Spatial Patterns of Soil Water and Vegetation in Arid Ecosystems and Their Applications for Shelterbelt Design – Examples from the Negev desert

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1. Introduction

In arid and semi-arid ecosystems water is the major limiting factor for plant growth and determined the vegetation pattern. It is a well-known fact from large-scale comparisons that standing biomass and rainfall show a close positive relationship (e.g. Shmida 1985). Vegetation cover and biomass show the same decrease from humid to arid climates as does mean annual rainfall, which is supposedly the controlling factor. On the other hand, soil and surface hydrology properties (e.g. field capacity, infiltration rates) effectively control the water distribution in the ecosystem, a fact that is aggravated in arid environments.

Information of the spatial and temporal accessibility of soil water in desert ecosystems is limited. The purpose of the studies is the application of plant water potential to estimate the spatial and temporal variations of soil water availability in different arid ecosystems of the Negev (Israel). As model plants typical evergreen shrubs, e.g. *Artemisia monosperma, Retama raetam, Thymelaea hirsuta* were chosen. Pre-dawn water potential (Ψ_{pd}) is measured by a pressure-probe (Scholander et al. 1965) and is used in this context as diagnostic tool to determined water availability on the landscape level (Veste & Staudinger 2005). The pattern will be linked to the hydrological processes in the different ecosystem and their implication for vegetation patterns.

2. Study sites

2.1 Central Negev

The Sede Boqer experimental site (Fig. 1A) is located in the Negev Highlands at an altitude of 480 m a.s.l. (Fig. 2, 34°47′E, 30°51`N). Rainfall is limited to winter season with an average of 97 mm and varied between 31 mm and 167 mm (Yair & Shachak 1987, Veste 2004). The upper slopes are rocky and composed by limestone and flinty limestones. Characteristic plants of the area are *Artemisia herba-alba, Retama raetama, Thymeleaea hirsuta* and *Zygophyllum dumosum* (Schreiber et al. 1995).

2.2 Sand dunes of the north-western Negev

The sand dunes of the northwestern Negev (Fig. 1B) are the eastern most part of the sand field covering the northern part of the Sinai Peninsula and the northwestern Negev (Veste, 2004). The southern most experimental site Nizzana (Fig 2, 30°56′N, 34°23′E) is characterized by vegetated linear dunes with mobile crests. The dunes reach heights of approx. 8 – 12 m. The climate is determined by a sharp gradient from semi-arid in north to the arid in the south. Average annual rainfall decreases from around 170 mm at the northern edge of the sand field near Yevul to approx. 90 mm near Nizzana. The rainfall is limited to the winter season (October to March). At the Nizzana experimental site the average annual rainfall is approx. 90 mm and varied between 30.1 mm (1997) and 141 mm (1995/96) (Littmann & Berkowicz 2006). Dominating shrubs at the investigation sites are *Anabasis articulata*, *Artemisia monsosperma*, *Thymelaea hirsuta*, *Convolvulus lanatus*, *Moltkiopsis ciliata*, *Echiochilon fruticosum* and *Retama raetam* (Veste et al. 2005).

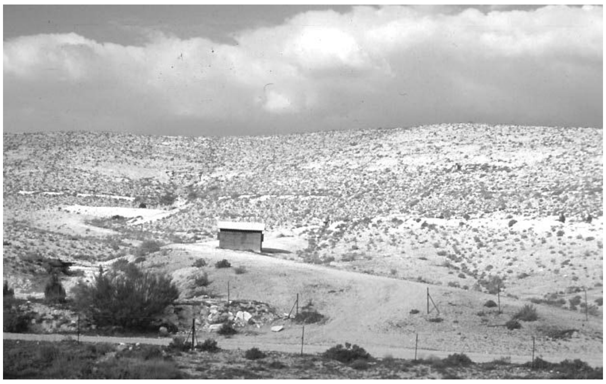

Fig. 1A: Study site Sede Boqer in the Central Negev Highlands

Fig. 1B: Study site Nizzana in the sand dunes of the north-western Negev

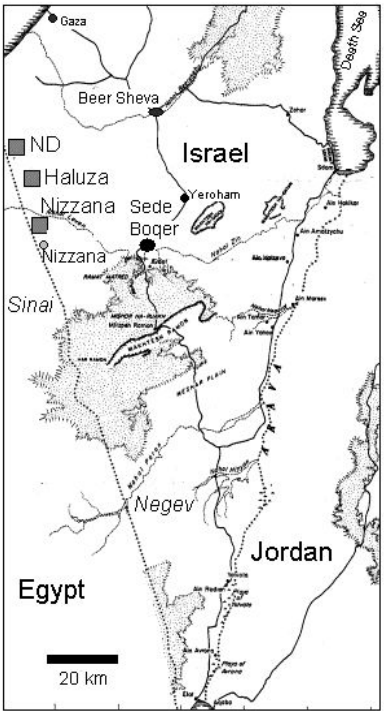

Fig. 2: Location of the study sites Sede Boqer and Nizzana in the Negev desert (Israel)

3. Investigated plant species

Retama raetam (Fabaceae): Is a stem-assimilating shrub with a height up to 2.5 m and has a wide ecological range, from Mediterranean coastal dunes to the dry Saharo-Arabian deserts of North Africa. In the Negev *Retama retama* is a common species of the loessial northern Negev, the central Negev Highlands, the stony southern Negev and the arid Arava-Valley.

Thymelaea hirsuta (Thymelaceae):

This shrub is evergreen with small leaves and can reach up to 2 m height. It has a Mediterranean and Saharo-Arabian distribution. *T. hirsuta* is characteristic for the coastal dunes of the northern Sinai and Israel and the inland dunes of the northwestern Negev. In the Northern Negev and the adjacent areas this shrub occurs in areas where the annual rainfall is 180 to 300 mm mostly in diffuse pattern (Danin 1978). In drier areas it is found in mesic habitats as wadis or at the foot of limestone slopes.

Artemisia monosperma (Asteraceae). *A. monosperma* is 0.5 – 1.5 m high and a typical plant of semi-stable sands of the northern Sinai, the northwestern Negev and of the Coastal Plain in Israel. It is adapted to slight sand movement.

4. Results and discussion

4.1 Negev Highlands

Pre-dawn water potential of *Thymelaea hirsuta* and *Retama raetma* shows that the spatial differences are more pronounced during the dry seasons (Fig. 3). The habitats differ in the soil water storage and soil volume. At the end of the rainy season the water potential on the slopes and in the wadi are similar (Veste & Breckle 1996b).

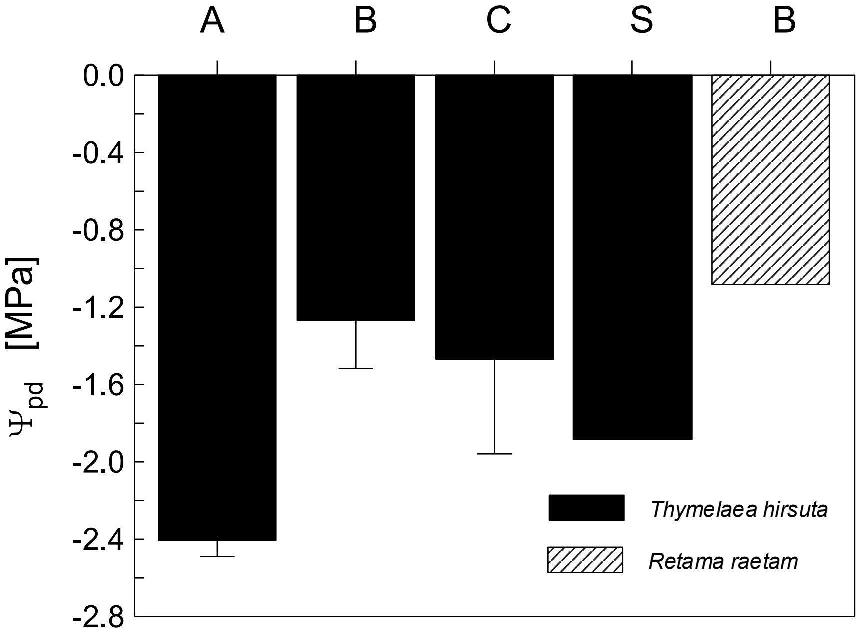

Fig. 3: Mean pre-dawn water potential (Ψ_{pd}) of *Thymelaea hirsuta* and *Retama raetam* in Sede Boqer. A. rocky surface, B: terraced wadi, C: non-terraced wadi, S: slope.

The water availability increased in the terraced part of the wadi system where infiltration is enhanced and soil volume is larger. Such stone terraces were used for runoff agriculture in the Negev since pre-historical times (Evenari et al. 1982, Yair 1983). In this part of the wadi the infiltration is increased and water availability is higher than in the neighbouring rocky parts and slopes (Fig. 3), where infiltration is limited and runoff occurs.

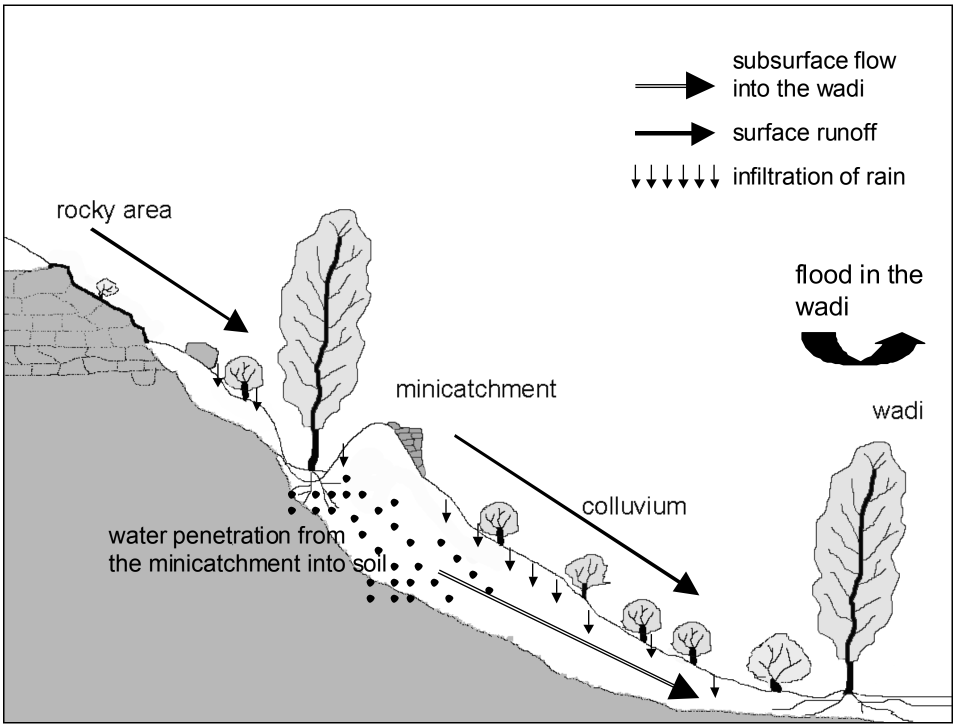

Fig. 4: Schematic drawing of surface and subsurface flows in Sede Boqer (after Schreiber et al. 1995, Yair 2001)

The spatial differences of water supply under natural conditions have also implications for the use of water harvesting techniques in arid regions. The knowledge about the runoff along slopes and sites where runoff water concentration occurs under natural rainfalls is important for the construction of minicatchments as emphasised by Yair (1983, 2001). For optimal water harvesting the minicatchments are located in the Negev Highlands at the interface between the rocky and colluvial slopes (Fig. 4). Runoff generated at the rocky parts can flow along the slopes into the catchments. Long-term investigation in the Central Negev Highlands showed that runoff from the upper hillslope (drainage area 200 – 250 m^2) to the lower part can increase the water amount by 2000 mm in wet and 200 mm in dry years by an average annual rainfall of 97 mm (Yair 1983, 2001), sufficient to support tree growth even in arid ecosystem. Furthermore, infiltrated water is not fully used by the planted trees or vegetation and penetrates in deeper soil layers. Subsurface flow occurs and can support the vegetation below catchments with water, which can be used by deep rooting plants (Fig. 4, Schreiber et al. 1995).

4.2 Sand dunes

Pre-dawn water potentials of *Artemisia monsosperma*, *Retama raetam* and *Thymelaea hirsuta* were in the rainy seasons showed no differences between the locations (Fig. 5). At the end of the drought periods pre-dawn water potentials dropped in the interdunes below –1.2 MPa, whereas the seasonal variation on the dune slopes is less pronounced (min. –0.75 MPa). This indicates a better water supply of the phanerophytes on the dune in comparison to the interdune area. In the sand dunes water can infiltrate in deeper layers of more than 3 m depth and lateral water flows are observed along the dune slope (Fig. 6). The upper soil layer drying out in summertime and water is only available in deeper layers (Yair et al. 1997). *Retama retime* and *Thymelaea hirsuta* developing a surface root system and tap roots to use the water from both layers.

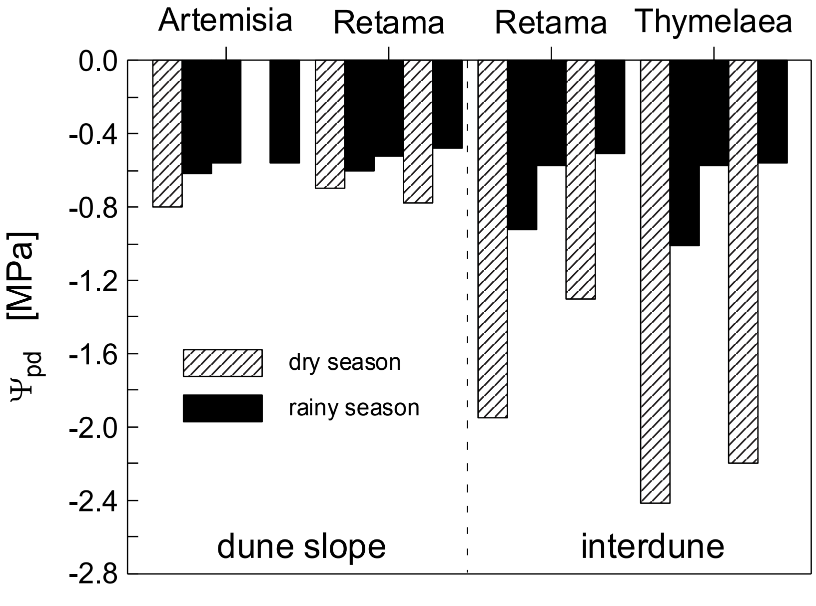

Fig. 5: Seasonal variation of pre-dawn water potential (Ψ_{pd}) of *Artemisia monosperma, Retama raetam* and *Thymelaea hirsuta* in the linear dunes of Nizzana

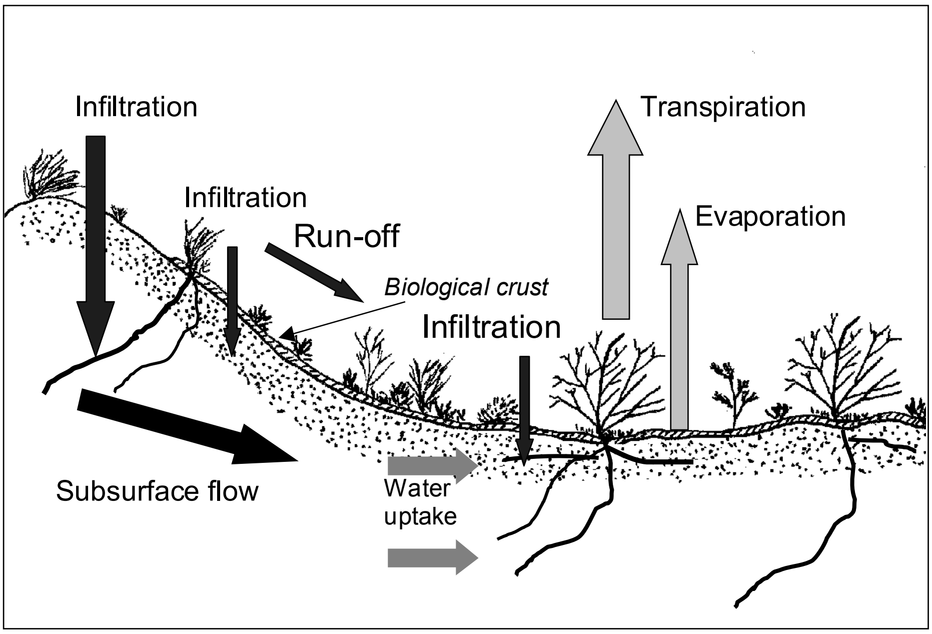

Fig. 6: Schematic diagram of the major hydrological processes
in the sand dunes of Nizzana (after Veste 1995)

The presented pre-dawn water potentials and additional gas exchange measurements (Veste & Breckle 1996, 2000) clearly indicate water uptake from water sources within deeper layers of the dune during the dry periods (Yair *et al.* 1997). The complex hydrological processes (Fig. 5) in the dune system have large impacts on the vegetation pattern. Subsurface flow can be observed within the dune (Yair et al. 1997). Furthermore, on encrusted slopes surface runoff towards the dune base can be observed in a sandy area. A so-called biological soil crust, build up by cyanobacteria, green algae, mosses and lichens, are causally related to these hydrological processes and plays an important role for the ecosystems (Veste et al. 2001, Veste 2005). The crust limits infiltration (Fig. 7) and runoff occurs (Yair 1990, Veste et al. 2001). All these processes result in a concentration of water at the dune base and a dense vegetation belt can be develop (Veste et al. 2005, Littmann & Veste 2005). The soil surface properties are key-factors for the determination of the water distribution and influencing the aridity of an ecosystem additional to climatic factors (Yair & Berkowicz 1989). Already a thin layer of fine material decreases infiltration and leads to increasing surface runoff, whereas sand cover enhance water infiltration (Yair & Bryan 2000). Moisture retention by fine grain material influence water infiltration to deeper depths, which may lead to a declining number of deep-rooting shrubs (Fearnehough et al. 1998).

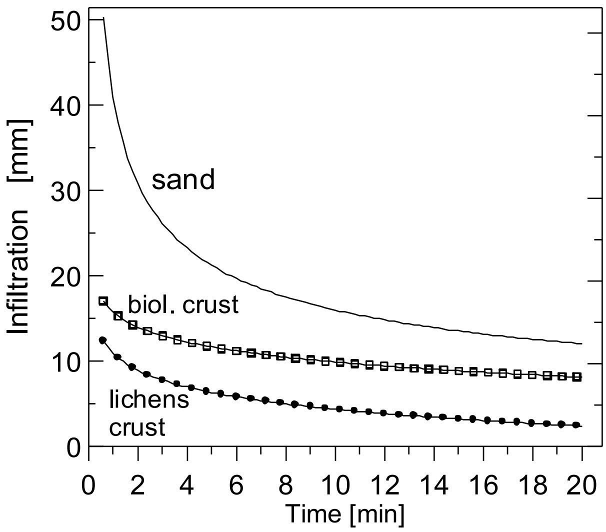

Fig. 7: Infiltration on sand, biological crust on north-facing slope and soil lichen crust in the Haluza sand field (after Littmann et al. 2000, Veste et al. 2001)

Furthermore, it could be shown by Littmann & Veste (2005) that the biomass index in the sand dune ecosystem is negatively linked to rainfall gradient. This is the most interesting finding pointing to patches of higher standing biomass in favourable habitats all over – and especially in the higher sand dunes of the southern, drier part – of the sand dune field. In several other studies a positive correlation was shown between the annual rainfall and standing biomass (Noy-Meir 1973, Seely 1978, Kutiel & Lavee 1999, Köchy & Jeltsch 2005). Reasons for the negative correlation are again changes of surface properties. 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). For example, topsoils covered mainly by soil lichens in the Haluza sands shows the lowest infiltration, whereas cyanobacterial crusts have a higher infiltration rates (Fig. 7). In this case the micro-scale hydrological processes controlled by the biological soil crust counteracts the meso-scale rainfall gradient and lowering the water availability for the standing biomass. An interesting observation are the changes in habitat preferences of several shrub species. In the southern parts *Retama raetam* settles in the stable interdunes and slopes, but move with increasing rainfall and stabilisation of the dune crest in the northern sites towards the dune top (Fig. 8) and is here rare in the interdunes. *Artemisia monosperma* is more uniform distributed in the northern parts and absent on mobile dune crests in the south. It seems that *Retama raetam* prefers area with higher soil water storage in the northern dunes, whereas in the south sand mobility is a limiting factor for colonization on the dune crests.

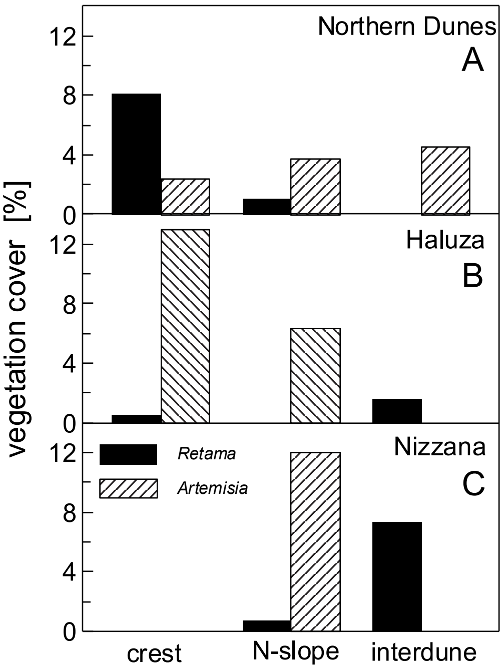

Fig. 8: Vegetation cover of *Retama raetam* and *Artemisia monosperma* in different geomorphologic units along the climatic gradient. For the location see Fig. 1 (after Veste et al. 2005)

5. Modeling vegetation pattern for shelterbelt design

A simple numerical approach to model the actual standing biomass distribution of a small area within the southern part of the sand dune field of the north-western Negev (Israel) near Nizzana (Littmann & Veste 2005) were developed and integrates probable boundary conditions that may be responsible for the vegetation patterns. Our results for several climatic, geomorphologic, hydrological and biological parameter characteristics along a transect from northwest to southeast (Fig. 2) allowed the development of a stochastic model for biomass distribution over the entire sand dune field (meso-scale). With the VegModel it was possible to compute and interpolate a biomass index value for each grid point on micro scale grid (Fig. 9). In fact, confirmatory assessments of biomass and vegetation cover of the existing vegetation revealed a very good interrelation with the values modeled for the respective sites.

Therefore, such a model reflects the vegetation pattern and helps to identify suitable places for vegetation planting in sand dunes. Coupling a biomass distribution model as described by Littmann & Veste (2005) and a water budget model with wind field modelling on regional and local scales will be an optimal tool for shelterbelts design in drylands.

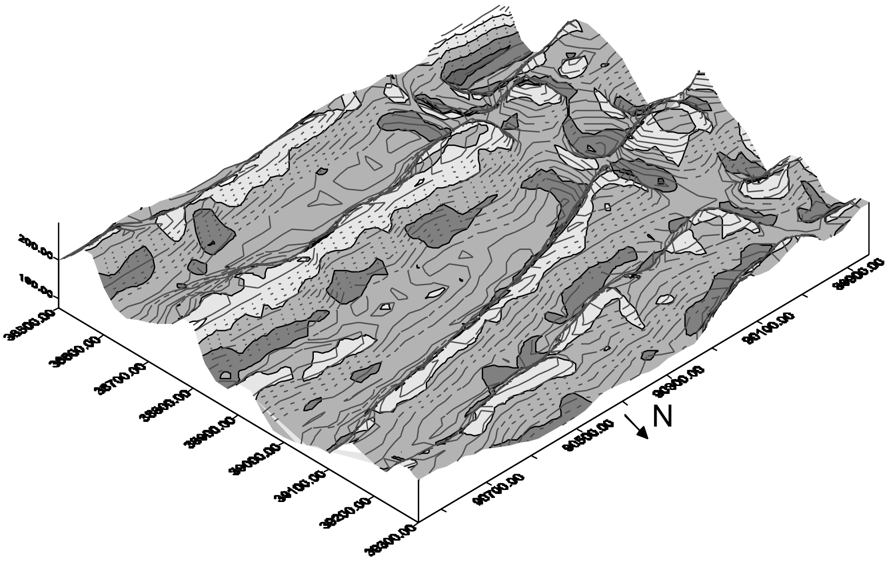

Fig. 9: Modeled vegetation cover by the VegModel in the sand dunes of
Nizzana. Light grey low vegetation cover, dark grey high vegetation cover (after Littmann & Veste 2005)

6. Conclusions

In arid regions rainfall and redistribution of water plays an important role for plant productivity and vegetation pattern. The vegetation patterns along the geo-ecological gradients are the result of a complex interrelation processes on meso-scale and micro-scale. For shelterbelt design and rehabilitation, respectively restoration the knowledge of natural ecological processes is needed. Linking spatial potential vegetation pattern, water budgets and wind field modeling will help to optimise shelterbelt design in arid and semi-arid regions in the future.

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