

CHARACTERISATION OF PRODUCTIVITY LIMITATION OF SALT-AFFECTED LANDS IN DIFFERENT CLIMATIC REGIONS OF EUROPE USING REMOTE SENSING DERIVED PRODUCTIVITY INDICATORS

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Received 9 February 2011; Revised 14 April 2011; Accepted 28 June 2011

ABSTRACT

Soil salinity is a global issue and one of the major causes of land degradation. The large scale monitoring of salt-affected areas is therefore very important to shed light on necessary rehabilitation measures and to avoid further land degradation. We address the productivity limitation of salt-affected soils across the European continent by the usage of soil maps and high temporal resolution time series of satellite images derived from the SPOT vegetation sensor. Using the yearly dynamism of the vegetation signal derived from the Normalised Difference Vegetation Index, we decomposed the spectral curve into its base fraction and seasonal dynamism fractions next to an index approximating gross primary productivity. We observe gross primary productivity, base fraction and seasonal dynamism productivity differences of saline, sodic and not salt-affected soils under croplands and grasslands in four major climatic zones of the European continent. Analysis of variance models and post hoc tests of mean productivity values indicate significant productivity differences between the observed salt-affected and salt free areas, between management levels of soils as well as between the saline and sodic character of the land. The analysis gives insight into the limiting effect of climate in relation to the productivity of salt-affected soils. The proposed indicators are applicable on the global level, are objective and readily repeatable with yearly updates, thus, might contribute to the global operational monitoring and assessment of degraded lands. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS: salt-affected soils; land productivity; remote sensing; climate; Europe

INTRODUCTION

Arid zones are the most vulnerable to degradation processes because of their fragile ecosystems but temperate regions in the northern hemisphere are also experiencing land degradation. Land degradation indeed is a global issue and together with climate change is now being given high policy priority, especially in view of accelerated population pressures. Terrestrial ecosystems and soil influence climate, among others, by exchanging climatically important gases with the atmosphere (Meir *et al.*, 2006). Degraded lands emit more carbon thus largely contribute to global warming. Soil properties and processes form a crucial part of the understanding of the terrestrial hydrologic cycle and of the functioning of terrestrial ecosystems. Soil degradation including soil salinity, erosion and waterlogging are among the main factors of land degradation and desertification with severe impacts on crop yields and agricultural production. Particularly occurring in arid and semi-arid regions, salinization and alkalinization are among the most common land degradation processes,

because of low or too erratic precipitation patterns. Under such climatic conditions soluble salts accumulate in the soil generally influencing soil properties and the environment and as a consequence, they lessen soil productivity (Farifteh *et al.*, 2006). The global extent of primary salt-affected soils is about 955 Mha, whereas secondary salinization affects some 77 Mha (Metternicht and Zinck, 2003). The monitoring of soil salinization is very important for decision making in order to undertake appropriate rehabilitation and reclamation steps and to avoid further land degradation.

Salts are likely to concentrate on the surface with a spectral contrast to other surface features that is likely to be detected by remote sensing. Remote sensing, indeed, has been widely used to map and to detect salt-affected areas for almost four decades now (Hunt and Salisbury, 1976; Goetz *et al.*, 1985; Goetz and Herring, 1989; Hick and Russell, 1990; Csillag *et al.*, 1993; Mougenot *et al.*, 1993; Verma *et al.*, 1994; Metternicht, 2001; Ben-Dor *et al.*, 2002; Dehaan and Taylor, 2003; Metternicht and Zinck, 2003; Farifteh *et al.*, 2006). Most of these studies are based on either visual or semi-automatic classification of digital images including also thermal bands, measurement of hyperspectral reflectance spectra and the mapping of saline soil endmembers

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and the use of expensive ground radiometers or laboratory radiometers with soil samples. Some of these studies suggest that the potential of remote sensing for the study of salt-affected soils but especially for slightly to moderately affected areas is restricted (Manchanda and Iyer, 1983; Jain *et al.*, 1988; McGowen and Mellyon, 1996; Metternicht and Zinck, 2003). The identified spectral bands on commercially used satellite sensors may not be optimal for the delineation of salinity because of, for example, water vapour absorption in the atmosphere (Csillag *et al.*, 1993). Data acquisition from passive sensors needs to be planned carefully as identification of surface salt should be carried out during the dry periods. On the other hand, the use of active sensors with polarimetric airborne radar to map soil dielectric properties (Taylor *et al.*, 1996a, Taylor *et al.*, 1996b) is limited as the images are needed to be acquired under uniformly wet conditions.

Salt-affected soils are not necessarily free of vegetation, halophytic species can be present naturally and salt tolerant crops can be cultivated. Because of the absorption in the visible and high reflectance in the near-infrared electromagnetic spectrum, the Normalised Difference Vegetation Index (NDVI) could be used to map salt-affected areas through the monitoring of halophyte vegetation. Szabó *et al.* (1998) and Zhang *et al.* (1997) successfully correlated remote sensing derived vegetation indices with soil salinity. However, Metternicht and Zinck (2003) report contrasting reflectance of the halophytic *Chenopodiaceae* species and *Cynodon dactylon* in the visible and near-infrared spectrum. Indeed, the NDVI has hardly been reported for mapping soil salinity, although Fernández-Bucesa *et al.* (2006) reported very good correlations between Landsat TM derived NDVI, electric conductivity and sodium absorption ratio. Pérez González *et al.* (2006) identified saline hydromorphic soils using NDVI of halophytic vegetation by correlating Landsat TM derived NDVI with the spatial variability of chemical and physical properties of a transect. However, according to Metternicht and Zinck (2003) the presence of vegetation might complicate the detection of salinity by NDVI because of spectral confusion with the salt reflectance properties. In order to overcome identification problems caused by different land management practices, vegetation cover or different soil types, the use of multitemporal images is suggested (McGowen and Mellyon, 1996). Lobell *et al.* (2010) used the average of the MODIS enhanced vegetation index and found strong relationship with soil salinity, which outperformed NDVI capturing one-third to half of the spatial variability in soil salinity.

The delineation and differentiation of saline and sodic soils is generally achieved by, for example, maximum likelihood classification of satellite derived vegetation indices with acceptable accuracy. However, for these methods to be operational high spatial, spectral and/or temporal resolution satellite

images with considerable costs and limited spatial coverage are needed. An analysis on a continental or global level with these methods is most probably out of the budget of research institutes or even of governmental organisations, and the time and man power necessary for the analysis would make such studies ineffective/inefficient. In order to overcome the problems of monitoring salt-affected soils by optical high resolution sensors on the global level, we propose to use biomass productivity indicators by time series of remote sensing images with high temporal resolution. Remote sensing sensors that provide global coverage with long time series have spatial resolution of 1 km (SPOT and NOAA satellites) or a resolution of around 250 m (MERIS and MODIS sensors) but with shorter series. The utilisation of low resolution satellite sensors has the obvious disadvantage of limited spatial observations. However, these sensors provide daily and global coverage for several decades with low cost or even cost free. Furthermore, the time series analysis method we apply is automatic without human intervention, thus is cost and time effective and is free of subjectively introduced errors throughout the processing chain that is a common drawback of image classification methods.

We have derived three productivity indicators from time-series (1998–2008) of SPOT vegetation images over Europe: an approximation of gross primary productivity (GPP), the base fraction indicating vegetation permanently covering the area and the seasonal dynamism that indicates the seasonally changing vegetation biomass. First, we have tested if there were differences in the GPP, base fraction and seasonal dynamism between four climatic zones of Europe and between cropland and grassland land covers. Second, we have investigated the identified productivity differences between salt-affected and not salt-affected soils under cropland and grassland management in the four climatic zones. Subsequently, we have divided the dataset into saline and sodic soils and analysed the productivity differences between the salt-affected and not salt-affected soils in addition to the differences between cropland and grassland land use types. In their study Wiegand *et al.* (1991, 1994) showed that NDVI could not differentiate between saline and sodic soils, whereas Smit *et al.* (2008) found that NDVI did not correlate to European grassland productivity. From our results we conclude that the here presented biomass productivity indicators derived from time series of remote sensing images can not only differentiate between salt-affected and not salt-affected soils but also between land use types on salt-affected soils and between saline and sodic soil types. Because of the good availability of time series satellite images these productivity indicators could provide optimal input to the operational assessment of local, continental and global land degradation issues.

DATA AND METHODS

Delineation of Saline and Sodic Soils

Two major data sources are available to delineate areas with high salt accumulation in Europe: the European Soil Database (ESDB, 2004) and the map of salt-affected soils in Europe compiled by Szabolcs (1974). The two spatial datasets were used by Tóth *et al.* (2008) to produce an updated map of salt-affected soils for the European Union (EU). The spatial extension of this map was elaborated for the purpose of our current study. Eastern segments of the digital version of the original map of salt-affected soils of Europe (Szabolcs, 1974) have been used to complement the recently produced map of the EU coverage. The new product—presented in Figure 1—consists of soil salinity information for the areas within the EU based on the combination of the ESDB (2004) and the map of Szabolcs (1974), following the methodology described in Tóth *et al.*, (2008). For regions outside the EU saline areas are delineated according to Szabolcs (1974).

Salt-affected (saline and sodic) soils of Europe are classified as follows:

- (1) Saline soils: soils in which high salt content is the dominant reason for limited agricultural potential.
- (2) Sodic soils: soils in which high proportion of exchangeable sodium is the dominant reason for limited agricultural potential.

Soils with medium and high salinity and sodicity were considered in the preparation of the maps and in our current analysis. Soils showing electrical conductivity (measured in saturation extract) values above 4dS m^{-1} were classified as saline, and soils having exchangeable sodium percentage more than six were classified as sodic. Other soils, with lower values of conductivity and exchangeable Na, were excluded from the assessments.

Taking the above conditions into account, soil mapping units were classified into five categories:

- (1) Saline soils cover more than 50 per cent of the mapping unit
- (2) Saline soils cover less than 50 per cent of the mapping unit
- (3) Sodic soils cover more than 50 per cent of the mapping unit
- (4) Sodic soils cover less than 50 per cent of the mapping unit
- (5) Potentially salt-affected areas

All areas outside the above categories were free from salt accumulation or risk of salt accumulation. In our analyses, we compared areas where salt-affected soils are dominant to lands of salt free soils. Therefore, areas of categories 1 and 3 were included in the statistical analyses. Potentially salt-affected areas and areas where salt-affected soils are not a dominant (categories 2, 4 and 5) were not considered.

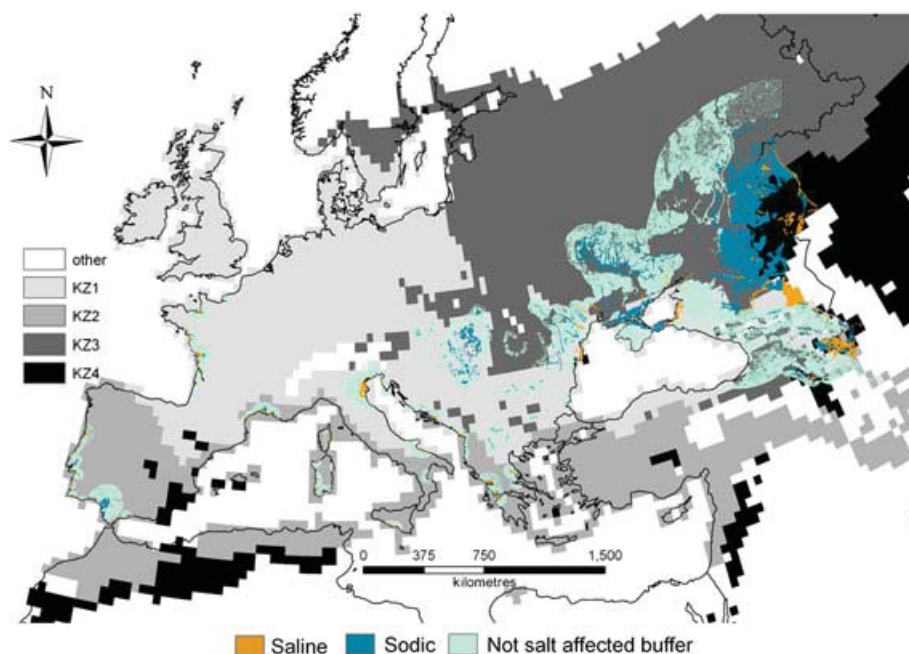


Figure 1. Spatial distribution of the saline and sodic soils and their respective buffers. See Table I for explanation of climatic zones.

Table I. Aggregation of the Köppen-Kottek climatic zones (see Figure 1)

Code of climatic zone in the current study	Name of climatic zone in the current study	Description of climatic zone (Kottek <i>et al.</i> , 2006).	Code of original climate class (Kottek <i>et al.</i> , 2006)
KZ1	Western transitional (suboceanic to subcontinental)	Warm temperate, humid	Cfa, Cfb
KZ2	Mediterranean	Warm temperate, with dry and warm summers	Csa, Csb
KZ3	Continental European (eastern, semiarid)	Snow climate, humid	Dfa, Dfb, Dfc
KZ4	Arid	Cold steppe/desert climate	Bwk, Bsk

Aggregation of Climatic Zones

Temperature and precipitation are the two main climatic variables that are decisive both in the development of salt-affected soils and in biomass productivity in general. A classification scheme of major climatic zones of the world, based on temperature and precipitation patterns, has been designed by Köppen (1900) and recently updated by Kottek *et al.* (2006). The European section of the updated map was used for our study and the climatic classes of Europe have been arranged into four groups. This arrangement was necessary in order to delineate distinct areas of salt-affected soils under characteristic climatic conditions for reliable statistical analysis of the biomass productivity indicators. The four climatic groups with their main characters and original Köppen codes are presented in Table I. Statistical analysis addressing saline and sodic soils was performed for each of the climatic zones below.

Satellite Data Processing

In order to derive the productivity indicators SPOT Vegetation time series data were acquired in decade format (10 days maximum composite) for 11 years covering the period from 1998 to 2008 for the spatial extent of Europe. The vegetation Programme allows daily monitoring of terrestrial vegetation cover at regional through global scale on a 1 km spatial resolution. These data were already successfully applied in several regional and global scale studies

dealing with vegetation biophysical properties, land cover assessment, monitoring of forest ecosystems, desertification and land degradation and the assessment of GPP.

Following the method of Reed *et al.* (1994) the SPOT vegetation data were smoothed using a five interval (here the decades) running median filter in order to adjust for eventual cloud contamination of the pixels. Consecutively, the original time series was overlaid with smoothed forward and backward lagged curves, which were determined from the original data set itself by means of a forward and backward computed moving average (MA) algorithm (Figure 2). In the method of Reed *et al.* (1994), the number of decades during the non-growing period was used to calculate the lag. We argue that over a whole continent with very diverse climatic regions, ecosystems, land use and land cover this number cannot be generally applied. Therefore, we computed the lag as the one standard deviation (expressed in days, see SD in Figure 2) from the barycentre of the area under the NDVI curve, which was averaged over all the years. This way the time series dynamism of each pixel under different climatic regions, land cover and ecosystems was incorporated in the derivation of the phenological measures. In-depth description of the method is given in Ivits *et al.* (2011).

The cross points of the original time series and the MA curves were used to define an approximation of the start and the end of the vegetative growing season for each year (Figure 2). GPP was approximated as the area under the

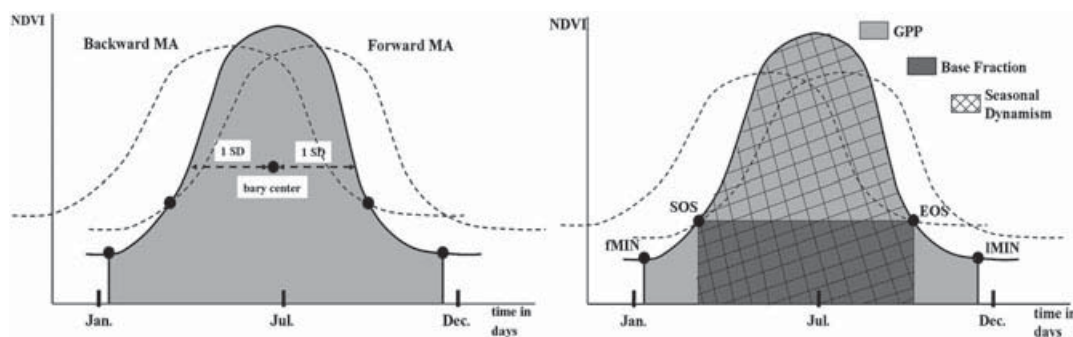


Figure 2. Schematic explanation of the phenological indices calculated from an NDVI 1 year time series curve using moving averages (MA). Abbreviations are explained in the text.

NDVI curve delimited by the calculated yearly first minimum (fMIN) and last minimum (IMIN) points. This area can be disaggregated into a base fraction that is more significantly related to a permanent vegetative cover and a Cyclic Fraction, which is representing the yearly seasonal dynamism of green matter production. The base fraction was calculated as the integral under the Start of Season (SOS) and End of Season (EOS) points, whereas the seasonal dynamism was derived as the integral below and above these points. We have derived the ratio of the base fraction over the seasonal dynamism in order to better relate to functional land cover types or combination of them. Higher ratio values

indicate larger base fraction, whereas lower ratio values indicate the dominance of seasonal dynamism throughout the yearly vegetation development. The GPP and ratio productivity indicators were extracted for each year (1998–2008) separately and subsequently averaged into one temporal mean value for each pixel in the study area (Figure 3).

Spatial Analysis

Two soil classes were considered: class 1 being saline and class 2 being sodic soils. Around each soil polygon a buffer was defined based on the extent of the individual polygons in order to test the performance of the remote

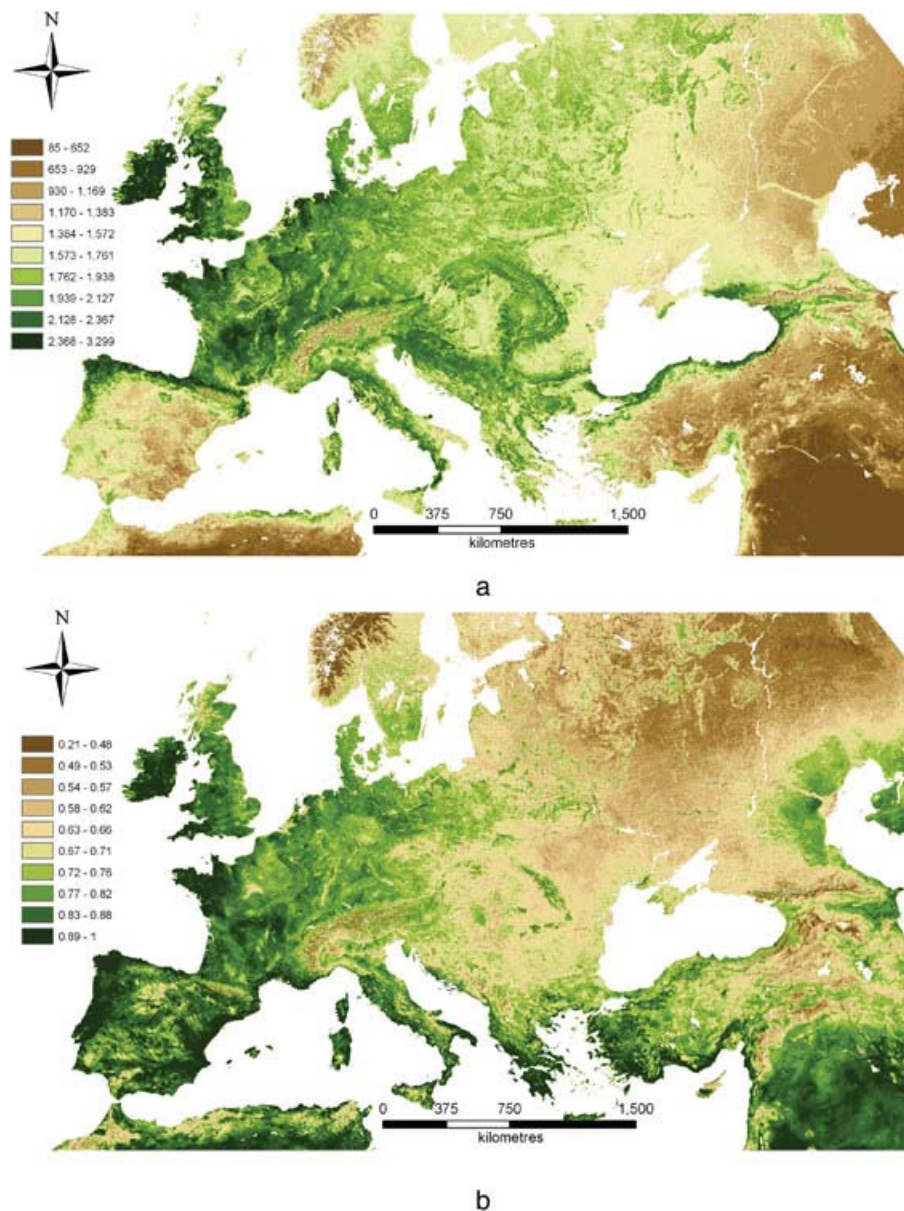


Figure 3. Mean GPP (a) and mean ratio (b) derived from time series of SPOT vegetation NDVI images averaged over the time-series 1998–2008 for Europe. GPP and ratio are explained in the text.

sensing indicators for differentiating salt-affected areas from areas not affected by salinity. Each polygon was approximated by its minimum bounding rectangle of equal edges. After calculating the area of the rectangles, the diagonal (D) of the minimum bounding rectangles was defined as follows:

$$D = \sqrt{\text{area}} \cdot \sqrt{2}$$

The computed diagonals were used as the distance around each polygon to calculate the individual buffers. Within the polygons attributed as saline and sodic soils and within their buffers, we have classified managed and natural systems based on the Global Land Cover (GLOBCOBER; Bicheron *et al.*, 2006). Both datasets (i.e. the soil classification and GLOBCOVER) were handled as raster data, and they were intersected in a GIS in order to create appropriate number of spatial entities for the subsequent statistical analysis. By means of zonal statistics, we have derived the mean value of the pixels of each productivity indicator underlying each of the spatial entities representing the following classes: (i) saline cropland (SalC); (ii) saline grassland (SalG); (iii) not saline cropland (NSalC); (iv) not saline grassland (NSalG); (v) sodic cropland (SodC); (vi) sodic grassland (SodG); (vii) not sodic cropland (NSodC); and (viii) not sodic grassland (NSodG).

Statistical Analysis

We have tested if there were significant differences between saline and sodic croplands and grasslands and the climatic zones in the derived productivity indicators GPP and the ratio of base fraction and seasonal dynamism. First, the GPP and the ratio were subject to a two-way ANOVA having two levels of soils (salt-affected, not salt-affected) and four levels of climatic zones (see Table I). We have tested the significance of the two ANOVA models with the GPP and the ratio being the independent variables, respectively. Furthermore, we have tested the main effect of salt-affected, of the climatic zones and the interaction effect of these variables on the productivity indicators. We report the degrees of freedom (df), the F -value and the significance of all the tests. This analysis tested if there was a general effect of salinity and climate on the average GPP and ratio biomass productivity.

Subsequently, we have divided the spatial data into saline and sodic areas under cropland and grassland management and analysed the productivity differences between the saline and the sodic groups. We have run a one-way ANOVA for saline and another one-way ANOVA for sodic soils within each of the four climatic zones. For both ANOVA, we had four levels of saline (SalC, SalG, NSalC, NSalG) and another four levels of sodic soils (SodC, SodG, NSodC, NSodG), respectively (see Spatial Analysis section for the

description of the soil classes). The homogeneity of variance assumption of ANOVA was tested with the Levene's test statistics. Because of the violation of this assumption (significant test result), we report the alternative Brown-Forsythe statistic, which is a robust version of the F -ratio for not homogeneous group variances. Post hoc tests were used to compare the mean productivity indicators between the salt-affected soils and their buffers and between the saline and sodic soils. Because of the violation of the homogeneity of variance assumption of ANOVA, we used Tamhane's test statistic, which gives a robust value against this criteria.

RESULTS

Spectral Signatures of the NDVI Curve

Figure 4 presents spectral signatures extracted from the NDVI time series for three consecutive years (2003, 2004 and 2005) for each saline and sodic soil group in the four aggregated climatic zones. Regarding seasonal peaks, the largest NDVI values are characteristic for the transitional zone. The continental zone exhibits similar behaviour, whereas the Mediterranean and arid zones show lower seasonal peaks. Regarding seasonal low NDVI values, the values increase in the order of continental, arid, transitional and Mediterranean, following the increasing temperature and growing season length in these zones. In the transitional and continental zones the data has strong seasonality and a characteristic growing season curve resulting from the extreme winter cold versus summer hot temperatures. In the arid zone and especially in the Mediterranean, the curves show less seasonality, and the growing season is less characteristic because of erratic rainfall patterns. The earliest biomass peak and the least seasonality are shown in the Mediterranean zone, because the average temperature is the largest in this zone. In the transitional and Mediterranean zones, sodic areas demonstrate the lowest NDVI values, whereas in the other zones, these low values are less evident. In the continental zone, the seasonal part of the saline and sodic NDVI curves follows a similar pattern but the yearly minima of sodic areas are deeper on the NDVI curve.

A characteristic feature of the NDVI curves is that sodic curves typically run lowest because of the combined effect of salinity and sodicity. In transitional and most evidently continental zones, the summer NDVI peak in salt-affected areas is smaller and narrower than in not salt-affected areas because the dry summer affects the biomass growth stronger in these soils. It is evident that most curves are composed of several crops, but it is the Mediterranean zone in which two kinds of crops, one early (e.g. presumably wheat/barley) and one late (e.g. sunflower) are planted. Accordingly, the NDVI curves of croplands in the Mediterranean express a second

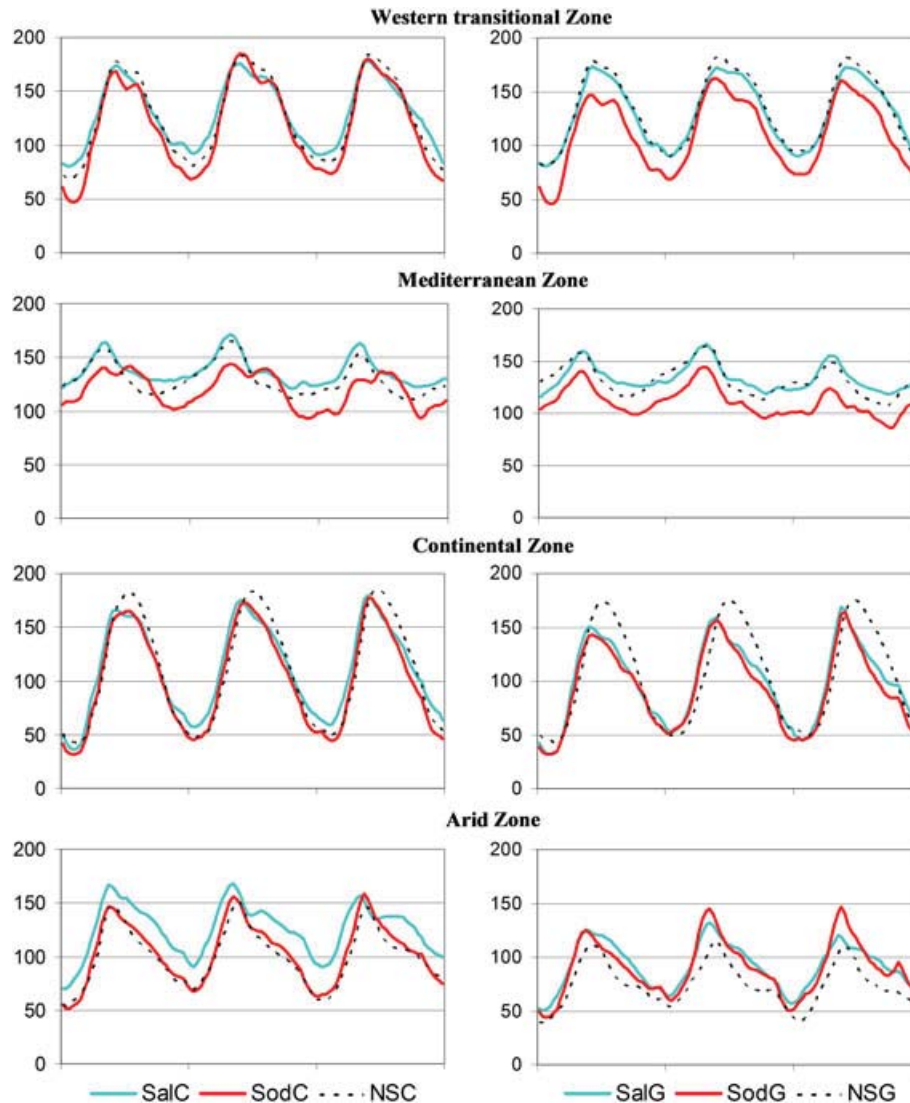


Figure 4. Extract (2003–2005) of the SPOT NDVI time-series showing spectral signatures for the four climatic zones for saline croplands (SalC), sodic croplands (SodC), not saline or not sodic croplands (NSC), saline grasslands (SalG), sodic grasslands (SodG) and not saline or not sodic grasslands (NSG). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

seasonal peak. Not salty areas have the highest NDVI values in the transitional and continental zones but similar values to saline croplands and to saline grasslands in the Mediterranean. In the arid zone, however, salt-affected soils appear to have higher NDVI values compared with not saline areas. Saline croplands exhibit the highest NDVI values in the arid zone followed by sodic and not salt-affected croplands. In the arid zone, salt-affected and not salt-affected grasslands have lower NDVI values compared with croplands because grasslands here are composed of barely vegetated lands. The yearly minima are the lowest in the continental and arid zones and the highest in the Mediterranean indicating a strong reflection of the soil background in the latter zone.

Productivity Differences between Salt-affected and not Salt-affected Soils

The mean GPP and ratio productivity values were subject to a two-way ANOVA with two levels of soils (salt-affected and not salt-affected) and four levels of climatic zones. Both models and all the main and interaction effects were significant (Table II, $p < 0.001$). Climate had the highest main effect on both GPP and ratio productivities. The interaction effect of climate and soil salinity on GPP productivity was lower than the main effect of salinity, whereas the interaction effect of climate and soil salinity on the ratio was higher than the main effect of salinity. Tamhane's post hoc comparison showed significant differences between salt-affected

Table II. Two-way ANOVA model results of the average GPP and ratio values with salinity and climate as factors

	df	GPP		Ratio	
		F	Significance	F	Significance
Model	7	6016.5	<0.001	21827.9	<0.001
Climate	3	7283.5	<0.001	24566.4	<0.001
Salt-affected conditions	1	464.3	<0.001	72.2	<0.001
Climate*Salt-affected conditions	3	290.6	<0.001	209.6	<0.001

and not saline soils. Salt-affected soils had lower mean GPP productivities than not salt-affected soils under all but the arid climate (Table III and Figure 5). In this region, salt-affected soils had significantly higher mean GPP productivity. There was a remarkable decreasing trend of mean GPP values from the transitional towards the arid climatic region. Under the continental climate, the ratio of salt-affected soils was significantly higher compared with not salt-affected soils evidencing the dominance of the base fraction, but in the other regions we did not observe significant differences between salt-affected and not affected areas. Highest ratio values were observed in the Mediterranean and smallest values in the continental regions, indicating the dominance of the base fraction in the former and high seasonal dynamism in the latter climatic zone.

Productivity Differences of Saline and not Saline Soils

One-way ANOVA was used to test productivity differences between saline and not saline croplands and between saline and not saline grasslands in each of the climatic zones. The mean GPP and the mean ratio productivity values of saline and not saline soils differed significantly ($p < 0.001$) in all climatic regions (Table IV). The Brown-Forsythe version of the F -statistics revealed that under similar climatic conditions GPP differentiates stronger between the observed saline areas and that the comparative difference between GPP and ratio was the largest in the Mediterranean. Under the continental climate however, the two productivity indicators yielded comparable F -statistics.

The post hoc comparison test revealed that the mean GPP productivity was significantly lower under saline croplands (SalC) as well as under saline grasslands (SalG) compared with not saline areas (NSalC and NSalG) in all but the arid climatic zone (Table V and Figure 6). In the arid region,

saline croplands and grasslands had significantly higher mean GPP biomass productivity compared with not salt-affected areas. The base fraction and seasonal dynamism were similar in the Mediterranean under saline and not salt-affected areas. Saline croplands had significantly lower base fraction than not saline croplands in the transitional zone (ratio of SalC versus NSalC) whereas in the continental and arid regions the base fraction of saline croplands was significantly higher compared with not saline croplands. Saline grasslands had significantly higher base fractions under the continental and arid regions compared with not saline grasslands whereas in the other climatic zones there was no significant difference between saline and not saline grasslands.

Productivity Differences of Sodic and not Sodic Areas

One-way ANOVA was used to test productivity differences between sodic and not sodic croplands and between sodic and not sodic grasslands in each of the climatic zones. The mean GPP and ratio productivity values of sodic and not sodic soils differed significantly in all climatic zones (Table VI). The Brown-Forsythe statistic revealed that GPP differentiated stronger between the sodic and not sodic areas in the transitional and continental regions and the largest comparative difference between the GPP and ratio was observed under the transitional zone. In the arid region on the other hand sodicity had a stronger affect on the ratio than on the GPP productivity differences. With other words there were larger differences between the ratio of sodic soils than between the GPP of sodic soils in the arid zone.

The post hoc comparison revealed that the mean GPP was significantly lower under sodic croplands (SodC) and sodic grasslands (SodG) compared with not sodic areas (NSodC and NSodG) in all but the arid climatic zone (Table VII and Figure 7). Under arid climate the mean GPP of

Table III. One-way ANOVA: Post hoc multiple comparison mean differences for salt-affected and not salt-affected lands in the four climatic zones

		Western transitional	Mediterranean	Continental	Arid
GPP	Salt-affected versus not salt-affected	-153.3;***	-104.9; ***	-139.9; ***	135.7; ***
Ratio	Salt-affected versus not salt-affected	0.001;	0.001;	0.03; ***	0.001;

*the mean difference is significant at the 0.05 level.

**the mean difference is significant at the 0.01 level.

***the mean difference is significant at the $p < 0.001$ level.

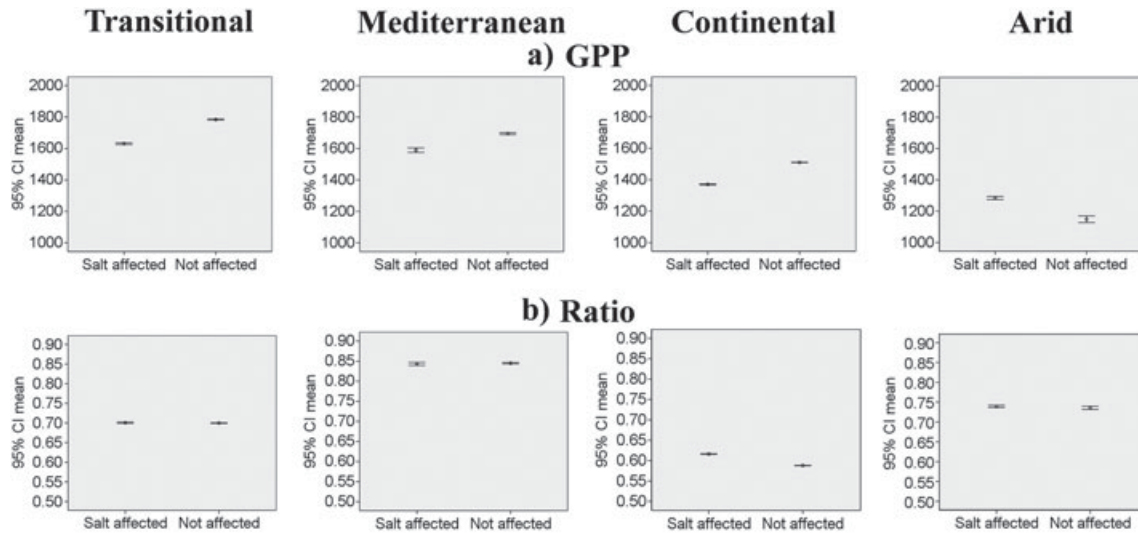


Figure 5. GPP and ratio means with 95 per cent CI on salt-affected and not salt-affected soils in the four climatic zones.

grassland was significantly higher compared with not sodic grasslands whereas there was no significant GPP difference between sodic and not sodic croplands. The base fraction and seasonal dynamism were similar in the Mediterranean under sodic and not sodic areas. The mean ratio of sodic croplands was significantly higher compared with not sodic croplands under the continental climate, indicating higher base fraction and lower seasonal dynamism but there was no significant difference between the ratio of sodic and not sodic croplands in the other climatic regions. Sodic grasslands had significantly higher base fractions compared with not sodic grasslands in the transitional and continental regions but similar ratio values in the other climatic zones.

Productivity Differences between Saline and Sodic Croplands and Grasslands

One-way ANOVA was used to test productivity differences between saline croplands and sodic croplands and between saline grasslands and sodic grasslands in each of the four climatic zones Table VIII. The effect of salinity was significant on GPP and on the ratio in all climatic zones. The Brown-Forsythe version of the F-statistic revealed that under the transitional, continental and arid regions the ratio differed stronger between saline and sodic soils than the GPP.

This was striking especially under the arid and under the transitional climates, whereas in the continental region the ANOVA yielded a comparative F-statistics for the average GPP and the average ratio values. Only under the Mediterranean region did salinity have a stronger effect on the GPP than on the ratio similarly to the results seen for the comparison of saline with not saline and sodic with not sodic soils.

The post hoc comparison revealed that the mean GPP productivity was significantly higher on saline croplands and saline grasslands compared with the sodic areas (SalC versus SodC and SalG versus SodG, Table IX and Figure 8) in each of the climatic zones. Within the same climatic regions we have observed larger productivity differences between the average GPP of saline and sodic croplands compared with the average GPP differences between saline and sodic grasslands. Largest differences between saline and sodic areas were observed in the Mediterranean. The mean ratio was significantly higher on saline areas than on sodic areas in all four climatic zones. This shows that on saline areas the base fraction dominates the yearly seasonal dynamism when compared with sodic soils. In the transitional, Mediterranean and arid regions we have observed larger ratio differences between saline and sodic croplands when compared with saline and sodic grasslands. Under the

Table IV. One-way ANOVA: Post hoc multiple comparison mean differences for saline lands in the four climatic zones

	Western transitional	Mediterranean	Continental	Arid
GPP	$F(3,4652.8)=326.7, p<0.001$	$F(3,4097.5)=30.6, p<0.001$	$F(3,2829.1)=45.1, p<0.001$	$F(3,1137.6)=78.1, p<0.001$
Ratio	$F(3,5301.2)=125.4, p<0.001$	$F(3,3926.8)=6.3, p<0.001$	$F(3,2672.9)=30.9, p<0.001$	$F(3,1429.5)=30.1, p<0.001$

Table V. One-way ANOVA: Post hoc multiple comparison mean differences for saline lands in the four climatic zones

		Western transitional	Mediterranean	Continental	Arid
GPP	SalC versus NSalC	-232.5; ***	-51.9; ***	-131.9; ***	309.7; ***
	SalG versus NSalG	-103.4; ***	-99.9; ***	-30.8;	214.9; ***
Ratio	SalC versus NSalC	-0.015;***	0.002;	0.014; ***	0.004; ***
	SalG versus NSalG	0.001;	-0.002;	0.023; ***	0.016; *

*the mean difference is significant at the 0.05 level.

**the mean differences is significant at the 0.01 level.

***the mean difference is significant at the $p < 0.001$ level.

continental climate however, the difference between the average ratio values of saline and sodic grasslands was larger than the difference between saline and sodic croplands.

DISCUSSION

Productivity Differences between Salt-affected and not Salt-affected Lands

The systematic decrease of GPP values from the Western transitional to the arid zone [Figure 5(a)] reflects the severity of climatic conditions (declining precipitation and temperature) resulting in decreasing biomass productivity. Not salt-affected soils in the western transitional zone showed the highest biomass yields and highest productivity difference compared with salt-affected soils followed by the productivity of not salt-affected areas of the continental and the Mediterranean zones, respectively (Table III). The findings from the transitional to continental zones are in agreement with data in the literature (Eynard *et al.*, 2005b; Smit *et al.* 2008) and confirm the general perception considering salt-affected lands as lands with low fertility (Eliasson *et al.*, 2010; Eynard *et al.*, 2005a;

FAO 2000). In the arid zone however, salt-affected soils in general had significantly higher biomass productivity than non-affected soils. In the arid region, relatively large proportions of the salt-affected areas are saline marshlands, which are—due to the abundant water availability—more productive than the surrounding dryer not saline lands. The reason for the increased water availability is the specific hydrogeological setting, which favours the formation of salt-affected soils, because water is provided under the surface despite the dry atmospheric conditions.

Diagrams of the ratio [Figure 5(b)] indicate that seasonal growth has very large importance within the total biomass under the continental and Western transitional climates compared with the other climatic zones, whereas in the Mediterranean, the seasonal dynamism is very low. Spectral signatures (Figure 1) reveal the lowest yearly NDVI minima and the highest yearly NDVI maxima in the continental and Western transitional regions, a result of large seasonal changes of temperature and water availability. In the Western transitional and continental climates, productivity differences between salt-affected and not salt-affected soils were much larger than in the Mediterranean where the base fraction

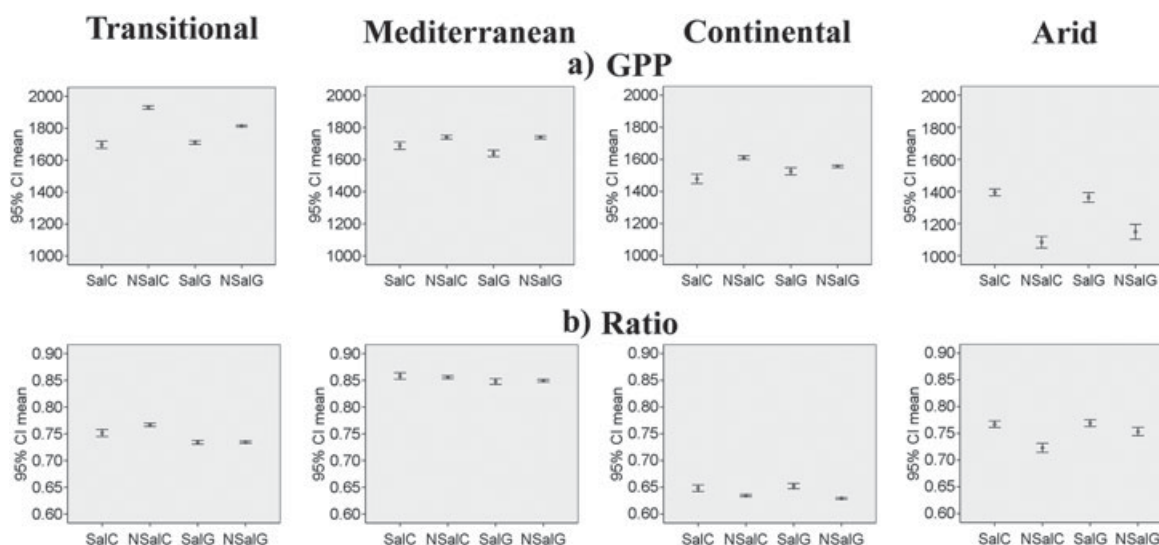


Figure 6. GPP and ratio means with 95 per cent CI on saline soil groups in the four climatic zones.

Table VI. One-way ANOVA: Post Hoc multiple comparison mean differences for saline lands in the four climatic zones

	Western transitional	Mediterranean	Continental	Arid
GPP	$F(3,11416.7)=618.6,$ $p<0.001$	$F(3,1133.1.6)=56.5,$ $p<0.001$	$F(3,36636.5)=2715.8,$ $p<0.001$	$F(3,888.1)=6.3,$ $p<0.001$
Ratio	$F(3,9276.2)=73.6,$ $p<0.001$	$F(3,1467.7)=8.7,$ $p<0.001$	$F(3,36547.9)=1753.7,$ $p<0.001$	$F(3,1260.7)=47.5,$ $p<0.001$

provides the dominant part of the yearly GPP. This indicates the strong climate dependence and the reaction of the productivity of salt-affected soils to seasonal dynamism. The lowest seasonal dynamism in the Mediterranean corresponds to the dominating part of 'evergreen' vegetation cover in this zone. The significant difference between the ratio of salt-affected and not salt-affected soils in the continental climate as opposed to non-significant differences elsewhere indicates the regional diversity of biomass growth dynamism [Figure 5(b)]. Seasonal changes of temperature and water availability result in highest seasonality in the continental region and in moderate seasonality in the transitional zone as opposed to low seasonal dynamism in the Mediterranean and arid regions.

Productivity Differences of Saline and not Saline Lands and Sodic and not Sodic Lands

Soil salinity limits biomass productivity. Results of our current analyses—besides underlining this fact—provide new data on the spatial variability and the magnitude of this limitation. Highest GPP and highest difference between the GPP of saline and non-saline croplands was seen in the Western transitional zone [Figure 6(a)]. At first instance, it might seem that management practices (e.g. amount of fertilisers or better agricultural measures) of crop cultivation could be the major factor supporting higher crop yields. However, we found evidence that the enhanced biomass yield in Western and Central Europe [Figure 3(a)] is not only due to better management practices but is also a result of complex climatic and edaphic factors. First, in the Western transitional zone we observed the largest productivity differences in the grassland land use type as well that reflect the importance of complex climatic and edaphic factors supporting and enhancing the yearly biomass yields. Second, productivity of saline croplands and grasslands under the Western

transitional climate reached the level of productivity of not salt-affected soils under the continental Zone in Europe (Table V). Third, post hoc comparisons indicate that in the transitional climate, the comparative advantage of salt free environment of croplands is larger than it is in the continental zone (GPP of SalC versus NSalC, Table V). Under the Western transitional climate, the balanced water availability from abundant precipitation not only secures water available for plants throughout the growing period but also facilitates decomposition and weathering, which secures higher yields. Water induced nutrient decomposition processes and general water availability is limited under the temperate continental climate because of cold and/or dry periods through larger part of the year. Therefore, the potentiality of soils with favourable characteristics will not be fully realised and yields of these soils will be lower. In the Mediterranean, the ratio of the saline and not saline soils was uniform (Table V).

Possibly because of the very low seasonality resulting from the combination of rather balanced temperature regime and erratic winter rainfall patterns, we observed irregular spectral signatures (Figure 1). It seems that for these reasons, in the Mediterranean the MA method is not sensitive enough to correctly identify the SOS and EOS points on the NDVI curve. Therefore, in the Mediterranean, the seasonal dynamism and the base fraction indicate similar productivity of saline and not saline croplands and grasslands, and here remote sensing methods reach their limits to assess vegetation dynamism. Although in the transitional zone the base fraction is significantly lower under saline croplands compared with non-saline croplands, the opposite is true for the continental and arid zones (Table V, SalC versus NSalC). In accordance with the literature (Huete, 1988; Farifteh *et al.*, 2006), we think that the difference in the

Table VII. One-way ANOVA: post hoc multiple comparison mean differences for sodic lands

		Western transitional	Mediterranean	Continental	Arid
GPP	SodC versus NSodC	-213.5; ***	-168.7; ***	-278.5; ***	37.8;
	SodG versus NSodG	-128.1; ***	-178.1; ***	-38.3; ***	81.8; *
Ratio	SodC versus NSodC	0.004;	-0.011;	0.029; ***	-0.011;
	SodG versus NSodG	0.010; ***	-0.001;	0.027; ***	0.012;

*the mean difference is significant at the 0.05 level.

**the mean diff. is significant at the 0.01 level.

***the mean difference is significant at the $p<0.001$ level.

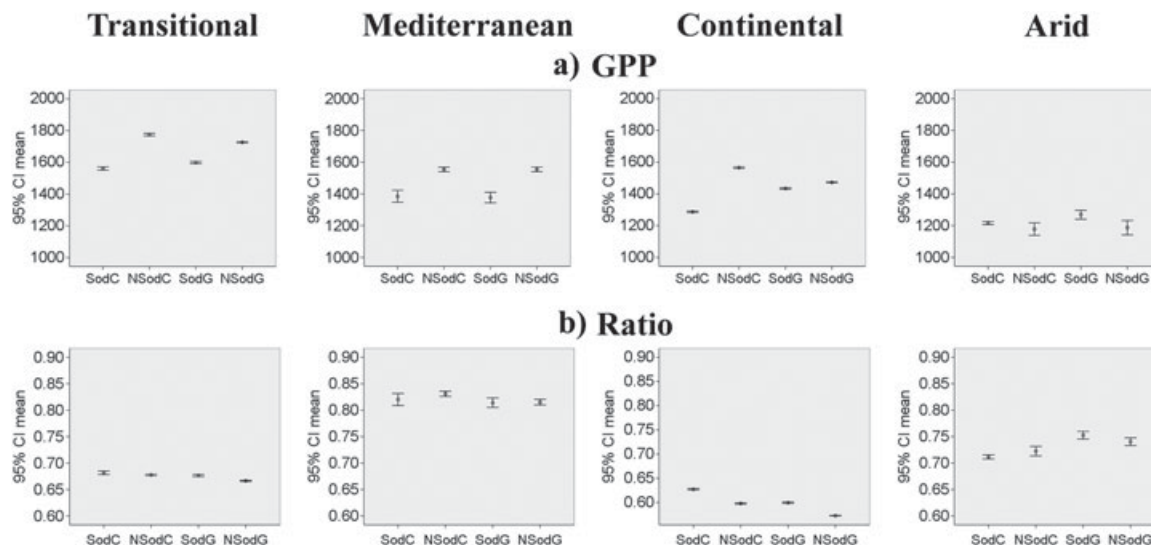


Figure 7. GPP and ratio means with 95 per cent CI under the observed sodic soil groups in the four climatic zones.

NDVI reflectance spectra of cultivated bare soil in varying climates influences this indicator and results in contrasting base fraction and seasonal dynamic fraction values. However, the degree of this influence cannot be read from our data, and we suggest further studies to investigate this problem. Grasslands, as permanent vegetation, have characteristic reflectance signature because of the seasonally changing biomass without much interference from reflectance signals of the soil background. In arid areas, the significantly higher base fraction of saline grasslands, as opposed to not saline grasslands, might be attributed to the local water abundance, as discussed before. In the Continental Zone, the relatively higher proportion of base fraction on saline lands might be due to the large share of natural protected areas (National Parks), which have less human interventions. Not salt-affected lands outside the National Parks are cultivated in larger proportions with biomass removal from the grasslands, resulting in lower base fraction values. It seems therefore that the ratio index could provide a useful indicator for the monitoring of areas under environmental protection and further research is suggested here to fully explore the usefulness of the ratio as ecosystem indicator.

Similarly to salinity, the productivity of sodic croplands and grasslands under the Western transitional climate reached the productivity of not salt-affected soils in the continental zone. We found however, that climatic and edaphic factors have a stronger effect on the productivity of sodic soils. Sodicty

limits GPP of croplands to a proportionally greater extent in the continental region (Table VII, SodC versus NSodC). Physicochemical properties and the associated negative reaction to extreme climatic effects explain the highest constraint sodicty causes over croplands in the continental region. Here a longer dry period is often followed by a period of enhanced rainfall, and the instant wetting of sodic soils causes impermeability of the upper layers. This, in turn, damages biomass production, and therefore the GPP difference between sodic and not sodic cropland is the greatest in the continental region. The largest limiting effect of sodicty on the GPP of grasslands on the other hand was seen in the Mediterranean (Table VII, SodG versus NSodG). In the Mediterranean, the NDVI spectral signature (Figure 1) of sodic grasslands is characteristically lower compared with not sodic areas resulting in significantly lower GPP values. The seasonal contrasts of climate, such as very dry summer and erratic winter rainfall affect the biomass growth of sodic grassland very severely in the Mediterranean causing reduced water availability, a specific handicap of sodic soils. Similar pattern can be observed under the Western transitional and Continental Zones for sodic grasslands as well, but the difference between the GPP values of sodic and not sodic grasslands was less significant.

In the Mediterranean, similarly to saline soils, the ratio indicator for sodic soil was uniform indicating very low

Table VIII. One-way ANOVA: post hoc multiple comparison mean differences for saline and sodic lands

	Western transitional	Mediterranean	Continental	Arid
GPP	$F(3,2841.3)=21.3, p<0.001$	$F(3,1850.1)=40.1, p<0.001$	$F(3,1387.1)=306.6, p<0.001$	$F(3,1938.1)=15.7, p<0.001$
Ratio	$F(3,3002.21)=376.2, p<0.001$	$F(3,1115.2)=28.7, p<0.001$	$F(3,1945.22)=332.3, p<0.001$	$F(3,2132.2)=122.3, p<0.001$

Table IX. One-way ANOVA: post hoc multiple comparison mean differences for saline and sodic lands

		Western transitional	Mediterranean	Continental	Arid
GPP	SalC versus SodC	135.7; ***	302.5; ***	191.8; ***	177.6; ***
	SalG versus SodG	112.1; ***	262.2; ***	91.7; ***	95.1; ***
Ratio	SalC versus SodC	0.070; ***	0.038; ***	0.021; ***	0.056; ***
	SalG versus SodG	0.057; ***	0.034; ***	0.053; ***	0.017; **

*the mean difference is significant at the 0.05 level.

**the mean difference is significant at the 0.01 level.

***the mean difference is significant at the $p < 0.001$ level.

seasonal dynamism and, as discussed before, low sensitivity of the MA method in capturing the SOS and EOS values. Contrary to what we have seen under saline areas, under the arid climate, there was no significant difference in the ratio values between sodic croplands and not sodic croplands (SodC versus NSodC) and between sodic grasslands and not sodic grasslands (SodG versus NSodG). With the increasing aridity, the importance of soil physical and chemical handicaps with respect to water (and nutrient) supply is gaining increasing significance. Although sodic soils perform comparably well under balanced precipitation regimes, physical soil conditions dramatically change with sharp changes of dry and wet periods. Contrary to the case of saline marshland, where water seemed to be a biomass enhancement factor, sodic soils become impermeable in case of sudden rainfall events that reduce biomass productivity and suppress seasonal dynamism and base fractions. This might explain the lowest productivity of sodic and not sodic croplands and sodic and not sodic grasslands, as well as the similar ratio values in the arid region. It seems therefore, that soil sodicity have clear limiting effect on biomass productivity, and the magnitude of the limitation is rather climate

independent. Similarly to saline grasslands in the continental region, the significantly larger ratio of sodic grasslands as opposed to not sodic grasslands is probably due to the presence of protected areas but the significantly larger base fraction under sodic croplands might be due to random variation and need further investigations.

Productivity Differences between Saline and Sodic Lands

Examining the differences in the GPP indicator of croplands and grasslands under different forms of salt-affected conditions in Europe, we can see that saline soils perform better than sodic soils in all comparisons (Table IX and Figure 8). Sodicity prevents water infiltration and restricts water availability, thus limits crop growth, whereas sodium free salinity (or salinity with low Na content) is less limiting for the water regime. Furthermore, additional differences in pH values between sodic and saline soils favours the presence of toxic sodium salts, such as Na_2CO_3 . Both inter and intra-annual variability of water stress might also be greater on sodic soils, resulting in lower temporal averages of GPP. A multi-year analysis is needed to verify this theory, where

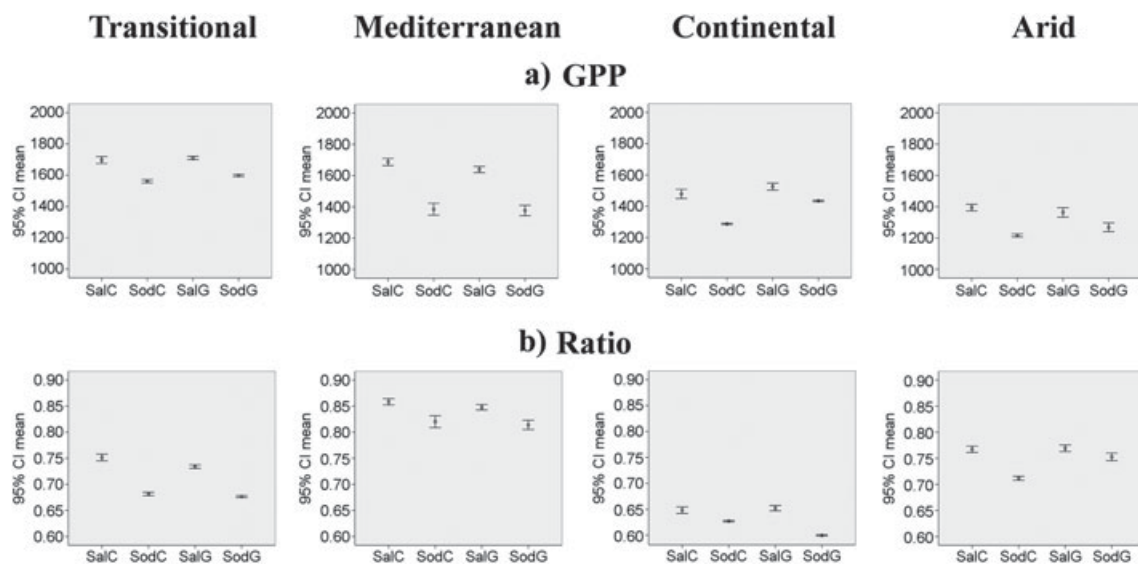


Figure 8. GPP and ratio means with 95 per cent CI under the observed saline and sodic soil groups in the four climatic zones.

the time series of decadal NDVI signal of observed vegetation reflectance values and the analysis of multi-year productivity values might give further insight into this problem. Further to the factors of edaphic water stress, botanical reasons can play a significant role in the productivity differences of saline and sodic grasslands. Because fewer Na tolerant plants (tolerating salt as well as seasonal and annual water stress) grow on sodic grasslands than the generalist halophytes growing on saline lands, the vulnerability of sodic ecosystems is higher, and the long term productivity is therefore lower.

Saline soils have significantly higher base fractions than sodic soils in all climatic regions and in both considered land use types (Table I). This indicates that under saline lands, the generally higher biomass productivity is largely due to the generally higher base fractions rather than higher seasonal dynamism thus a more permanent vegetation cover. This is evident from the spectral curves of the NDVI time series in Figure 1. In the Western transitional, continental and arid zones, the yearly NDVI signal of saline croplands starts up from higher NDVI values compared with sodic croplands similarly to the spectral signals of saline and sodic grasslands in the Western transitional and Mediterranean regions. Apart from probable management differences in some cases, the convincing trend suggests the more favourable plant growth conditions during the vegetative season in salt-affected soils if the salt complex has low proportion of exchangeable sodium. In other words, the limiting effect of sodium is the most pronounced in the most active period of the growing season.

SUMMARY

Soil salinity and sodicity limit biomass productivity. Results of our current analyses—besides underlining this fact—provide new data on the spatial variability and the magnitude of this limitation. GPP productivity was shown to follow a West–East decreasing trend in Europe. Although GPP of not salt-affected lands was generally higher, we found higher productivity of salt-affected soils compared with not salt-affected soils in the arid regions. This is probably due to the presence of saline marshlands where water is available in contrast to not salt-affected dry lands. This is supported by the significantly higher GPP productivity of saline croplands and grasslands compared with not saline lands, whereas the productivity of sodic lands was uniformly low. We suggest that the enhanced GPP productivity observed in the western part of the continent is not only due to the better management practices (e.g. higher amount of fertilisers or better agricultural measures) but also because of the balanced water regime and better nutrient decomposition processes. This was observed on both forms of salt-affected soils, whereas in case of sodicity edaphic factors (i.e. water impermeability) proved to have even stronger GPP limiting effect. Seasonal dynamism

expressed in the ratio index was shown to be a good indicator of productivity differences in Europe and of the related effect of climate because of its sensitivity to seasonal changes of temperature and water availability. However, in the Mediterranean, the ratio index was not sensitive to productivity differences of saline or sodic soils and to land use forms because of the very low seasonality of the vegetation signal, and here, remote sensing methods reach their limits to assess vegetation dynamism. We have shown that in varying climates, the NDVI reflectance spectra of croplands strongly influence this indicator and results in contrasting base fraction and seasonal dynamic fraction values. Cultivated lands are subject to complete biomass removal, and we suggest follow-up research on to what extent the low NDVI values are due to ecosystem functions or biased signals. In contrast, under continental grasslands with permanent vegetation cover, the higher proportion of base fraction on both saline and sodic lands could be due to the large share of natural protected areas with low human interventions, and we suggest further study of this index as an ecosystem state indicator. The productivity of saline soils was higher than the productivity of sodic soils in all comparisons because of reduced water infiltration of sodic soils, whereas sodium free salinity (or salinity with low proportion of exchangeable Na) is less limiting for the water regime consequently for biomass productivity. Additionally, the presence of toxic sodium salts might also limit biomass productivity of sodic soils and the analysis of the effect of intra-annual and inter annual water availability through multi-year productivity indicators is strongly suggested. This finding is supported by the significantly greater base fraction of saline lands, indicating that the limiting effect of sodium is the most pronounced in the most active period of the growing season.

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