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Evaluating the Effect of Nutrient Levels of Major Soil Types on the Productivity of Wheatlands in Hungary

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Soil nutrient status is one of the most important constituents of land productivity. The research presented in this article is aimed at describing the influence of nitrogen, phosphorous, and potassium availability on crop yields across the major soil types of Hungary, under different climatic conditions. For this purpose, historical times series data from a 5-year period (1985–1989) regarding soil, land management, and crop yield of more than 80,000 fields, representing approximately 4 million ha of arable land, were statistically analyzed. The database was recently recovered from statistical archives stored in the format of digital records of the early 1980s and were used to study the productivity of major soil types for winter wheat cropping under balanced fertilizer input. Calculations were made to quantify the effects of soil nutrient levels. The evaluation was also performed for optimal and suboptimal climate conditions. Results show that the effect of nitrogen availability (as obtained from organic-matter content) had the largest influence on winter wheat yields. Up to a 26% difference in yields was observed, both on those soils with balanced material regimes and on those with leaching material regimes, under optimal climatic conditions. The effect of different levels of phosphorous was most significant under optimal climatic conditions on soils with balanced material regimes, reaching up to 17% difference between soils with very low and high phosphorous levels. The effect of different levels of potassium was the least significant in soils with balanced material regimes (maximum 8% difference among categories) and somewhat more pronounced in soils with leaching material regimes. Differences between the effects of nutrient levels due to climatic variation were also observed. According to our findings, stable production can be planned on croplands with average nutrient availability, regardless which of the two soil types they belong to. On the other hand, yield gap can be detected on fields with both low and high nutrient levels among optimal and suboptimal years, for all three nutrients [nitrogen–phosphorus–potassium (N–P–K)] of the analysis. Although our findings are based on historical data, most of the main relationships described are valid under current climatic and management conditions as well.

Keywords Climatic variability, nitrogen, phosphorus, potassium, productivity, soil nutrients

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Introduction

Nutrient dynamics of soil is regulated by soil characteristics and management and also influences the yield potential of the land (Tóth and Máté 1999). The sustainability of agricultural land use can only be guaranteed if the processes of material and energy flow associated with crop production can be controlled and influenced. This means the management and maintenance of optimal soil nutrient status as well.

Land productivity assessment, involving the evaluation of the effect of nutrient levels on the soil-specific yield potential, can provide options to optimize land-use planning and nutrient management with environmental and economic criteria (Rajsic and Weersink 2008; Carr et al. 1991; Gaál, Máté, and Tóth 2003).

Land productivity analyses are based on the principle that the production potential of soils can be determined from individual soil attributes and their combinations that have the greatest influence on the capacity of the soil to supply nutrients and water (Bocz, Debreczeni, and Debreczeni 1979; Tóth and Kismányoky 2001; Fischer et al. 2006). However, with regards to the effect of nutrients, most of the scientific research focuses on the effect of the fertilizer input rather than on the inherent level of soil nutrients (Kirda, Derici, and Schepers 2001; Li, Li, and Li 2004; Mahler, Koehler, and Lucher 1994).

Nutrient levels are most often taken into consideration in crop growth models (Arora, Singh, and Singh 2007), nutrient balance accounting (Öborn et al. 2003), fertilizer efficiency studies (Alcoz, Hons, and Haby 1993; Fageria and Baligar 2005) and applied fertilizer recommendations (Csathó, Árendás, and Németh 1998; Patócs 1987). Pathak et al. (2003) reported quantitative evaluation of soil nutrient supply based on soil nutrient data from 22 sites of diverse tropical and subtropical regions of India. Pathak et al. (2003) established relationships among indigenous nitrogen (N), phosphorus (P), and potassium (K) supply to wheat production and soil organic carbon (C), Olsen P, and ammonium acetate–extractable K, respectively. Wu (1993) reported quantitative measures of nutrient effect for paddy soil rice fertility assessment by quantifying links between nutrient levels and yields. Bindraban et al. (2000) proposed a classified set of nutrient stock and nutrient depletion categories for land quality indicator development. Similar approaches are used in many fertilizer recommendation systems (Csathó, Árendás, and Németh 1998; Patócs 1987). These systems are built on statistical analyses of reliable productivity information and relevant fertility factors.

To enhance the information base of the soil nutrient–crop productivity domain, we have analyzed the linkages among N, P, and K levels and winter wheat yields. The main objective of our study was to investigate the variability and magnitude of the yield response of winter wheat to different N, P, and K nutrient levels of different soil types under different climatic conditions.

Materials and Methods

Information content of the Hungarian national field-level soil, fertilization, and yield database, the so-called the National Pedological and Crop Production Database (NPCPD; in Hungary AIIR) was analyzed statistically. The NPCPD was compiled in the 1980s and was made available for the research by the Central Plant and Soil Protection Service, Budapest, in data storage format of the early 1980s. After recovering the information from the historical files, the dataset has been converted to modern database formats that could be read by statistical software packages of up-to date computing technologies.

The NCPDP contains yield data for five consecutive years (1985–1989) for an average of 80,000 cultivated plots covering approximately 4 million ha of arable land each year. The NPCPD also contains data on the soil type of the plots, information on major soil attributes, results of nutrient tests, and the amounts of fertilizers applied.

Crop fields with winter wheat cultivation were selected for our study.

Our investigation was aimed at discovering how the different nutrient levels in different soils influenced yields. In the previous stages of the land productivity analysis, the effect of soil types and fertilization were explored (Tóth, Máté, and Makó 2005). In the present phase of the research, the effect of nutrient levels was studied.

As actual crop yields are the most reliable parameters for soil productivity studies (Dumanski and Onofrei 1989), measured yield levels were compared with nutrient levels of soils.

Climatic Components in the Analysis

The climate of Hungary is a continental climate, with hot summers and cold snowy winters. Average annual temperature is 9.7 °C. Temperature extremes are approximately 42 °C in the summer and −29 °C in the winter. Average temperature in the summer is 27 °C to 35 °C and in the winter is 0 °C to −15 °C. The average yearly rainfall is approximately 600 mm. The effect of climatic variability within the country was taken into account using the ratios reported by Szász (2002) for 75 different meteorological regions of the country. These ratios, which characterize the differences in yield expected on the basis of the meteorological conditions in various years, in different meteorological regions, and for major crops, were used to normalize the crop yields recorded in plots of the database.

The effects of soil nutrient parameters were analyzed in relation to the expected (average) yields that resulted from neutralizing the meteorological effects with this method. Analysis of the effects under optimal climate conditions were based on the results of data from the year 1988, as this year produced the greatest yields within the test period as well as over a longer time perspective (Figure 1). Data from 1986 was chosen to analyze the effect of suboptimal climate conditions, following similar logic (Figure 1).

Categorization of Soil Types to Terrain Groups

In this step of the data preparation, fields with intensive (N $>$ 125 kg ha^{-1}) and balanced fertilization were selected.

The selected fields were grouped by their soil types and major soil characteristics (soil texture, pH, and carbonate) into so-called terrain groups according to the procedure described by Patócs (1987). The basic concept of this grouping is that certain taxonomic soil units show similarities in their nutrient regime, and these similarities determine their fertilization response and yield capabilities. Thus, 126 units of the Hungarian taxonomic soil classifications were grouped into six terrain groups based on the material and energy flow and attributed soil characteristics (I, soils with balanced material regime; II, soils with leaching material regime; III, heavy clay soils; IV, sandy soils; V, saline soils; and VI, soils with shallow rooting depth). Detailed analyses of nutrient effects were performed for the terrain groups separately. In this article, results of terrain groups I and II are introduced. Typical soil units in terrain group I were Calcic Hapludoll and Agriudoll (Chernozem- or

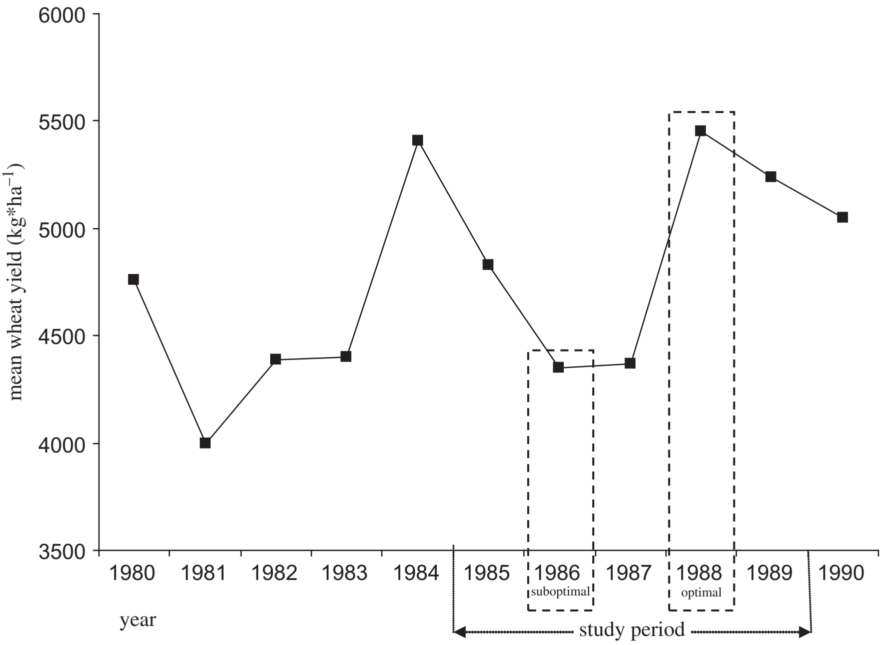

Figure 1. Mean wheat yields in Hungary 1980–1990.

Pheozem-like soils) and a reference soil unit in terrain group II was the Hapludalf (brown forest soil).

Classification of Nutrient Levels of Terrain Groups

In the next step of the study, crop fields of terrain groups were classified by the measured NPK levels. Classes of nutrient levels were set by the boundary conditions defined after Patócs (1987) for the terrain groups using standard soil tests (Buzás 1988, 1993). The method of Patócs was used because it is still in wide use for calculating fertilizer needs. With this method, organic matter is applied as a proxy to estimate nitrogen availability in soils, based on assumptions on the mineralization rates of organic N in different soils. Although many of the new systems directly use available N measurements for this purpose, to keep a coherent framework for our analysis and secure full utilization of our database, we used the approach of Patócs during our study.

Limit values and conditions of nutrient level classes for nitrogen, phosphorus, and potassium are given in Tables 1–3 respectively.

Analysis of the Effect of Nutrient Levels on Productivity

For the analysis of the effect of nutrient level, expected (mean) wheat yields were calculated for the six different nutrient level classes for N, P, and K separately. From the mean yield levels of the nutrient classes, an overall mean yield level was calculated and used as a reference yield level for further comparisons.

The ratio between the mean yield of the given nutrient class in the terrain group and the reference yield results in a coefficient that can be used as a measure of difference in

Table 1
Nitrogen level categories in terrain groups I and II based on measured data and boundary conditions[a]

		Soil organic matter (%)					
Terrain group	Saturation percentage	Very low	Low	Medium	Sufficient	Good	Excessive
I	<42	<1.5	1.51–1.8	1.81–2.3	2.31–2.8	2.81–3.25	>3.25
	>42	<2.0	2.01–2.3	2.31–2.8	2.81–3.3	3.31–3.75	>75
II	<38	<1.0	1.01–1.25	1.26–1.6	1.61–2.0	2.01–2.5	>2.5
	>38	<1.25	1.26–1.5	1.51–2.0	2.01–2.5	2.51–3.0	>3.0

[a]Measurements are based on methodology given by Patócs (1987) and Buzás (1988, 1993).

Table 2
Phosphorous level categories in terrain groups I and II based on measured data and boundary conditions[a]

		Ammonium-lactate-soluble P_2O_5 mg 1000 g^{-1}					
Terrain group	$CaCO_3$ (%) or $pH_{(KCl)}$	Very low	Low	Medium	Sufficient	Good	Excessive
I	$CaCO_3$% < 1	<80	81–110	111–150	151–190	191–250	>250
	$CaCO_3$% > 1	<120	121–160	161–200	201–240	241–300	>300
II	pH < 5.5	<45	46–90	91–130	131–180	181–200	>200
	pH 5.5–6.5	<60	61–110	111–150	151–200	201–240	>240
	pH > 6.5	<75	76–120	121–170	171–220	221–280	>280

[a]Measurements are based on methodology given by Patócs (1987) and Buzás (1988, 1993).

Table 3
Potassium level categories in terrain groups I and II based on measured data and boundary conditions[a]

		Ammonium-lactate-soluble K_2O mg 1000 g^{-1}					
Terrain group	Saturation percentage[b]	Very low	Low	Medium	Sufficient	Good	Excessive
I	<42	<150	151–200	201–240	241–280	281–320	>320
	>42	<200	201–250	251–300	301–340	341–380	>381
II	<42	<120	121–150	151–180	181–210	211–250	>250
	43–50	<140	141–170	171–200	201–235	236–275	>275
	>50	<160	161–190	191–220	221–255	256–300	>300

[a]Measurements are based on methodology given by Patócs (1987) and Buzás (1988, 1993).
[b]Saturation percentage with the method of Arany [in Hungary K_A; see Buzás (1988, 1993)].

Table 4
The effect of different nitrogen levels on the productivity of soils in terrain groups with different material regime

Terrain group	N level[a] (based on organic matter %)	Mean yield (adjusted by climate factor) (kg/ha)	SD	n	Mean yield of terrain group (kg/ha)	Weighted average yield of terrain group (kg/ha)[b]	Coefficients of nutrient level effect
I	1	5766	1478	1706	6294	6180	0.93
	2	5948	1365	5064			0.96
	3	6209	1307	20133			1.00
	4	6347	1254	29448			1.03
	5	6381	1245	15325			1.03
	6	6427	1309	11178			1.04
II	1	5001	1375	1188	5469	5365	0.93
	2	5357	1348	5272			1.00
	3	5494	1347	23331			1.02
	4	5525	1416	18812			1.03
	5	5443	1419	7335			1.01
	6	5368	1338	3012			1.00

[a]Nutrient levels: 1, very low; 2, low; 3, medium; 4, sufficient; 5, good; 6, excessive.
[b]Mean value of the average yields on different nutrient levels.

the productivity of soils with given nutrient levels. This coefficient is called the "indicative coefficient of nutrient level effect" (Tables 4–6).

This analysis was undertaken for each terrain unit for the three distinguished climatic year types, and results were compared. The data were processed and evaluated using MS Excel and SPSS statistical software package (SPSS Inc. 2000).

Results and Discussion

Effect of N, P, and K Levels on Long-Term Average Yields

The results of examinations that were carried out on the basis of the NPCPD, with wheat as the indicator crop, showed that nutrient level of terrain groups (based on soil properties) had a considerable influence on expected yields. Results in Tables 4–6 show the magnitude of impacts may range between 6% and 26% in the case of the three main nutrients (NPK) studied. This assumption can be drawn from the differences in the coefficients of nutrient level effects, the main indicator we used to describe the influence of the given nutrient levels on wheat yields. Combined effects of nutrient availability of the studied macroelements may result even greater variance in yields. The differences between the characteristics (range, saturation points) of nutrient effects on the two terrain groups may originate from the soil-specific differences in morphology, texture, pH, organic-matter content, and complex pedological features. For instance, soils in terrain group II might tend to have different physical characteristics originating from higher clay content (Tóth et al. 2008) that also results in alteration of potassium effects.

Table 5
Effect of different P_2O_5 levels on the productivity of soils in terrain groups with different material regime

Terrain group	Al-soluble P_2O_5 level[a]	Mean yield (adjusted by climate factor) (kg/ha)	SD	n	Mean yield of terrain group (kg/ha)	Weighted average yield of terrain group (kg/ha)[b]	Coefficients of nutrient level effect
I	1	5909	1387	3278	6294	6200	0.95
	2	6069	1328	5442			0.98
	3	6176	1312	11774			1.00
	4	6295	1242	15150			1.02
	5	6370	1277	20796			1.03
	6	6382	1286	26414			1.03
II	1	4955	1423	2788	5469	5407	0.80
	2	5285	1399	10914			0.98
	3	5530	1359	15051			1.02
	4	5587	1344	13648			1.03
	5	5617	1382	6045			1.04
	6	5471	1381	10504			1.01

[a]Nutrient levels: 1, very low; 2, low; 3, medium; 4, sufficient; 5, good; 6, excessive.
[b]Mean value of the average yields on different nutrient levels.

Table 6
Effect of different K_2O levels on the productivity of soils in terrain groups with different material regime

Terrain group	Al-soluble K_2O level[a]	Mean yield (adjusted by climate factor) (kg/ha)	SD	n	Mean yield of terrain group (kg/ha)	Weighted average yield of terrain group (kg/ha)[b]	Coefficients of nutrient level effect
I	1	6061	1326	4271	6294	6255	0.97
	2	6135	1346	10426			0.98
	3	6223	1289	15349			0.99
	4	6345	1269	14098			1.01
	5	6410	1323	11291			1.02
	6	6358	1254	27419			1.02
II	1	5195	1433	2952	5469	5426	0.96
	2	5356	1358	5172			0.99
	3	5481	1368	8397			1.01
	4	5512	1351	10702			1.02
	5	5561	1346	12518			1.02
	6	5452	1417	19209			1.00

[a]Nutrient levels: 1, very low; 2, low; 3, medium; 4, sufficient; 5, good; 6, excessive.
[b]Mean value of the average yields on different nutrient levels.

It is worth noting that mean yield levels of soils with similar nutrient level categories were higher in terrain group I in each case. This fact underlies the importance of complex soil factors (structure, moisture regime, etc.) on land productivity. Our findings are in agreement with the literature regarding the fertility of Chernozem-like soils and soils with luvic properties (Biczok, Lasztity, and Ruda 1988). Results also confirm the expected advantages of performing fertility classification based on terrain groupings according to nutrient reaction of soils with similar characteristics (Tóth, Máté, and Makó 2005). It can be assumed that the most precise land productivity model can be achieved by studying and quantifying the soil attributes with the greatest influence on the capacity of the soil to supply water and nutrients, for each soil type. The fact that wheat is a crop with low potassium demand, and different levels of potassium availability showed the smallest effect on mean wheat yield, underlines the importance of performing land productivity evaluation for different crops separately.

Effect of N Levels on Productivity in Varying Climatic Conditions

Yield performance and consequent indicative coefficient value of the influence of nutrient levels on productivity (Table 4 and Figure 2) under optimal climatic conditions was considerably higher in the upper zone of nitrogen availability in both terrain groups. However, saturation points were different for soils with different material regimes. (Since saturation point in terrain group II falls to nutrient level 4, it is worth considering a reclassification of the categorization, or at least renaming of classes of nutrient levels for nitrogen.) The lower level of nitrogen availability decreased yields to a larger extent in years with optimal climate, in both terrain groups, and this phenomenon is reflected in low coefficient values. The spread of the indicative coefficient values was larger in both terrain groups in the suboptimal years when compared to the "average" years, indicating that increasing nutrient content is also important under climatic constrains (suboptimal years). This is also the case under favorable conditions (optimal years). Gyuricza and Birkás (2000) have reported similar results by investigating climatic effects on corn yields of brown forest soils. In agreement with the results presented by Kunzova and Hejcman (2009) on the fertility of black soils in the Czech Republic, our studies also showed that in an average year there was a constant increase of yields with increasing level of nitrogen content in terrain group I. However, in terrain group II, the yield reaction followed a saturation and then declining curve with the increasing levels of nitrogen content in soils (Table 4).

Effect of P Levels on Productivity in Varying Climatic Conditions

When evaluating the effect of phosphorous by terrain groups, we can assume that in terrain group I, the difference between the impact of low and high amount of available P is largest in optimal years, meaning an increasing positive yield reaction to P up to level 5 (Figure 3). In suboptimal years, in contrast, hardly any impact of increasing level of P can be observed. Terrain group II shows different phosphorous reaction: meteorological effects show little impact. The increase with the greater amount of nutrient in soil is observed to P levels 4 (optimal years) and 5 (average and suboptimal years) followed by a decrease at the excessive levels. These results confirm the validity of nutrient level categories laid down by Patócs (1987) from the viewpoint of their effect on fertility.

Effect of K Levels on Productivity in Varying Climatic Conditions

Potassium effects show different trends, throughout the years and in comparisons of different terrain groups (Figure 4). In terrain group I, in an optimal year, the spread of

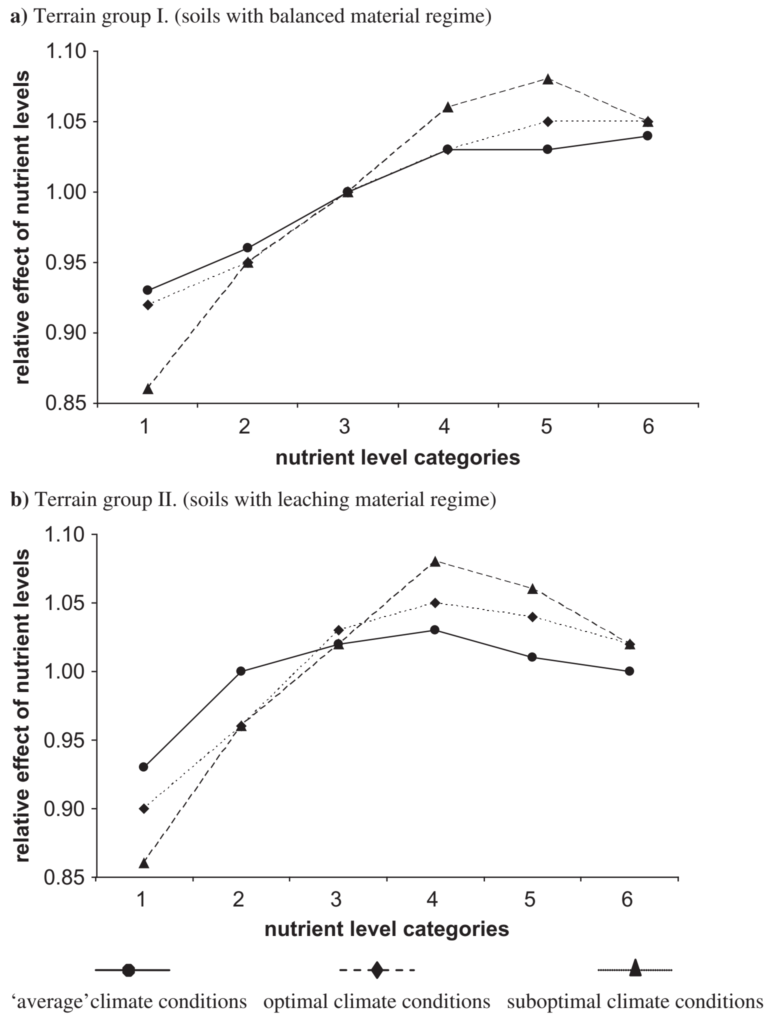

Figure 2. Effect of nitrogen level and climatic year type on wheat yields.

the relative effect of nutrient level was larger over the spectrum of different K contents, showing the dynamics of K is strongly linked to available water. In years when water is not a limiting factor, the greater K levels will positively influence yields until a saturation point at category 5 of the K level. Conversely, under suboptimal climate conditions, the effect of greater K levels on yields remains at a surplus of only a 2–3%, demonstrating the influence of dry fixation of potassium on crop yields. These results are in agreement with data in the corresponding literature (Sárdi and Csitári 1998).

Conclusions

Theoretically, the nutrient component of soil productivity can be quantified by nutrient factor values associated to nutrient levels according to the method introduced in this article. However, the fertilizer response of different soil types within the same terrain group

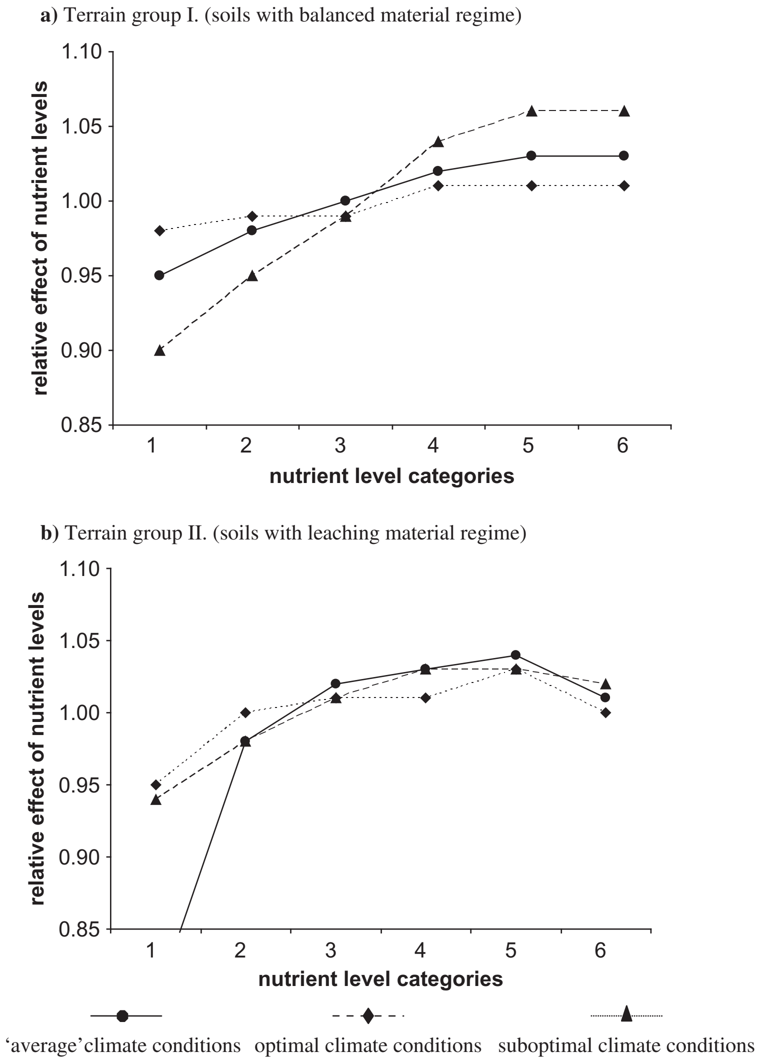

Figure 3. Effect of phosphorous level and climatic year type on wheat yields.

(and taxonomic soil class) may be different. Therefore, further studies will be necessary to calculate the parameters and to validate the method for different soil types.

The validity of the concept to distinguish nutrient reactions based on different climatic year types is verified by the results (Figures 2–4). These results demonstrate that the difference between expected crop yields—and underlying land productivity—vary across the years. If comparing the results with the terrain groups I and II, it becomes evident that the productivity and the seasonal variability of soils with balanced nutrient regime (terrain group I) are very different from that of soils with properties resulting from leaching genetic processes (terrain group II).

The results show that nutrient reactions—manifested in yield levels—differ by nutrient levels, the inherent nutrient dynamic of soils (grouped into terrain groups based on

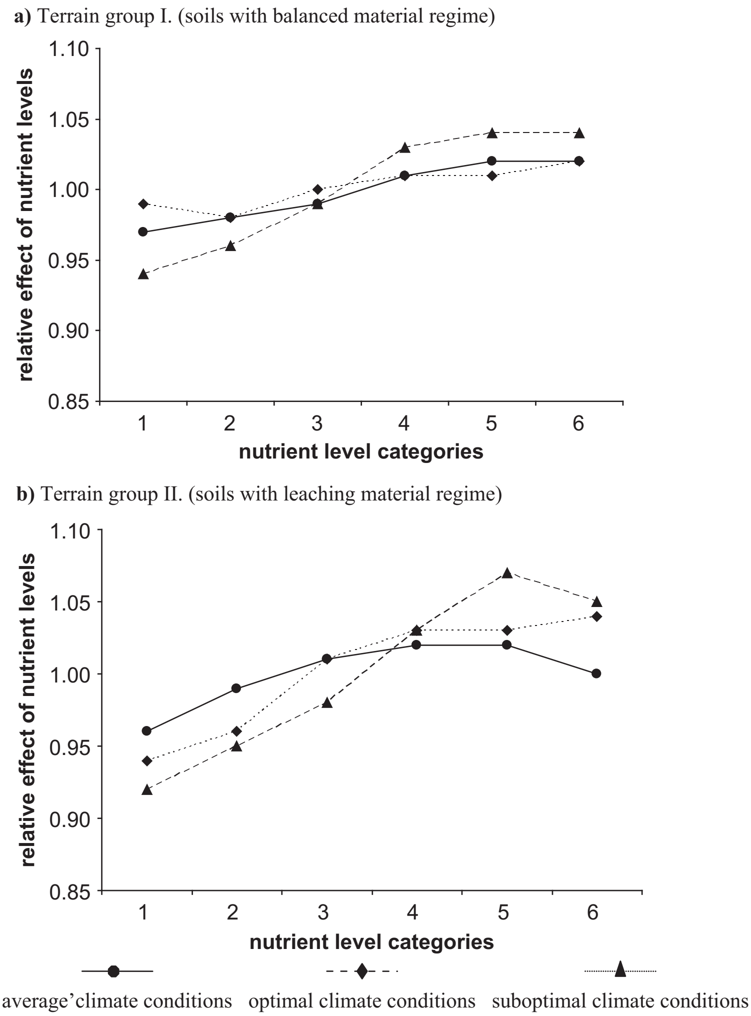

Figure 4. Effect of potassium level and climatic year type on wheat yields.

similarities in the nutrient dynamics), and climatic conditions. The effect of variation within terrain groups on the fertility for a specific crop can be described on the basis of crop yield, soil, and nutrient level data. The relative influence of soil nutrient level on the crop productivity of different terrain groups (and soil types) was expressed in a quantitative manner. Productivity differences due to varying nutrient levels were most pronounced in the case of different nitrogen availabilities. However, the effect of varying levels of available P and K can also result a nearly 20% yield difference.

The influence of the annual variability of climatic factors was smaller than the underlying soil nutrient level factors. Considerable seasonal differences in the overall yield variability were observed, mainly in lands with lower nutrient status. Differences in optimal years were always greater than in suboptimal years, meaning that good nutrient conditions are most beneficial under favorable climatic conditions.

These results underline that the nutrient factor in the potential yield ratings of soils (land productivity evaluation system) should be calculated separately for different terrain groups, nutrients, and climatic year types.

The results obtained so far suggest a number of new planning options. One of the main applications of the results could be the development of a land productivity evaluation system that will provide a more reliable and comprehensive method of incorporating the effect of measurable nutrient levels to allow well-founded decisions on land use.

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