbohydrate before reoxidation. Initial synthesis is to a three carbon atom product. C3 plants reach optimal production of 60 to 80 mg CO_2/0.1 m^2/ day (about twice current levels) somewhat above C4 plants, which have advantages in lower latitude, higher temperature environments. Thus one might expect, if other factors remain unchanged, that dune grasses will grow more rapidly as global warming proceeds.

Increased production, perhaps **30** to 40% above present levels may be further stimulated by increases in wind blown sediment and, in NW Europe by the 10 to 15% increase in precipitation forecast by the IPCC (Houghton *et al.* 1990). Plants may be able to survive greater burial; at present Ammophila species appear to be able to maintain growth up to about 0.6 m of accretion per year (Disraeli 1984; Carter 1988). Together these factors may lead to an increase the rate of sediment accumulation in vegetated foredunes, which Carter and Wilson (1990) suggest may be around 8–12 m^3/m shoreline/year under favourable conditions. However, against this, dune vegetation may suffer from increasing drought due to enhanced levels of evapotranspiration, and more competition for relatively limited nutrients. Generally, as Crawford (1989) notes, dune vegetation occupies a highly stressed environment, in which productivity is restricted by numerous factors operating over scales from individual plants to entire regional dune fields, so that a simple discussion of CO, optima is potentially misleading. Progressive destabilisation of dune systems as sea level rises is likely to occur, with increases in blown sand triggering widespread ecological adjustments. How well the vegetation responds to such changes may be resolved only at site level.

Summary

The future of coastal dunes under rising sea level is still very much open to question. It is possible to identify possible changes, most of which indicate increasing instability and change. As water levels rise, so shoreline erosion will release large volumes of sediment. Some of this material is likely to accumulate onshore, either augmenting existing ridges or forming new ones. The response of vegetation will be crucial. Although a general outlook suggests the productivity and thus survivability and effectiveness, will increase, the growth of dune vegetation is ecologically constrained and more exact predictions are difficult. It is possible to envisage a broad spectrum of responses ranging from progradation of new foredunes to the remobilisation of coastal sand sheets. Managing such a diverse range of impacts will require considerable scientific evaluation and assessment. It is unlikely that conventional engineering techniques will suffice, and it may be essential to encourage a more dynamic environment, unfettered by economic demands, if dunes are to fulfil their full potential as natural, front-rank coastal defences.

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