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Three types of gradients in the saline ecosystem

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Abstract. The aim of this study was to combine saline ecosystem structure and function by three aspects of the gradient concept: spatial, temporal and functional. The saline meadow was investigated in the vicinity of soda factory in Janikowo in the Kujawy region, central Poland. Three vegetation zones in the salinity gradient were distinguished on the meadow: the *Salicornia europaea* zone, the *Puccinellia distans* zone and the *Elymus repens* zone. The results demonstrated that taking into account spatial, temporal and functional gradients, new (informative and ordering) aspects in the collected empirical data sets can be found. Spatial gradient analysis revealed that existence of the two neighbouring *Salicornia europaea* and *Puccinellia distans* zones is dependent on lower energy than existence of the neighbouring *Puccinellia distans* and *Elymus repens* zones. Temporal gradient analysis shows the biggest amplitude between the lowest and the highest Cl^- concentration values in the *Salicornia europaea* zone. Therefore the system could be considered as one of the smallest buffer capacity and a labile one. Gradients of vegetation functional changes after decrease and equalisation of the meadow salinity demonstrated that changes in a number of species and in structure of above-ground biomass were recorded at the first stage. At the next stage, only changes in species above-ground biomass were found. The new information obtained by the gradient analysis, especially the one dealing with buffer capacity of the system and changes in species richness after decrease of salinity, could be informative for landscape management.

Key words: spatial gradients, temporal gradients, functional gradients, salinity, inland salt-marshes, zonation.

1. Introduction

Characteristics of ecosystems usually deal with ecosystem structures and functions. These two poles were usually investigated separately for different purposes and based on different methods. The structural approach was mostly based upon statistically oriented, descriptive concepts such as spatial diversity and heterogeneity of specific system elements. The functional research were often connected with the concepts of flows, balances, movements and dynamics, and focused on energetic values (Odum 1995), thermodynamic concepts (Weber et al. 1989) and network theories (Ulanowicz 1986).

In case of saline systems, ecological structures and functions were investigated separately as well. Many studies were focused on vegetation-environment relations (Adam 1990; Chapman 1960). Investigations of saline ecosystems' functions were often oriented, as in case of other ecosystems, on energetic values (Quin et al. 2000; Odum 1974).

Integration of structural and functional ecosystem characteristics is difficult. However structures and functions can be understood as systems of interacting gradients that result in different quantitative states of ecological variables (Müller 1998). Gradients symbolise spatial, functional or temporal differences in structures or energetistic and material units in ecological systems.

Accepting this point of view, the present research aimed at integrating saline ecosystem structure and function by analysing three types of gradients in the system: spatial, temporal and functional.

2. Materials and methods

The research was carried out on the saline meadow in the vicinity of soda factory in Janikowo, in the Kujawy region, central Poland (fig. 1). Wastes from the soda factory, collected in the open sediment traps, constituted the source of salinity for the investigated meadow. As a result of inappropriate tightening of the sediment traps' bottoms, the wastes infiltrate into the soil, causing consequently the soil salinity (Cieśla & Dąbkowska-Naskręt 1984; Czerwiński et al. 1984). The meadow was separated from the border of the setting tank by the road. On one side it was bounded by the ditch, on the other side it adjoined the arable field situated on the slightly higher ground. The middle part of the meadow had lower location and was slightly sloping up towards the borders. The distinct zonation of vegetation was observed on the meadow. Three vegetation zones were distinguished along the salinity gradient: *Salicornia europaea*, *Puccinellia distans and Elymus repens* zone.

In order to describe the spatial vegetation pattern, one part of the meadow was mapped by the parallel transects method (Faliński 1990). Transects were located every 1 m and domination of species (cover > 5%) was recorded along each of them. Apart from that, in each vegetation zone phytosociological relevés were taken following the Braun-Blanquet approach (1964). Nomenclature follows Flora Europaea (Tutin et al. 1964–1980).

In each vegetation zone, soil samples of 0–25 cm (an average of 5 randomly selected points) were taken as well. The moisture was determined in fresh samples by the method of drying at 105°C. In the air-dried samples, sieved by 1.02 mm mesh, the following parameters were estimated: organic matter content by the deflagration at 550°C, total nitrogen by the Kjeldahl method, electrical conductivity of the saturated extracts (EC_e) by the conductivitymeter. In the soluble extracts (1:5, soil to distillate water) the following parameters were determined: pH by the potentiometric method, EC by the conductivity meter, Ca^{2+}, K^+, Na^+ by the photo-flame method, Mg^{2+} by the atomic absorption spectrophotometer, HCO_3^- with 0.01 n H_2SO_4 using the methylorange indicator, SO_4^{2-} by the nephelometric method, Cl^- with 0.1 n $AgNO_3$ using $K_2Cr_2O_7$ indicator. The content of anions and cations are given in percentage (g/100g dry soil). The total dissolved salts were calculated by summing up anions and cations. Furthermore, Ca^{2+}/Na^+ ratio and Cl^- concentrations in the soil water were calculated.

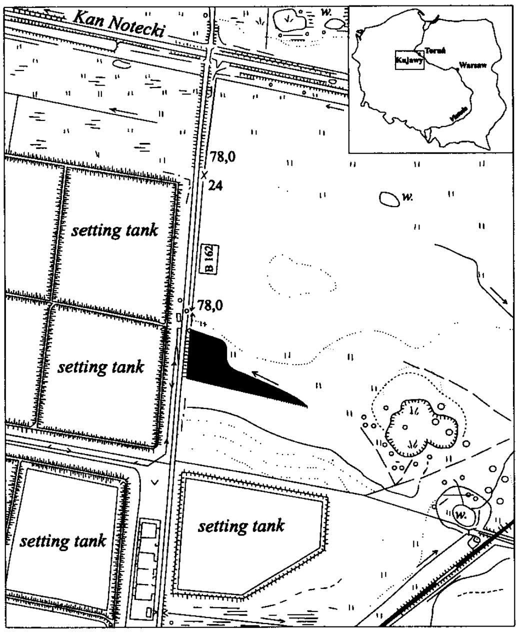


Figure 1. Location of the investigated area

Every four weeks, from May to end of October 1997, soil samples of 0–5 cm were taken along every vegetation zone in order to monitor a salinity level. In those samples Cl^- concentration was assigned as a salinity measure.

In order to describe functional relations between vegetation structure and soil salinity level a transplant experiment was performed. The salinity could be thought as a land degradation factor in the area next to the soda factory and therefore vegetation changes, after eliminating the gradient and equalising the salinity on the meadow, were analysed. At the end of May 1996 five vegetated soil-blocks (25 x 25 x 25 cm) from the *Salicornia europaea* zone and five blocks from the *Puccinelia distans* zone were randomly dug out and transplanted to the *Elymus repens* zone with the lowest salinity. To regard transplantation effect the control served blocks randomly dug out in three zones, five in each zone, and randomly replanted in the home site. The 20 cm zone around each transplant was cleared every 4 weeks from the end of May till the end of October 1996 and 1997. After two growing seasons transplants were dug out again and above-ground biomass was determined. Gradients of changes in the vegetation structure were described on the base of species biomass after elimination of the salinity gradient. The Shannon diversity index with $\log_2$ was calculated (Pielou 1975). The initial stages of succession were represented by blocks replanted in the *Salicornia europaea* and *Puccinellia distans* zones. The blocks transplanted into the *Elymus repens* zone represented successional stages towards the optimal stage represented by blocks replanted in this zone. It was assumed that vegetation of the *Elymus repens* zone is the optimal one at the salinity level along this zone.

3. Results

3.1. Spatial gradients

The spatial pattern of vegetation on the meadow where *Salicornia europaea, Puccinellia distans* and *Elymus repens* dominated in the three respective zones is presented in fig. 2. Contribution of other species in each vegetation zone is demonstrated in tab. 1. At the same time each vegetation zone is characterised by soil properties (fig. 3). Differences between values of spatial parameters within the mapped area can be comprehended as gradients, which symbolise certain state variable or a system feature within a certain area.

Table 1. Species composition of the three vegetation zones

	1. *Salicornia europaea* zone			2. *Puccinellia distans* zone			3. *Elymus repens* zone		
Relevé number	1	2	3	4	5	6	7	8	9
Salicornia europaea	**3**	**5**	**5**	1	–	+	–	–	–
Puccinellia distans	1	+	1	**4**	**5**	**5**	–	–	+
Elymus repens	–	–	–	–	–	–	**5**	**3**	**5**
Spergularia marina	+	–	–	–	–	–	–	–	–
Atriplex hastata var. salina	+	–	+	–	–	–	–	–	–
Atriplex nitens	–	–	+	–	–	–	–	–	–
Epilobium palustre	–	–	+	+	1	1	+	+	1
Sonchus arvensis	–	–	–	–	+	+	–	–	–
Deschampsia cespitosa	–	–	–	–	+	–	–	–	–
Taraxacum officinale	–	–	–	–	+	+	–	–	–
Cirsium vulgare	–	–	–	–	+	–	+	–	+
Galium verum	–	–	–	–	–	+	–	+	–
Cirsium arvense	–	–	–	–	–	+	+	3	+
Polygonum aviculare	–	–	–	–	–	–	+	–	–
Lamium pupureum	–	–	–	–	–	–	–	+	–
Agrostis stolonifera	–	–	–	–	–	–	–	+	–
Plantago major	–	–	–	–	–	–	–	–	+
Sonchus oleraceus	–	–	–	–	–	–	–	–	+

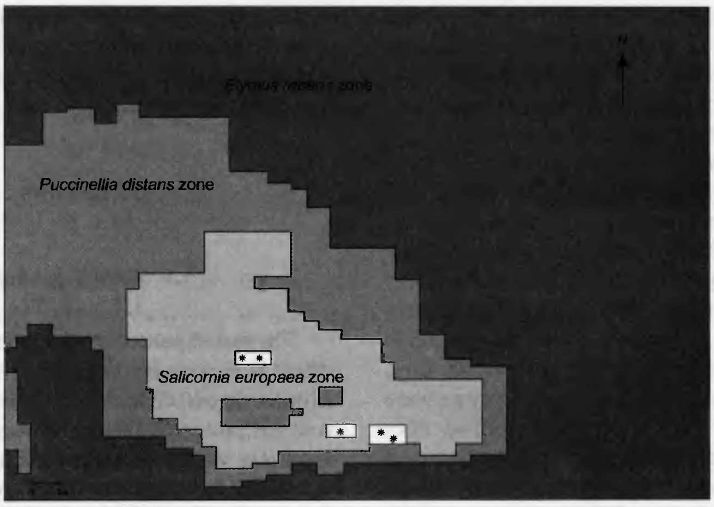


Figure 2. Spatial distribution of the vegetation zones; * – individuals of *Salicornia europaea* on the bare soil

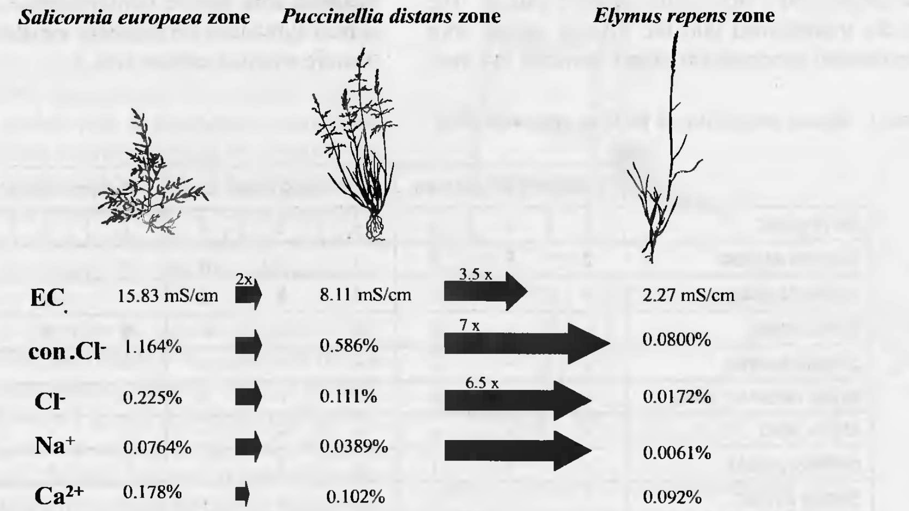


Figure 3. Spatial pattern of salinity gradients; EC_e – electrical conductivity of saturated extract; con. Cl^- – Cl^- concentration

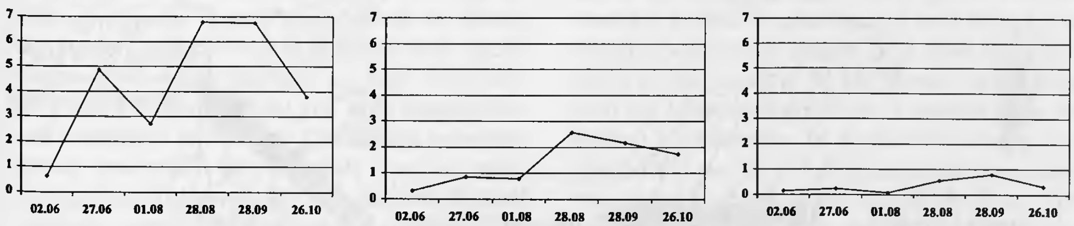
The biggest differences among the properties describing the soil salinity were recorded for EC_e, Cl^- concentration, Na^+ and Ca^{2+} contents. The highest salinity was recorded along the *Salicornia europaea* zone where EC_e reached 15.8 mS/cm, Cl^- concentration – 1.16 %, Cl^- content – 0.22 %, Na^+ – 0.0764 %, Ca^{2+} – 0.178 %. In the *Puccinellia distans* zone above parameters were ca. 2 times lower (fig. 3). The lowest salinity was recorded in the *Elymus repens* zone, where EC_e reached only 2.27 mS/cm, and this is related to slightly saline soils according to Jackson's scale of soil salinity (Jackson 1958). In this scale, 2 mS/cm is the border value for saline soils. Soils with conductivity below 2 mS/cm are classified as non-saline. In the *Elymus repens* zone Cl^- concentration reached 0.08 %, Cl^- content – 0.0172 %, Na^+ – 0.0061 %, Ca^{2+} – 0.092 %. Gradient analysis carried out for neighbouring zones demonstrated that observed spatial vegetation pattern was maintained by gradients of different sizes (fig. 3). The balance in species distribution between the *Salicornia* *europaea* zone and the *Puccinellia distans* zone was maintained by two times higher values of the analysed parameters, whereas the balance between the *Puccinellia distans* zone and the *Elymus repens* zone – by 3.5–7 times higher values.

3.2. Temporal gradients

The spatial gradient patterns discussed above are always connected with the temporal features of a variable or gradient. The gradients responsible for existence of certain spatial vegetation patterns are not stable – they are changing slowly or dynamically over the time. Therefore different gradients must be also characterized by their temporal features and as well as spatial properties. Temporal gradients can be defined as differences in values of a state variable within a defined temporal duration.

In all investigated vegetation zones, differences in Cl^- concentration in the soil were recorded over the growing season (fig. 4). In spring the salinity was at the lowest level and similar along three zones. The highest salinity was recorded in August and September when precipitation was relatively low and evaporation relatively high. The highest temporal gradient of Cl^- concentration was recorded in the *Salicornia europea* zone and reached 6.16, next in value – in the *Puccinellia distans* zone – 2.25 and in the *Elymus repens* zone – 0.708. The highest salinity along the *Salicornia europaea* zone was connected with a lower location of that part of the meadow in relation to the remaining area. The salinity value was mostly dependent on evaporation due to relatively low vegetation density along this zone. During dry periods Cl^- concentration increases in the upper levels of the soil, whereas during heavy rains it decreases as Cl^- anions are washed down the soil.

Salicornia europaea zone | *Puccinellia distans* zone | *Elymus repens* zone



min. – 0.636%
max. – 6.679%
mean – 4.20% s – 6.16

min. – 0.319%
max. – 2.570%
mean – 1.41% s – 2.25

min. – 0.078%
max. – 0.786%
mean – 0.355% s – 0.71

Figure 4. Temporal gradients of Cl^- concentration in soil level 0–5 cm of three vegetation zones; min. – minimum value, max. – maximum value, s – amplitude

3.3. Functional gradients

This type of gradients is directly connected with spatial and temporal gradients because their hierarchy provides some basic structure for constraints and control mechanisms in the ecosystem. Functional gradients describing a given vegetation zone as a separate functional unit in the analysed saline system were not investigated but the chain of functional changes was analysed in the vegetation after a decrease and equalization of the meadow salinity – in other words: after elimination of the salinity gradient. Vegetation changes were described as gradients of species biomass and species diversity in the experimental plots over the time.

During the first succession stage, after two years of transplantation into the *Elymus repens* zone with the lowest soil salinity, transplants have lower above-ground biomass than in the home site (fig. 5). Transplants of *Salicornia europaea* in the *Elymus repens* zone have mean biomass of c.a. 127 g/m², whereas in the home site – c.a. 569 g/m². The smaller differences were recorded on *Pucci-*

nellia distans transplants, where in the *Elymus repens* zone the mean biomass reached c.a. 600 g/m² and in the home site – c.a. 774 g/m². This decrease of biomass was related to loss of dominant species i.e. *Salicornia europaea* and *Puccinellia distans*. At the same time, invasion of glycophytes on the *Salicornia europaea* transplants resulted in increase of the Shannon diversity index. Glycophytes entered the *Puccinellia distans* transplants irregularly. *Elymus repens* dominated there, what resulted in lower Shannon diversity index, although a number of species was higher than in the home site. The final succession stage, after elimination of the soil salinity gradient in the investigated meadow, will be represented by vegetation typical for the *Elymus repens* zone, and this was assumed at the beginning. The total mean above-ground biomass of species along this zone was of the same range as in the *Salicornia europaea* and *Puccinellia distans* zones and reached c.a. 600 g/m². However the Shannon diversity index was lower because of strong dominance of *Elymus repens*. The expected last stage of changes, after elimination of the salinity gradient on the meadow, will be connected with an increase of *Elymus repens* biomass (fig. 5). The other species will decline.

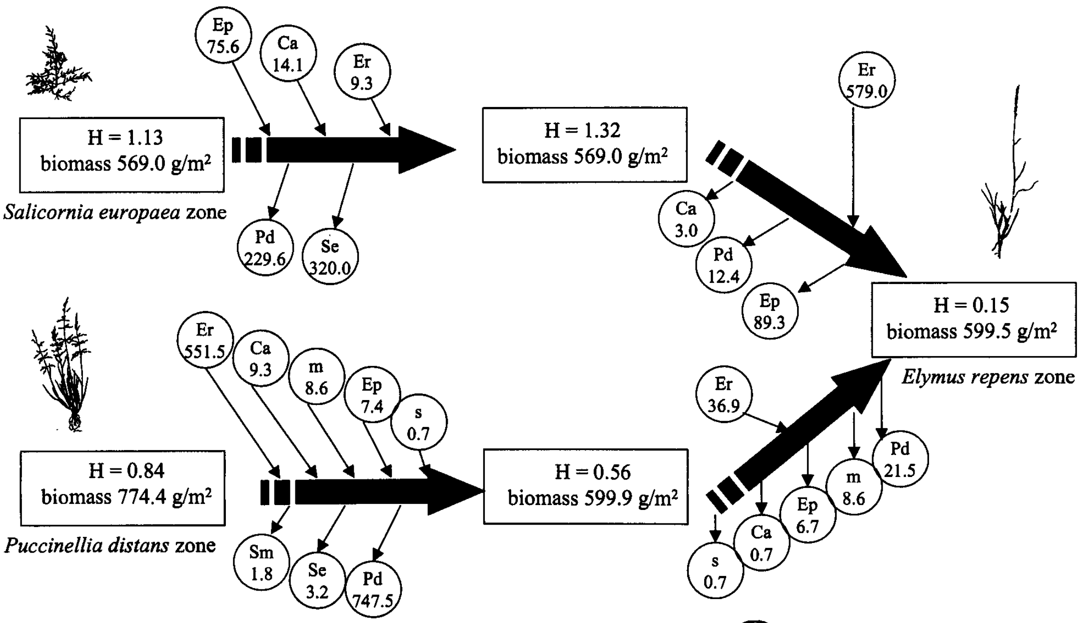


Figure 5. Chain of functional changes in the vegetation structure after elimination of salinity gradient; H – Shannon diversity index, biomass – total above-ground biomass of species. Arrows indicate inputs and outputs of species biomass [g/m²] into and out of the system. Se – *Salicornia europaea*, Sm – *Spergularia marina*, Pd – *Puccinellia distans*, Er – *Elymus repens*, Ep – *Epilobium palustre*, Ca – *Cirsium arvense*, m – moss, s – seedlings

4. Discussion

Above results demonstrated that taking into account spatial, temporal and functional gradients, some new (informative and ordering) aspects in the collected empirical data sets can be found. This new information could integrate structure and function of the saline ecosystem.

Several studies demonstrated relations between vegetation zonation in saline meadows and soil salinity (Burchil & Kenkel 1991; Piernik et al. 1996; Cantero et al. 1998; Alvarez Rogel et al. 2000, 2001). The analysis of spatial gradients additionally revealed that observed spatial vegetation pattern was preserved by gradients of different sizes. The balance in species distribution between the *Salicornia europaea* zone and the *Puccinellia distans* zone was maintained by two times higher values of EC_e, Cl^- concentration and Cl^-, Na^+, Ca^{2+} content, whereas the balance between the *Pucci-*

nellia distans zone and the *Elymus repens* zone – by 3.5–7 times higher values. Based on the above, a conclusion could be drawn that existence of the distinct *Salicornia europaea* zone was dependent on mechanisms limiting expansion of the perennial grass *Puccinellia distans*. In this case competitive ability of the perennial species is higher than of annual *Salicornia europaea*. Distribution of the latter one very often depends on available open space (Ellison 1987). On the other hand *Elymus repens* is known to be a stronger competitor compared to *Puccinnellia distans*, being a strong competitor as well (Reyel et al. 1996; Beyshlag et al. 1996). Therefore the balance between the *Elymus repens* and *Puccinnellia distans* zones must be maintained by special mechanisms and high energy.

The analysis of temporal gradients in Cl^- concentration demonstrated that the highest gradient was recorded in the *Salicornia europaea* zone, next in the *Puccinellia distans* zone and the smallest one in the *Elymus repens* zone. This allows conclusion about the buffer capacity and stability of vegetation zones. If temporal gradients are small, the system will be highly buffered and stable (Patten 1992). If the gradients are high, there will be a small buffer capacity and high quantitative and qualitative influences. The highest temporal salinity gradient in the *Salicornia europaea* zone was dependent on evaporation due to relatively low vegetation density there. During dry periods, Cl^- concentration increased in the upper parts of the soil, whereas during heavy rains it decreased as Cl^- anions were washed down the soil. In the *Puccinellia distans* zone and the *Elymus repens* zone changes in moisture and Cl^- concentration could be buffered by dense vegetation. Transplantation experiment confirmed liability of the *Salicornia europaea* zone, because after two growing seasons no individuals of glasswort were found on *Salicornia europaea* transplants in the *Elymus repens* zone. In the similar experiment, Wilkoń-Michalska (1976) observed the growth of *Salicornia europaea* transplanted to *Potentillo-Fectucetum arundinaceae* association during only three growing seasons.

The relation between spatial, temporal and finally functional gradients is evident. Functional gradients are determined by chain of ecological processes at certain stage of phytocenoses. The vegetation structure and zonation in the investigated meadow were related to the salinity gradient. This gradient implied some control mechanisms of the observed ecosystem stage. Following the present results one could conclude that elimination of the salinity gradient is accompanied by a chain of functional vegetation changes. Functional gradients demonstrated that changes in a species number and in above-ground biomass structure were recorded at the first succession stage. A lot of glicophytic species invaded the *Salicornia europaea* and *Puccinellia distans* transplants in the *Elymus repens* zone. At the same time *Salicornia europaea* died on those transplants and *Puccinellia distans* considerably decreased. At the next stage only changes in above-ground biomass of the species were found – a considerable increase of *Elymus repens* and decrease of other glycophytes.

The results of the present study comprise lots of information related to functions of the investigated saline system and therefore they could have a practical approach. Vegetation changes after eliminating the salinity gradient led to species richness decrease. In total 18 plant species were recorded in the phytosociological relevés from three vegetation zones on the meadow. In the *Elymus repens* zone with the lowest salinity, only 11 species were recorded. Occurrence of *Salicornia europaea*, *Spergularia marina* and *Atriplex hastata var. salina* was directly related to the salinity gradient. The *Salicornia europaea* zone was the most labile one on the meadow. It would be the most sensitive to disturbances and environmental changes. Therefore the desalinisation concept in the landscape management should take into account losses of species richness, whereas the protection concept should consider buffer capacity of vegetation zones. In general, taking a practical approach to the gradient concept one could conclude that landscape management should enable the ecosystems to perform a long-term creative, self-organised pattern of gradient dynamics (Müller 1998).

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