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Quantifying landscape-ecological succession in a coastal dune system using sequential aerial photography and GIS

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Abstract. This contribution presents an attempt to measure the path of habitat and vegetation succession in a coastal dune system (Kenfig Burrows, South Wales) using remote sensing and GIS. The loss of slack habitats associated with the continuing stabilization of this dune system is a major cause for concern. These habitats support a range of plant species, including the rare fen orchid, *Liparis loeselii,* as well as other hydrophytes. A decrease in their areal extent implies a reduction in biodiversity. To quantify the overall rate and spatial dimension of these changes, a series of aerial photographs dating from 1962 to 1994 were digitized and analysed in an image processing system. The resultant maps, transferred to a vector-based GIS, were used to derive a transition matrix for the dune system over this period of time. The results indicate that there has been a marked reduction in the total area of bare sand (19.6% of the dune system in 1962, but only 1.5% in 1994) and a decline in both the areal extent and the number of dune slacks. Over the same period of time, there has been an increase in *Salix repens* dominated habitats, at the expense of pioneer species. Analysis of the habitat maps, together with hydrological data, within the GIS suggests that even the dry slacks have the potential for further greening and to support invasive species. In terms of habitat management, however, there is still scope to restore many of the slacks to their original state. It is estimated that at least 24% of the area occupied by partially and moderately vegetated slacks could be rehabilitated.

Keywords: Biodiversity; Dune slack; Dune stabilization; Dynamical landscape; Kenfig Burrows; *Liparis loeselii*; Multispectral image.

Introduction

The coastlines of the world, over 440 000 km in length, represent both a dynamic natural environment and an important context in which a diverse range of human activities, as well as geomorphological and biological processes, interact. Apart from their economic and recreational importance, coastal zones assume significance for the following reasons: (1) there is often high diversity – both biodiversity and landscape diversity – in a very small area; (2) they are active in both geological and geomorphological terms; and, (3) they offer an important – quite often unique – habitat for animals and plants. Owing to the increasing pressures on coastal areas in the form of recreation, pollution and mineral extraction, the need for integrated coastal zone management (ICZM) is increasingly evident. One of the main aims of ICZM is to resolve the issues and conflicts relating to the various pressures outlined above, while considering the requirements for nature and landscape conservation.

Issues of biodiversity and nature conservation are perhaps most pronounced for dune systems, which form ca. 20% of the area occupied by world's coastal land forms and which are especially rich in species of plants and animals. Coastal dune systems also offer particularly suitable sites to study the ecological significance of the life cycles and growth form of plants. This is because, unlike many other terrestrial habitats, they frequently provide sites that are in a state of succession: thus, they combine the special interests of a successional sequence and, because the process of dune formation is often continuous, they may contain the earliest phase of succession as a permanent feature of the area. These features not only make them areas of special research interest, but have also led to some of them being categorized as Protected Areas. Biodiversity, however, the key to ecological equilibrium, can only be maintained in coastal dune systems where dune and vegetation succession are active and ongoing. The over-stabilization of coastal dunes – often as much a problem as erosion – leads to a loss of biodiversity

Accurate vegetation and habitat maps are essential prerequisites to an improved understanding of the problems associated with dune landscapes, to monitor vegetation succession therein and, hence, to plan and institute effective conservation and management programmes. They can form the basis of, and produce the spatial dimension to, resource information systems and change-detection techniques. Conventional surveying techniques and *in situ* measurements clearly have an important role in producing such maps, but they are time-consuming, manpower-intensive and, hence, expensive C particularly in the context of long-term monitoring programmes. For this reason, attention is increasingly being focused on the use of airborne and satellite remote sensing data, combined with the spatial analytical capabilities of modern Geographical Information System (GIS) technology. Hartog et al. (1992), for example, combined aerial photography and GIS to derive transition matrices in a study of the succession of dune vegetation structure resulting from changes in the level of groundwater in the Amsterdam Waterworks dunes. They present ideas as to how these data can be used to analyse spatial patterns on the dune surface and to model landscape succession. Similarly, Davis et al. (1994) provide an account of the use of remotely-sensed images (Landsat-TM data and aerial photographs) and GIS technology to characterize vegetation communities in SW California. The authors demonstrate how a vector-based GIS, combined with remotely-sensed data, can be used to produce improved landscape-ecological maps compared to those generated using traditional mapping and manual cartographic procedures.

Study area

The study area examined in this contribution is the Kenfig Burrows National Nature Reserve (Kenfig) in S Wales (Fig. 1).

Kenfig is a remnant of a much larger sand dune system that once stretched along the coast of south Wales from the River Ogmore to the Gower Peninsula C was established as a Site of Special Scientific Interest (SSSI) in 1977 and, at 600 ha, is one of the largest of the 50 National Nature Reserves in Wales. It contains 575 plant species, of which 550 are native to the UK. Of these, 50% belong to the native Welsh flora and 23 are nationally scarce species. Kenfig is, however, experiencing a reduction in biodiversity due to the continuing stabilization of the dune system. The three main consequences of the stabilization process are that: (1) there has been accelerated succession towards a dune-heathland climax, due to the expansion of vegetated areas at the expense of areas of mobile sand; (2) sand mobility has almost stopped; and (3) the surviving pockets of original dune habitat are increasingly fragmented and isolated. The significance of the loss of biodiversity associated with over-stabilization is highlighted by reference to a number of important plant species.

- Kenfig is the stronghold of the rare and declining fen orchid, *Liparis loeselii*, supporting more than 95% of the total British population. This species is the only higher plant occurring in Britain to be listed as a priority species in Annex II of the original EC Habitats and Species Directive. It is also listed as requiring protection under the 1992 Bern Convention and is on Schedule 8 of the Wildlife and Countryside Act, 1992. Despite this, it is still in decline in Britain. At Kenfig, it occurs in wet dune slacks which are being invaded by *Salix repens*, *Phragmites australis* and *Hippophae rhamnoides* (Jones 1992)
- *Ammophila arenaria* (Marram grass) in the foredune areas is declining due to competition from other plant species.
- *Rumex rupestris* and *Limosella subulata*, both pioneer species, are now almost lost.

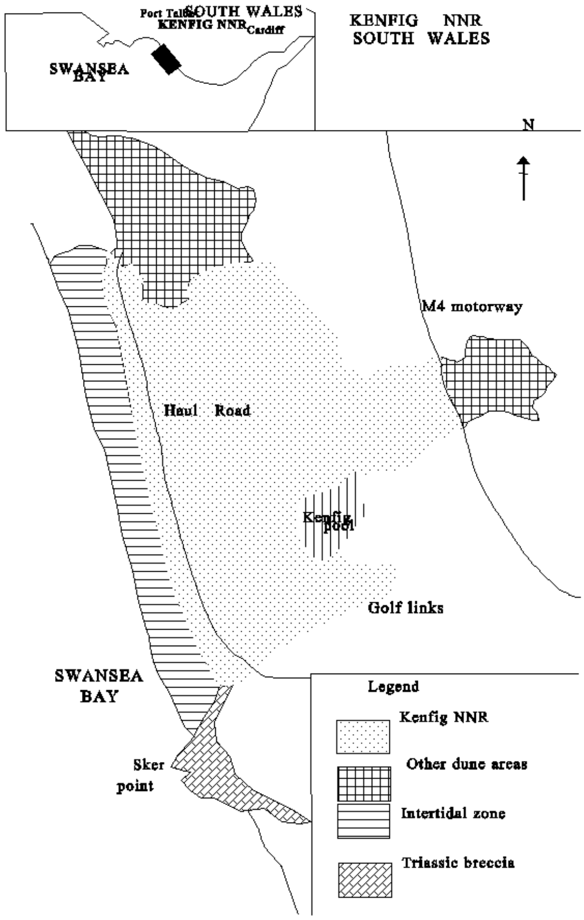


Fig. 1. The Kenfig Burrows National Nature Reserve in S Wales

To help conserve biodiversity and to preserve the unique nature of the Kenfig dunes, there is a pressing need to monitor and understand vegetation and dune succession in the area, including the processes that have led to the present succession towards a dune-heathland climax status.

Table 1. Details of aerial photographs used in the study.

Year	Type	Scale
1962	B/W Panchromatic	1:10 000
1971	B/W Panchromatic	1:5000
1991	Colour	1:10 000
1994	Colour	1:25 000

Aerial photography and aerial photo-ecology

The need for plant ecologists to study the vegetation relationships of entire regions was emphasized as early as 1926 (Howard 1970). Today, this regional approach is encouraged by applying aerial photographs and satellite imagery to the study of both vegetation and terrain. It is at the level of macro-ecology that aerial photographs are most valuable where they help to correct the imbalance between plant geography and plant ecology. Aerial photographs can be used to identify and delineate plant assemblages at the physiognomic or formation levels (Howard 1970).

The concept of a *photo-community,* refers to a distinct assemblage of plant species discernible in (stereo-pairs of) aerial photographs at a specified scale. This concept, however, has its limitations, since the photo-community varies not only with scale but also with several other factors such as photo texture, tone etc. In this study, the photo-community concept has been used to a limited extent, but the emphasis has been more towards the delineation of habitats and vegetation densities. The vegetation types corresponding to the habitats have been inferred with the assistance of recent vegetation maps and ground checks.

Methodology

The methodology adopted in this study is similar to that used by Hartog et al. (1992). Thus, we have visually interpreted the aerial photographs (Table 1) based on the keys developed by Hartog et al. (1992), although these will not be described here. Fig. 2 shows aerial photographs of the northern part of the study area acquired during 1962 and 1994.

Clearly, there are limitations to the ability to identify and map the many types of vegetation species and communities in Kenfig NNR using panchromatic or colour aerial photographs, the most important ones being the spatial scale and spectral limitations of these media.

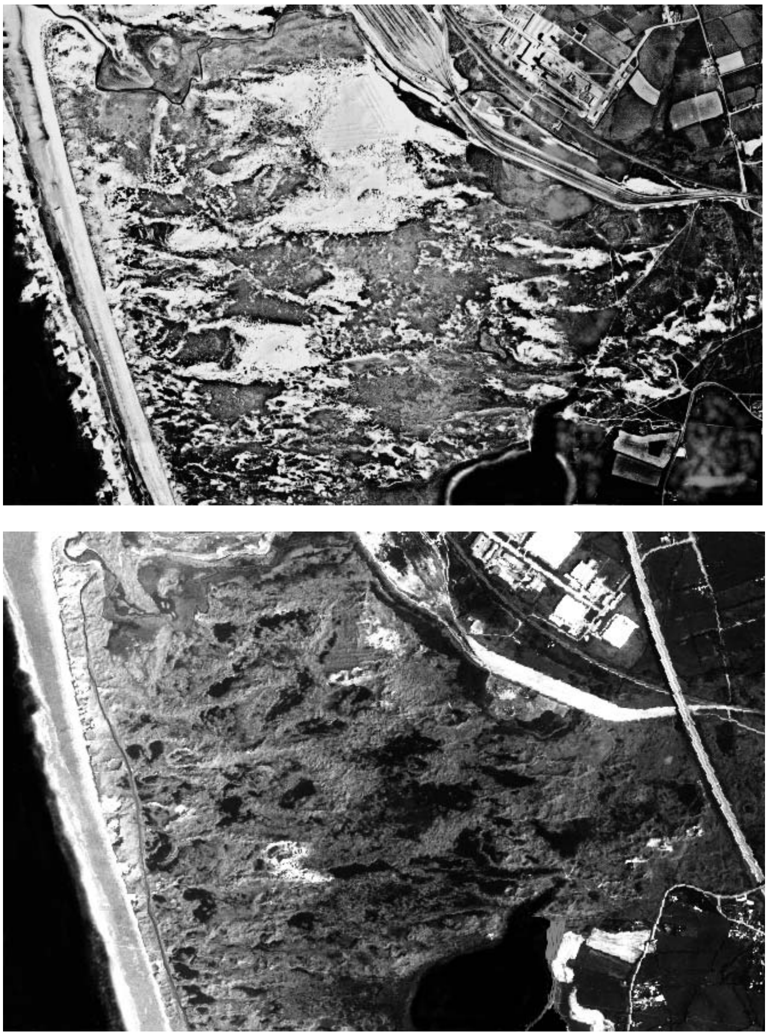
As mentioned earlier, the focus of studies of ecological diversity and nature conservation has shifted from species to habitats, with this change in emphasis accelerating in recent years. This general observation is also true for Kenfig, where loss of habitat has been the major cause for concern among the nature reserve managers. Consequently our aim has been to map habitats based on a visual assessment of vegetation density and structure in aerial photographs. Taking into account the nature of the study, the scale of photographs used, and the structure of the vegetation at Kenfig, a simplified classification of habitats was produced (Table 2).

The habitat maps generated from the aerial photographs were digitized using a semi-automatic approach involving scanning, conversion to grids, and then semi-automatic digitizing. The vector coverages generated in this way were subsequently geo-referenced, co-registered and rectified with reference to control points derived from Ordnance Survey maps of 1:10000 scale.

The Haul road which runs parallel to the coast along the western margin of the reserve was laid after 1962 and has had an influence on the morphology of the dunes, vegetation and hydrology of the adjoining areas (Jones 1993). To have a common area of study before and after 1962, the Haul road has been used as the western boundary and has been superimposed on the habitat map of 1962. A similar procedure was adopted using the M4 motorway as the eastern boundary which is present in the 1991 and 1994 photographs but not in the 1962 and 1971 photographs. Each parcel of a given habitat is thus a closed polygon in a coverage. The vector coverage for a given year comprises a number of different layers, where each layer contains polygons representing the parcels of a given habitat. The attributes of each polygon in any given coverage include its area, perimeter, habitat type and hydrotype (Fig. 3).

Table 2. Classification key of habitats used in this study and their corresponding NVC types.

Habitat classification	Corresponding NVC types
OS = Open sand	Mobile dunes SD4-SD6
PVD =Partially vegetated dunes	Semi-fixed dunes SD7a-SD7g
MVD = Moderately vegetated dunes DVD = Densely vegetated dunes	Dune grassland SD8, SD9 and SD12
PVS = Partially vegetated slacks MVS =Moderately vegetated slacks DVS = Densely vegetated slacks	Dune slacks SD13-SD17
WL/S = Woodland/Scrub	Scrub and Woodland SD18 and W



a

b

Fig. 2. Aerial photographs of Kenfig Burrows acquired during (**a**) 1962 and (**b**) 1994. Note the presence of the Haul Road in the west and the motorway (M4) in the east in the 1994 photograph.

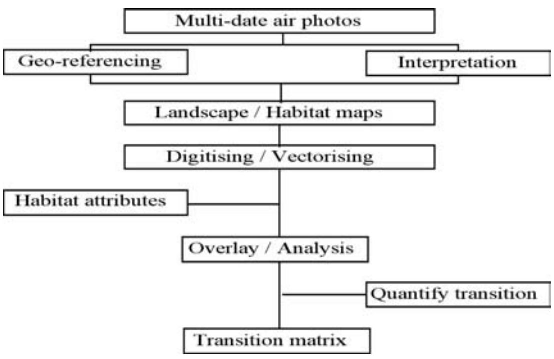


Fig. 3. Schematic representation of research methodology.

Vector GIS and dune-landscape succession analysis

Overlays were produced of the individual habitat maps for each year considered in this study. The resultant change vectors present a vivid picture describing the type of successional changes that took place between 1962 and 1994. The changes are reflected not only in terms of an increase or decrease in the areal extent of individual habitats, but also in terms of partial or complete change of each habitat parcel into another stage in the successional sequence.

To understand the nature of landscape/habitat succession, each habitat was compiled as a separate layer (i.e. vector coverage) and overlays were constructed between corresponding layers from different years. A total of 156 vector coverages, representing all the habitat/landscape types for the four years in consideration, were generated. Fig. 4 is an example of a vector coverage containing the eight habitat/ landscape types. The

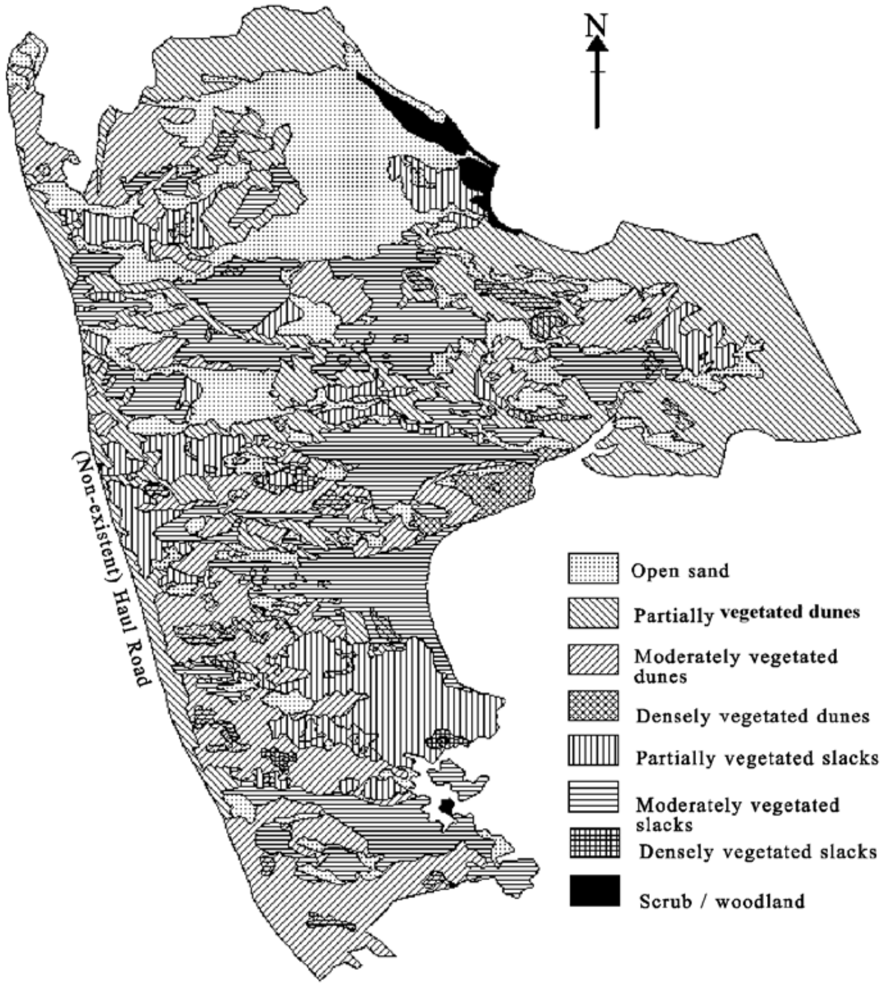


Fig. 4. An example of a digital vecto erage of the landscape/habitat map o Kenfig Burrows National Nature Res derived from aerial photographs acqu in 1962.

areal extent of each of the habitats/landscape types was computed for each of the years studied. The results confirm that there has been a general greening of the dune system since 1962. In other words, there has not only been a substantial decrease in the areal extent of open sand/mobile dune, but also a reduction in the generation of dune slacks and an increase in the biomass on existing slacks. The most likely explanation of this is that there has been a decrease in the mobility of the dunes, as a consequence of over-stabilization.

A quantification of the change brought about in the dune system over the years, described qualitatively above, is given in Fig. 5. This shows that about 20% (ca. 82 ha) of the study area within the reserve was covered by mobile sand during the early sixties, but that this had reduced to a mere 1.5% (6.5 ha) by 1994. Similarly, the areal extent of the partially-vegetated sand/dunes (PVD) reduced from 26% in 1962 to 2.7% by 1994. On the other hand, the area of moderately vegetated dunes (MVD) increased from 18.7% to 56.8% over the same period of time.

In the case of the dune slacks, the partially vegetated slacks have reduced in extent from ca. 12% to 1.6%: this is a result of their transition into more densely vegetated slacks (0.24% in 1962 to 5.65% in 1994). The slacks also have a tendency to transform into woodlands, the area of which has increased eightfold. Table 3 provides an overview of the changes in the spatial structure of vegetation in the dune and slack habitats. A more detailed analysis of the successional changes for specific habitats, inferred from Table 3, is as follows. In 1994, the open sand (OS) cover had reduced to 5.6% of its areal extent in 1962. This was due to development of vegetation on the dunes.

Thus, 8.8% of the open sand habitat had been transformed into partially vegetated dune habitat, 64.5% transformed into moderately vegetated dune, and 0.6 % to densely vegetated dune by 1994. While this general

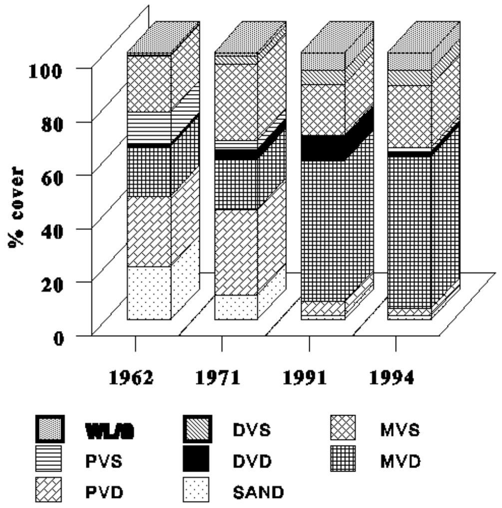


Fig. 5. Transition diagram showing changes in the type and the areal extent of landscape / habitat units between 1962 and 1994. For abbreviations see Tables 2 and 3.

trend indicates the greening and stabilization of the dunes, there is also evidence of some erosion/dune mobility which has resulted in the conversion of 1.2% of the partially vegetated dunes into open sand. Analyses of the change vectors between 1971 and 1991 show that the geomorphological process of erosion/dune mobility seems to have almost ceased sometime after 1971.

A similar analysis for the dune slacks shows that significant erosional/dune mobility processes were in operation during 1962 and for some years later, resulting in certain areas of the slacks being converted to dune habitats. By 1994, however, 24.7% of the partially-vegetated slacks (PVS) had been converted into moderately vegetated slacks (MVS). This conversion was principally along the periphery of the slacks. Comparison of vegetation growth on the dunes and in the slacks indicates that the dunes were greening at a faster rate than the slacks. In the dune habitat, the areal extent of PVD conversion to MVD is higher than any other type of habitat conversion. The rate of succession towards densely vegetated dunes (DVD) and scrubland is not as effective as the succession towards moderately vegetated dunes (MVD). Field observation showed that MVD habitats could easily be restored to OS status by mowing or removing the vegetation cover. Restoration of DVD into OS is more difficult as it involves intensive, repeated mowing and complete removal of *Hippophae* (including the roots) by manual cutting and injection of herbicide into the roots.

The interest of the managers of the NNR lies more with the slacks, as they are the habitats that support the rare species, such as *Liparis loeselii,* and that are being invaded by *Hippophae rhamnoides* and *Salix repens*. In this context, 71.5 % of the area under PVS in 1962 had been transformed to MVS, DVS (densely vegetated slacks) or WL/S (woodland/scrub) by 1994. The areas of PVS that existed in 1994 were the ones created due to erosion during or soon after 1962. Similarly, 70.6% of MVS has been transformed to DVS and WL/S, while only 29.9% has remained as MVS. This study has brought to light the fact that there was some kind of erosional and dune mobility process going on after 1962, as a small percentage of vegetated dunes and slacks have been converted into open sand or less vegetated landscapes.

Slack hydrology as an attribute

Overlays of the habitat maps of different years has helped to quantify the direction, amount and rate of transition/succession, described above. As the hydrological regime plays an important role in determining vegetation growth and the subsequent successional trend in the dune system, an attempt was made to demarcate slack areas that are undergoing rapid transition due to hydrological factors. The dune slacks at Kenfig were classified into one of four types by Jones (1993) based on their hydrological status:

Type 1 slacks are typified by very shallow winter-flooding. During periods of flooding the water table displays a subdued response even to prolonged periods of heavy rainfall.

Type 2 slacks are similar to the above, but flood to a greater depth. The depth of flooding rarely exceeds 30cm, however, and for most dip-wells in the group was found to lie between 10cm and 25cm;

Type 3 are characterized by deep winter-flooding; and

Type 4 slacks are characterized by extremely deep winter-flooding.

A vector (point) coverage consisting of 192 dip-well locations (Jones 1993) C together with their corresponding hydrological characteristics (hydro-type/attribute) C was combined with the habitat change vector maps. This indicated that: (1) slack types 2 and 3 are the most vulnerable to transition to denser vegetation types; (2) faster vegetation development occurred in areas originally characterized by slack types 2 and 3; and (3) after becoming moderately vegetated, hydrological factors have little impact on the transition into dense slack and woodland.

Table 3. Transition matrix showing habitat changes for part of Kenfig NNR between 1962 and 1994. Key: OS = open sand; PVD = partially vegetated dune; MVD = moderately vegetated dune; DVD = densely vegetated dune; PVS = partially vegetated slack; MVS = moderately vegetated slack; DVS = densely vegetated slack; WL/S = woodland/scrub. Figures in italics = area in ha. All other elements of the matrix = percentage of area in 1962.

		1994								
		OS	PVD	MVD	DVD	PVS	MVS	DVS	WL/S	
		6.17	*11.20*	*189.80*	*49.50*	*6.76*	*92.09*	*23.55*	*33.07*	
1962	OS	*76.64*	5.36	8.80	64.50	0.62	1.58	14.25	1.18	2.63
	PVD	*104.48*	1.17	1.98	73.50	0.40	0.89	15.02	0.15	7.41
	MVD	*75.20*	0.90	1.15	55.10	35.20	1.65	6.10	-	0.20
	DVD	*3.70*	4.10	-	-	93.80	-	-	-	2.10
	PVS	*47.63*	0.001	1.21	24.70	2.51	0.95	41.60	23.20	5.98
	MVS	*83.03*	-	0.52	-	-	-	29.90	55.60	15.00
	DVS	*0.98*	-	-	-	-	-	-	50.86	49.20
	WL/S	*3.98*	-	-	-	-	-	-	-	100.00

Limitations of this study

The most difficult (and perhaps error-prone) part of studies such as this is rectification of the aerial photographs to some reference map projection. Although the utmost care was taken in geo-referencing the photographs and rectifying them, the scale of the photographs was different for each date, so that distortion and subsequent error in matching may have resulted in a small percentage of error creeping in the geometry of the vectors and eventually in the change statistics. A second consideration is that colour photographs, had they been available for all the years under consideration, would have provided more reliable information on vegetation type and density.

Conclusions

The general conclusion that can be drawn from the integration of aerial images and GIS used in this study is that, while the processes of erosion and dune mobility were active at Kenfig NNR at the start of the period considered (1962-1994), the dunes have become increasingly stabilized and there has been a cessation of dune-slack generation. It was also noted that the greening of the dunes has been slower than that of the slacks, and that at least 25% of the slacks could be restored to the conditions that support the survival of rare and pioneer species given appropriate management practices.
Habitat monitoring is an important prerequisite to the management of coastal dune systems, which are highly dynamic in nature. Aerial photographs provide a reasonably good source of information about the temporal changes and transitions that have taken place in recent decades. Their value in this context derives from the comparatively long time-series of data that they provide (cf. the multispectral images produced by digital remote sensing devices). GIS is an ideal tool with which to examine both the amount and the rate of transition of habitats, as well as to demarcate the areas that need urgent attention in terms of management and conservation. In combining these technologies, this study has helped to highlight those areas and habitats that could be rehabilitated under appropriate management programmes and, ultimately, to ensure that the biodiversity of this coastal dune system is maintained.

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