Modelling Spatial Patterns of Vegetation in Desert Sand Dunes

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ABSTRACT   A stochastic numerical approach was developed to model the actual standing biomass in the sand dunes of the northwestern Negev (Israel) and probable boundary conditions that may be responsible for the vegetation patterns investigated in detail. Our results for several variables characteristic for the prevailing climate, geomorphology, hydrology and biologicy at four measurement stations along a transect from northwest to southeast allowed for the development of a stochastic model for biomass distribution over the entire sand dune field (mesoscale) and at Nizzana experimental station (microscale). With this equation it was possible to compute and interpolate a biomass index value for each grid point on the mesoscale and micro scale. The spatial distribution of biomass is negatively linked to distance from the sea, to rainfall and relief energy.

KEY WORDS   arid ecosystems, modelling, biomass, Negev, Nizzana

1   Introduction

Vegetated sand dunes are typical of several arid and semi-arid deserts. They occur *e.g.* in the Kalahari, the Sinai and Negev Deserts and Inner Mongolia, northern China. Spatial distribution of the vegetation and its height play important roles in the formation of these sand dune systems (Tsoar and Møller 1986, Thomas 1988). Sand dune fields are predominantly fixed by standing biomass while the degree of sand dune stabilization will largely depend on the spatial patterns of the perennial vegetation cover. However, those patterns are effectively controlled only by two abiotic boundary conditions: a) sand movement as the equilibrium dynamics of stable and mobile units (Littmann and Gintz 2000) and b) local water availability (Yair *et al.* 1997, Veste *et al.* 2006). The dunes of the Sinai-Negev sand fields are separated by a political border which leads to different land-use practices and vegetation cover. Intensive grazing and trampling by goats, sheep and camels resulted in desertification on the Egyptian side, whereas on the Israeli side the vegetation remained undisturbed for several decades (Tsoar *et al*. 1995). Sand mobilisation is very often a huge problem of desertification in such regions (Mainguet 1999). Therefore, sand dunes fixation and restoration of a natural vegetation cover are major tasks in combating desertification (Sun and Fang 2001; Sanbei Shelter-Forest System Construction Bureau 1999).

In general, vegetation pattern and biomass productivity in deserts depend mainly on the rainfall regime and soil water availability. As a result of various factors a distinctive vegetation pattern may be observed. In extreme arid regions the vegetation is concentrated around runoff channels, dry valleys and depressions where surface runoff is collected. In sandy habitats with annual rainfall above 100 mm, the vegetation pattern is more diffuse (Danin 1983). However, in the sand dunes of the northwestern Negev a small scale mosaic distribution of vegetation is found and various habitat types can be distinguished (Veste 1995). More detailed knowledge about the spatial distribution of biomass may be of great importance, especially for the restoration of areas affected by desertification.

In this paper we will present a novel simple numerical approach to model the actual standing biomass distribution of a small area within a sand dune field of the northwestern Negev (Israel) near Nizzana and discuss probable boundary conditions that may be responsible for the vegetation patterns investigated in detail.

2   Study area

2.1   Geography and climate

The sand dunes of the northwestern Negev are the eastern most part of the sand field covering the northern part of the Sinai Peninsula and the northwestern Negev (Fig. 1). In the southern parts the dunes are linear in an east-west direction (Fig. 1), whereas north of the Wadi Nizzana the dunes are a combination of barchanoid and longitudinal dunes. Linear dunes with

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heights of 8–18 m, in an east-west direction, are typical forms in the southern parts of the Negev dune fields. The climate is determined by a sharp gradient from the north to arid conditions in the south and average annual rainfall decreases from around 170 mm at the northern edge of the sand field near Yevul to approximately 90 mm near Nizzana (Littmann and Berkowicz 2006, Veste *et al*. 2005). The rainfall is limited to the winter season (October to March). Mean annual temperature at the Nizzana experimental site is around 20°C (mean minimum 12.5°C; mean maximum 26.5°C). Arenosols are the major soil types investigated.
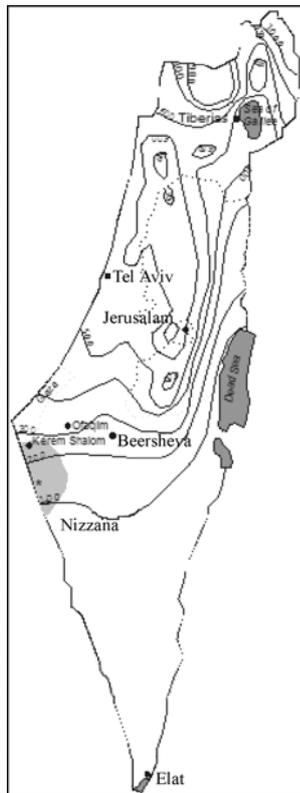

FIGURE 1   Location map of the sand dunes in the northwestern Negev (Israel)

2.2   Vegetation

Vegetation surveys in the area were conducted by Danin (1996), Tielbörger (1997) and Veste *et al*. (2005). Dominating shrubs at the investigation sites are *Anabasis articulata*, *Artemisia monsosperma*, *Thymelaea hirsuta*, *Convolvulus lanatus*, *Moltkiopsis ciliata*, *Echiochilon fruticosum* and *Retama raetam*. The mobile dune crests are dominated by *Stipagrostis ciliata* and *Heliotropium digynum*. *Cornulaca monacantha* is restricted to the southern dune parts of Nizzana. *Artemisia monosperma* and *Moltkiopsis ciliata* are typical for semi-stable and stable dune crests and slopes.

3   Methods

3.1   VEGDUNE model

The VEGDUNE model is based on input data for the following abiotic variables: distance from the sea (an indirect variable for the degree of continentality, computed trigonometrically for each grid point), relief energy (a measure for the complexity of the terrain expressed as the cross product of the elevations of four edges of a grid cell); percentage of mobile sand per unit, infiltration rate and infiltration depth, radiation balance, rainfall, dewfall, evapotranspiration, the frequency of stable layers and dew point temperature differences. The width of the geometric grid was 100 m for the mesoscale simulation and 10 m for the microscale simulation. These variables were used in a stepwise multiple regression analysis and those variables showing a correlation of at least 95% with the actual biomass index at the four stations were selected for the formulation of the regression equation:

Biomass Index = –0.4×distance from sea – 2.2×relief energy – $8.9 \times 10^{-4} \times$ rainfall + 23.439 7   (1)

The equation shows biomass to be negatively linked to all three significant variables, which implies an effect of a mesoscale climatic gradient (decreasing biomass with increasing aridity) and of microscale factors (biomass controlled by topographical features and their related physical processes).

3.2   Measurements of vegetation variables

The biomass index for the regression analysis was determined in the four interdune stations along the geo-ecological gradient. In 5 m×5 m plots for each perennial shrub, height and cover were measured and multiplied. In each geomorphologic unit 5–10 plots were chosen to estimate the vegetation cover (Dietz and Steinlein 2002, Veste *et al*. 2005). From the aerial photo (Fig. 1) seven characteristic areas were selected for the measurements of the vegetation cover by means of an image analysis system using the approach by Dietz and Steinlein (1996).

4   Results and discussions

4.1   Meso-scale application of the VEGDUNE model

Biomass indices were computed and interpolated for each grid point on the mesoscale grid over the entire dune field. The VEGDUNE model was validated on the mesoscale by assessments of the vegetation cover in 16 locations selected randomly across the entire transect. On this scale we found a very good interrelation with the values modelled for the respective sites (Fig. 2). The mesoscale model revealed

patches of high standing biomass in small depressions between steep sand dune slopes in many parts of the southern dune field, irrespective of rainfall totals. It is shown that the biomass index is negatively linked to rainfall (Eq. 1) and this is a most interesting finding, pointing to patches of higher standing biomass in favourable habitats over the entire sand dune field—especially in the higher sand dunes of the southern, drier part—of the study area. In several other studies a positive correlation was shown between annual rainfall and standing biomass (Noy-Meir 1973, Seely 1978, Kutiel and Lavee 1999). Reasons for the negative correlation are changes of surface properties. In the entire dune system a so called biological soil crusts has been built up by cyanobacteria, green algae, mosses and lichens which play important roles in the ecosystems (Veste *et al*. 2001, 2006, Veste 2005). Along the transect, infiltration rates decrease from south to north and compensate the effects of increasing rainfall for the standing crop (Littmann *et al*. 1998, Veste *et al*. 2005).
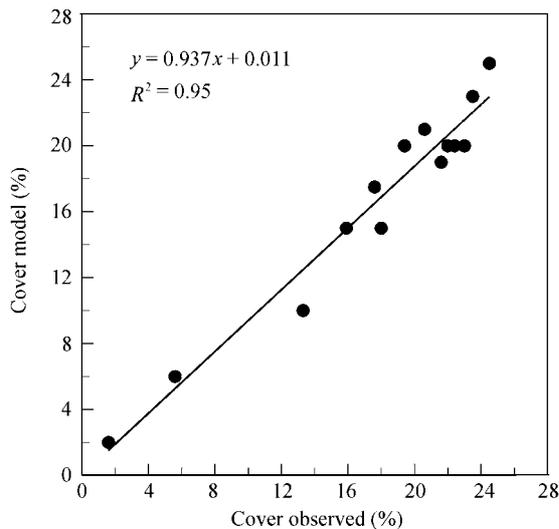

$$y = 0.937x + 0.011$$
$$R^2 = 0.95$$

FIGURE 2   Correlation between measured vegetation cover and modelled cover for validation of the VEGDUNE model

4.2   Microscale application of the VEGDUNE model

After the validation of the biomass data on the mesoscale the equation was applied to the microscale on a digital surface model of Nizzana. The output of the microscale model shows a very realistic simulation of the spatial pattern of standing biomass in the sand dunes at Nizzana (Fig. 3). Measurements of the vegetation cover of the area by image analysis of aerial photography confirmed these findings (Fig. 4). At the Nizzana site the highest vegetation cover occurs at the

dune base, whereas the lowest density can be found on the mobile dune crests (Fig. 5). In this ecotope sand stability is another controlling factor for the vegetation (Littmann and Gintz 2000). The relative dune height (expressed as relief energy) is one major factor for the ecotope differentiation. The vegetation has also a feedback on the near-ground wind velocity and on sand mobility. Nevertheless, stable dunes and dune bases are favourable habitats for shrubs from the viewpoint of their water relations (Veste *et al*. 2006). Deep infiltration in good rainy years leads to subsurface flow and additional water supply at the dune base (Yair *et al*. 1997) resulting in a dense vegetation cover up to 45% (Fig. 5). However, the biomass on the south-facing slopes was partly overestimated. These steep dune slopes are not covered by biological soil crusts and the mobile sand prevents the establishment of more vegetation. The data provided in Fig. 5 show as well a close relationship between standing biomass and vegetation cover for the sand dune vegetation. Only few studies show such a close relationship (Dietz and Steinlein 2002). From these it can be concluded that the biomass index modelled by the VEGDUNE model reflects the standing biomass as well as the vegetation cover.
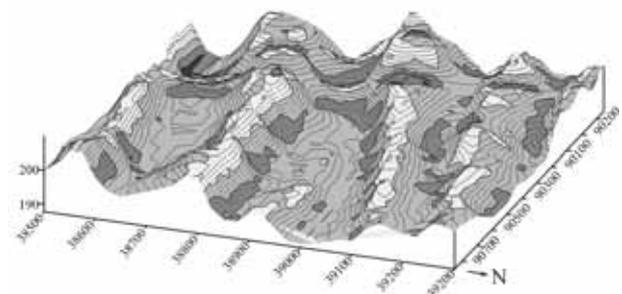

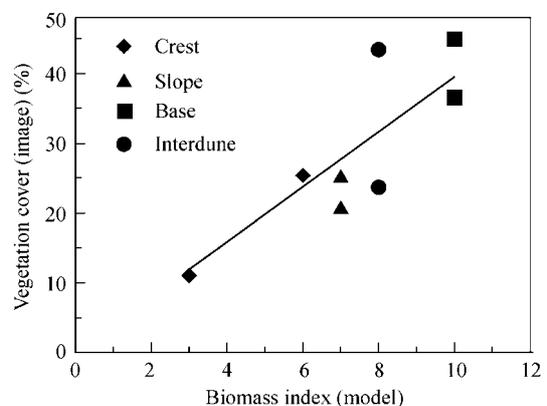**FIGURE 3   Modelled biomass indices on the sand dunes of Nizzana (see Fig. 1)**

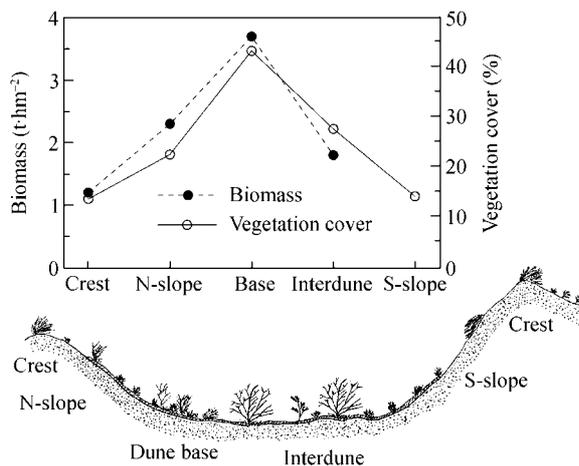**FIGURE 4   Modelled biomass index (from Fig. 3) and measured vegetation cover from airphoto**

FIGURE 5   **Mean biomass (dry weight) and mean vegetation cover along a geomorphologic catena at the study site Nizzana**
Modified after Veste *et al.* (2005)

5   Conclusions

Our results for several variables characteristic for the prevailing climate, geomorphology, hydrology and biology at the four measurement stations allowed the development of a stochastic model for biomass distribution over the entire sand dune field (mesoscale) and at the Nizzana test site (microscale). We conclude that:

1) The major controlling factor determining the biomass distribution is the relief energy and the relative dune height;

2) On the mesoscale the biomass index is negatively correlated to the rainfall amounts due to changes in surface properties;

3) The VEGDUNE model is an optimal tool for the prediction of biomass distribution in rehabilitation projects.

Acknowledgements

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