Multivariate Nutrient Diagnosis of the Carrot Crop

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Abstract. Compositional nutrient diagnosis (CND) provides undistorted (linearized) variates amenable to principal component analysis (PCA) using a row-centered logratio transformation of foliar nutrient data. Our objectives were to carry PCA on raw or transformed nutrient data for carrot (*Daucus carota* L.) crops and to compare the critical value approach (CVA), diagnosis and recommendation integrated system (DRIS), and CND diagnoses using independent data. PCA conducted on percentage or log-transformed data produced similar multivariate structures difficult to interpret. PCA conducted on DRIS indexes and on row-centered logratios produced PCs ($K-Ca^+$), ($N^+K-Ca-Mg^+$), and ($P-Mg^+$) and PCs ($K-Mg^+$), ($N-Ca^+$), and (P^-), respectively. Nutrient contrasts were easiest to interpret with CND and reflected either K-Mg antagonism or N dilution and Ca accumulation over time. CVA diagnosis of independent samples was generally not in line with DRIS or CND. DRIS and CND diagnostic indexes were highly correlated ($r = 0.98$ to 0.99). By summing bivariate DRIS functions, the DRIS index calculation procedure effectively row-centered the nutrient values for carrots. DRIS and CND index diagnosis indicated treatment-dependent Ca shortage. In contrast, CND PC diagnosis indicated overall stationary values for PC ($N-Ca^+$) whatever treatment was applied. CND PC diagnosis is a multivariate (PCA) approach providing simplified computational effort and a theoretical basis for further improvements in foliar diagnosis.

The critical value approach (CVA) and the diagnosis and recommendation integrated system (DRIS) are current interpretive systems for diagnosing nutrient concentrations or equilibria in selected plant tissues. CVA uses crude components expressed as proportions of dry matter (DM) or as concentrations in the sap or the petioles. DRIS uses dual ratios of original components that are first standardized by DRIS functions and further transformed into DRIS indexes (Walworth and Sumner, 1987). CVA and DRIS could carry distorting or redundant information due to nutrient interactions in the plant and to the bounded-sum constraint that is limited to 100% of components in the foliage (Parent and Dafir, 1992).

Holland (1966) anticipated that a reasoned application of principal component analysis (PCA) could lead to a greater understanding of the effects of fertilization treatments on leaf composition compared to univariate, dual-ratio, or trivariate diagnostic tools. PCA reduces the number of interdependent variables into a smaller number of independent PCs that are linear combinations of

original variates. Using the PCA approach to compositional data analysis (Aitchison, 1986), Parent and Dafir (1992) developed the compositional nutrient diagnosis (CND). CND requires less computational effort than DRIS by computing row-centered logratios from original concentration values instead of using various procedures of function and index calculations.

An improved knowledge of nutrient balance in horticultural crops is necessary to comprehend the nature of nutrient interactions in the plant and to facilitate the interpretation of analytical results. In southwestern Quebec, the carrot is the main vegetable crop cultivated in organic soils. Fertilizer management of the carrot crop could use plant analysis to attain optimum nutrient balance with minimum nutrient application.

Our objectives were to conduct PCA on raw or transformed carrot leaf nutrient data, to elucidate their multivariate structure for carrot crops, and to compare CVA, DRIS, and CND diagnoses of independent samples.

Rationale

From CVA to CND. The nutrient expression for diagnosing with CVA is a percentage relative to DM. Thus, for any nutrient A, B, or C, no adjustment to other nutrients is provided.

DRIS expands CVA by considering further adjustment of a given nutrient to another nutrient, i.e., by dual ratioing nutrient values expressed as percentages. Nutrient percentages and dual ratios for independent samples are first compared to DRIS norms

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using one of two equations to compute DRIS functions (Walworth and Sumner, 1987). The calculation of DRIS indexes from DRIS functions could adjust or row-center the nutrient under diagnosis relative to all other nutrients and DM. The nutrient for which a DRIS index is computed should appear preferably as numerator or denominator in the DRIS functions to be added up (Hallmark et al., 1991). A generalized nutrient imbalance index (NII) can be calculated by summing DRIS indexes irrespective of sign (Walworth and Sumner, 1987). Until now, the DRIS indexes have not been projected into a multidimensional space using PCA, which is our aim for improving diagnosis.

Multinormal data distribution is a prerequisite for conducting multivariate analyses (Legendre and Legendre, 1984). Nutrient data are relative and typically compositional, and, as such, are not directly amenable to standard statistical linear modeling due to the bounded-sum constraint to 100% (the DM content) of plant components (Aitchison, 1990). Before conducting PCA, DM should be split into nutrient proportions and a filling value R between 100% and the known proportions, as follows (Aitchison, 1986):

$$R = DM - A - B - C - \dots \quad [1]$$

where DM = 100% or 1 and A, B, C, ... are nutrient proportions or fractions.

If a proportion is changed, other proportions must either fill the gap or recede. Thus, the compositional structure imposes a particular covariance pattern to all components.

The minimum requirement for describing a pattern of variability of compositional data is dual ratioing (Aitchison, 1990), which seems to be met to some extent by DRIS. A way to obtain a symmetric treatment of all D fractions of a whole is to replace the single divisor in dual ratios by the geometric mean G of the D components, including the filling value (Aitchison, 1986):

$$G = (A \times B \times C \times \dots \times R)^{(1/D)} \quad [2]$$

The CND nutrient variates used for computing PCA are row-centered logratios defined as follows (Parent and Dafir, 1992):

$$V_A = \ln(A) - \ln(G) = \ln(A/G), \dots, V_R = \ln(R/G) \quad [3]$$

Variates V_A to V_R are scale-invariant multinutrient ratios (with common scale G), the linearized (undistorted) estimates of original components. For a single specimen, [Eq. 3] can be expanded to a summation of dual ratios:

$$V_A = [1/D] * [\ln(A/A) + \ln(A/B) + \ln(A/C) + \dots + \ln(A/R)] \quad [4]$$

Similar to DRIS, the mean and SD of row-centered logratios characterizing the high-yielding subpopulation are the CND nutrient norms. The CND nutrient index is computed as a standardized distance between the norm and the corresponding row-centered logratio in independent samples. For instance, CND index I_A for nutrient A is computed as (norms indicated by asterisks)

$$I_A = (V_A - V_A^*)/SD_A^* \quad [5]$$

CND nutrient diagnosis requires only the computation of R, G, row-centered logratios, and CND indexes. There is no need for calculating and standardizing dual ratios before computing indexes, as in DRIS.

From univariate to multivariate diagnosis. Several options can

be formulated in the way to conduct PCA using concentration, DRIS, or CND variables:

- 1) If we use concentration data, nonellipsoidal data distribution patterns may spoil the covariance structure of linear models (Aitchison, 1990).
- 2) Dual ratios cannot be treated directly by PCA due to systematic auto-correlation among ratios containing the same nutrient. The only single nutrient expression in DRIS is the DRIS index. Some distortion could occur by using DM instead of R. The value of DRIS indexes could also vary depending on which DRIS function is used for computation (Hallmark et al., 1991). DRIS indexes are standardized at the steps of computing DRIS functions and PCA factors (correlation matrix). The validity of such an approach may be questioned, but there seems to be no alternative to the DRIS index for conducting PCA.
- 3) Row-centered log-ratios provide appropriate expressions for relative nutrient levels freed from the bounded-sum constraint.

The aim of PCA is to reduce dimensionality of objects by removing redundancy and random effect among related variables. Objects are projected into a euclidean space in PC coordinates. If the space is made circular or spheroidal, a critical radius can be designed to scan every dimension of the space and capture high-yielders or target yields. Two options are envisaged to build the multidimensional space.

In the first option, PCA is conducted exclusively using the high-yielding subpopulation if sufficient data are available. As a result, PCs are linear combinations of standardized variables referred to above as CND indexes [Eq. 3]. CND nutrient norms (means and SDs of the high-yielding subpopulation indicated by asterisks) are used for standardization, as shown below for the five major nutrients of the carrot databank:

$$PC_j = a_{j1}(V_N - V_N^*)/SD_N^* + a_{j2}(V_P - V_P^*)/SD_P^* + a_{j3}(V_K - V_K^*)/SD_K^* + a_{j4}(V_{Ca} - V_{Ca}^*)/SD_{Ca}^* + a_{j5}(V_{Mg} - V_{Mg}^*)/SD_{Mg}^* \quad [6]$$

$$\text{or } PC_j = a_{j1}I_N + a_{j2}I_P + a_{j3}I_K + a_{j4}I_{Ca} + a_{j5}I_{Mg} \quad [7]$$

where PC_j is the j th PC, and a_{j1} to a_{j5} are PC score coefficients for standardized variables.

To obtain maximum relationships among standardized variables, PCs are varimax-rotated (Vandamme et al., 1978). To be declared significant, PCs must have eigenvalues $>100/p$, where p is the total number of variates under analysis (Ovalles and Collins, 1988). Alternatively, PCs showing eigenvalues <1 could be considered nonsignificant (Legendre and Legendre, 1984). Only PC loadings in eigenvectors having values greater than the selection criterion (SC) are given significance (Ovalles and Collins, 1988). The selection criterion is computed as follows:

$$SC = 0.5/(\text{PC eigenvalue})^{0.5} \quad [8]$$

where the eigenvalue is the sum of the squares of loadings computed as follows:

$$\text{eigenvalue} = b_{j1}^2 + b_{j2}^2 + b_{j3}^2 + \dots \quad [9]$$

PC orthogonality allows independent diagnoses on every axis

of the multidimensional space. Critical PC_js can be assessed probabilistically using confidence intervals (Parent et al., 1993), the chi-square distribution (Dagnélie, 1977), or empirically using independent fertilizer experiments.

In the second option, if the high-yielding subpopulation is too small for conducting PCA (as was the case for the carrot databank) or if the structure of the whole population needs to be investigated, PCs can be formulated as linear combinations of standardized variables using population means and SDs (indicated by the “o” superscript) for standardization, as shown below for the five major nutrients:

$$PC_j = a_{j1}(V_N - V_{N^o})/SD_{N^o} + a_{j2}(V_P - V_{P^o})/SD_{P^o} + a_{j3}(V_K - V_{K^o})/SD_{K^o} + a_{j4}(V_{Ca} - V_{Ca^o})/SD_{Ca^o} + a_{j5}(V_{Mg} - V_{Mg^o})/SD_{Mg^o} \quad [10]$$

where PC_j is the jth PC and a_{j1} to a_{j5} are PC score coefficients for standardized variables.

The CND PC index I_{PCj} for the jth PC is calculated as follows:

$$I_{PCj} = (PC_j - PC_j^*)/SD_{PCj}^* \quad [11]$$

where I_{PCj} is the PC index for the independent sample and PC_j^{*} and SD_{PCj}^{*} are the CND PC norms (means and SDs of PC values for the high-yielding subpopulation).

Standardization using [Eq. 11] produces circular or spheroidal bodies. The high-yielding subpopulation can be mapped in as PC index coordinates within the whole dataset.

Since CND produces a system of PC axes perpendicular to one another, either CND PCs [Eq. 7] or PC indexes [Eq. 9] can be used to compute a euclidean distance d, which is the total length of the hypotenuse in an n-dimension ellipsoidal or spheroidal space as calculated following the Pythagorean theorem (Legendre and Legendre, 1984):

$$d = \text{either } (\sum PC_j^2)^{0.5} (j = 1 \text{ to } n) \text{ or } (\sum I_{PCj}^2)^{0.5} (j = 1 \text{ to } n) \quad [12]$$

Materials and Methods

One hundred and three commercial carrot fields were surveyed during 3 consecutive years in the organic soil area of southwestern Quebec, Canada. Plots 30 × 30 m were delineated in each field for foliar sampling and crop harvesting. The most recently mature leaf was collected at the eight- to 10-leaf growth stage. Ten to 20 subsamples were composited at each sampling. Foliar tissues were oven-dried at 70C, ground in a Wiley mill, wet-digested, and analyzed for N by the standard micro-Kjeldahl digestion and for P, K, Ca, and Mg by plasma emission spectroscopy (Spectra Span 6; Beckman) after dissolving the ashes (550C for 4 h) in dilute HCl (Jones and Case, 1990). Marketable yields (Mg·ha⁻¹) were estimated on three 2-m-long beds in each plot. Exploratory PCA on row-centered logratios [Eq. 3] indicated that the high-yielding subpopulation would produce >45 Mg·ha⁻¹.

The means and coefficients of variation of dual nutrient ratios in the high-yielding subpopulation were the DRIS norms. Ratios or inverse ratios were introduced into DRIS functions to maintain the nutrient under diagnosis either as denominator or numerator at the step of computing DRIS indexes (Hallmark et al., 1991).

PCA was conducted on percentage data, log-transformed percentage data, DRIS indexes, and row-centered logratios from the whole population using the correlation matrix. DRIS and CND diagnoses were compared using foliar and yield data from Haworth et al. (1966), who collected carrot tops for mineral analyses 2 months after seeding. Thus, sampling stage was later than developmental stage used to derive DRIS and CND norms. Statistical analyses were conducted using Systat 5.0 (Systat, 1989) and Microsoft Excel 4.0 (Microsoft, 1992).

Results and Discussion

PCA. PCA conducted on percentage data produced two significant PCs that, together, explain 59.4% of total variance (Table 1). The results were similar using log-transformed percentage data (data not shown). The first PC was positively correlated with N, P,

Table 1. Parameters of the varimax-rotated principal component analysis over percentage data of the carrot databank from southwestern Quebec and diagnosis and recommendation integrated system (DRIS) indexes using the nutrient under consideration always as numerator in added up DRIS functions.

Nutrient	Principal components (PCs)				
	Percentage data		DRIS indexes		
	N ⁺ P ⁺ Ca ⁺ Mg ⁺⁺	K ⁺	K ⁻ Ca ⁺	N ⁺ K ⁻ Ca ⁺ Mg ⁺	P ⁻ Mg ⁺
<i>PC loading</i>					
N	<u>0.701</u>	-0.249	0.017	<u>0.829</u>	-0.042
P	<u>0.706</u>	0.065	0.105	0.127	<u>-0.894</u>
K	-0.004	<u>0.926</u>	<u>-0.874</u>	<u>-0.416</u>	0.179
Ca	<u>0.631</u>	0.389	<u>0.840</u>	<u>-0.508</u>	0.024
Mg	<u>0.709</u>	0.060	0.002	<u>0.533</u>	<u>0.588</u>
<i>Eigenvalue</i>					
	1.889	1.079 ^y	1.481	1.419	1.180 ^y
<i>PC score coefficient</i>					
N	0.395	-0.288	0.014	0.589	-0.073
P	0.373	0.006	-0.047	0.131	-0.776
K	-0.074	0.869	-0.589	-0.311	0.057
Ca	0.308	0.316	0.583	-0.353	0.158
Mg	0.375	0.002	0.086	0.351	0.492

^zPrincipal component (underlined loadings identify factor).

^yTotal variance is 5 under each heading.

Ca, and Mg and designated as ($N^+P^+Ca^+Mg^+$). The second PC was correlated with K and designated as (K^+). PC structure was not interpretable on a physiological basis and thus proved useless for multivariate diagnosis.

Three PCs that explain 81.6% of total variance were derived from DRIS indexes (Table 1). PC (K^-Ca^+) could be interpreted as a K–Ca antagonism (Marschner, 1986) or a K–Ca contrast related to K dilution and Ca accumulation over time (Walworth and Sumner, 1987). PC ($N^+K^-Ca^-Mg^+$) could be segmented into a reverse N–Ca relationship over time and a K–Mg antagonism. A K–Mg antagonism was observed as a reverse relationship in greenhouse nutritional studies with carrots (Southards and Miller, 1962) and in field experiments (Bishop et al., 1973). The P–Mg relationship could also be related to plant metabolism and to dilution–accumulation processes over time (Marschner, 1986, Walworth and Sumner, 1987).

Three significant PCs accounted for 82.5% of total variance using row-centered logratios (Table 2). PCs (N^-Ca^+), (K^-Mg^+), and (P^-Ca^+) could be interpreted as antagonistic or dilution–accumulation processes as above. PC (P^-) indicated that, in contrast with other elements, P could be diagnosed in isolation by CND. CND nutrient and PC norms are presented in Table 3. Reconstituting percentage data from [Eq. 3] using row-centered logratios and $\ln(G)$ values presented in Table 3, means of CND high-yielders were 3.20% for N, 0.47% for P, 5.24% for K, 3.08% for Ca, and 0.45% for Mg. Compared to CVA norms for upper plant parts (3 cm above ground) at midseason (Bergmann, 1988), these P, K, and Ca levels appeared excessively high.

The DRIS nutrient norms are presented in Table 4. Seven of the 15 DRIS dual ratios showed significant variance ratios between low- and high-yielding subpopulations. Two of the five row-centered logratios and one CND PC also showed significant variance ratios (Table 3). Thus, DRIS and CND identified nutrient imbalance in carrot crops producing lower yields.

Comparing CVA, DRIS, and CND using independent data. Haworth et al. (1966) found that carrot yields and nutrition were influenced significantly by the application of farmyard manure

(FYM) and mineral fertilizers.

CVA diagnosed N and Ca sufficiency in many treatments (Table 5). Besides, foliar P was sufficient and foliar K was either deficient or sufficient in treatments not amended with FYM. Foliar P and K were apparently excessively high in FYM-amended plots. Foliar Mg levels seemed sufficient in most cases.

DRIS and CND indexes diagnosed relative K, P, and Ca shortage in plots not receiving FYM and relative Ca and P shortage in FYM-amended plots (Tables 6 and 7). Foliar K was the most deficient while foliar N and Mg appeared excessive in plots not amended with FYM. Foliar P and, primarily, Ca seemed deficient in FYM-amended plots. The order of nutrient limitations generally agreed between DRIS and CND. DRIS and CND indexes were highly correlated ($r = 0.979$ to 0.994). Thus, the DRIS index calculation procedure effectively row-centered nutrients after summing up bivariate DRIS functions. Since the well correlated CND and DRIS indexes are already standardized variables, there is a conceptual problem to proceed any further with PCA using DRIS or CND indexes. According to the theory of compositional data analysis (Aitchison, 1986), the appropriate expression for compositional variates to be used in PCA is the row-centered logratio.

CND PC indexes, euclidean distances, and DRIS NIIs are presented in Table 8. DRIS NII was highly correlated with CND euclidean distance ($r = 0.988$). DRIS NII varied between 12.8 and 24.4 in non-FYM-amended plots and from 6.8 to 9.4 in FYM-amended plots, thus indicating the beneficial effect of FYM on nutrient balance in carrots. Correspondingly, euclidean distances varied between 4.40 and 6.97 in non-FYM-amended plots and from 2.44 to 3.74 in FYM-amended plots.

Since PCs are linear contrasts between nutrient variates, interpretations of CND PC indexes should consider the sign of the nutrient (Table 8). CND PC diagnosed nutrient imbalance primarily in PCs (K^-Mg^+) and (P^-), since CND PC (N^-Ca^+) was relatively constant and apparently imbalanced whatever treatment was ap-

Table 2. Parameters of the varimax-rotated principal component (PC) analysis on row-centered logratios computed from the carrot databank collected in southwestern Quebec.

CND ^z variate	K^-Mg^{+y}	N^-Ca^+	P^-
<i>PC loading</i>			
V_N	0.123	<u>-0.889</u>	0.240
V_P	0.057	0.006	<u>-0.973</u>
V_K	<u>-0.894</u>	0.121	0.175
V_{Ca}	0.080	<u>0.738</u>	0.415
V_{Mg}		<u>0.855</u>	0.054
0.106			
<i>Eigenvalue</i>			
	1.555	1.353	1.219 ^y
<i>PC score coefficient</i>			
V_N	0.040	-0.676	0.262
V_P	0.012	0.073	-0.805
V_K	-0.568	0.033	0.113
V_{Ca}	0.101	0.529	0.296
V_{Mg}	0.559	0.077	0.107

^zCND = compositional nutrient diagnosis.

^yPrincipal component (underlined loadings identify factor).

^xTotal variance is 5 under each heading.

Table 3. High-yielding subpopulation and whole population statistics of foliar row-centered logratios, geometric means, and compositional nutrient diagnosis nutrient factors.

Parameter	Mean	SD
<i>High-yielding subpopulation</i>		
V_N	0.018	0.093
V_P	-1.894	0.143
V_K	0.510	0.116**
V_{Ca}	-0.021	0.092**
V_{Mg}	-1.937	0.175
$\ln(G)^z$	1.146	0.102
K^-Mg^+	-0.073	0.933
N^-Ca^+	0.839	0.739**
P^-	0.434	1.001
<i>Whole population</i>		
V_N	0.077	0.107
V_P	-1.844	0.140
V_K	0.480	0.158
V_{Ca}	-0.159	0.149
V_{Mg}	-1.928	0.156
$\ln(G)$	1.105	0.092

^zNatural logarithm of the geometric mean used to reconstitute percentage values from row-centered logratios [Eq. 3].

**Variance ratio between low- and high-yielding subpopulations significant at $P \leq 0.01$.

Table 4. Diagnosis and recommendation integrated system (DRIS) norms for carrots grown in Quebec organic soils.

Nutrient	Ratio		Inverse ratio	
	Mean	CV (%)	Mean	CV (%)
N ^z	32.2	11.1	3.14×10^{-2}	11.1
P	4.84	20.5	2.17×10^{-1}	24.8
K	52.8	12.3**	1.92×10^{-2}	12.3**
Ca	31.0	11.4**	3.27×10^{-2}	11.8**
Mg	4.67	22.7	2.29×10^{-1}	32.3
N/P	6.91	21.2	1.51×10^{-1}	19.5
N/K	6.18×10^{-1}	14.5**	1.65	14.6**
N/Ca	1.05	14.1**	9.77×10^{-1}	13.6*
N/Mg	7.25	24.3	1.45×10^{-1}	21.7
P/K	9.23×10^{-2}	19.8**	11.3	22.5
P/Ca	1.56×10^{-1}	18.5**	6.63	20.7
P/Mg	1.06	20.1*	9.77×10^{-1}	20
K/Ca	1.72	15.1**	5.94×10^{-1}	15.7**
K/Mg	1.20×10	27.7	8.95×10^{-2}	26.3*
Ca/Mg	6.97	23.9	1.51×10^{-1}	21.5

^zBased on nutrient concentrations in g·kg⁻¹.*,** Variance ratio between low- and high-yielding subpopulations significant at $P \leq 0.05$ and 0.01 , respectively.

Table 5. Foliar and yield data from a fertilizer experiment on carrot crops grown on a mineral soil at varied rates of manure, N, P, and K (adapted from Haworth et al., 1966).

Fertilizer	Rate	Foliar concn (%)					Yield
added	(kg·ha ⁻¹)	N	P	K	Ca	Mg	(Mg·ha ⁻¹)
Without manure							
N	35	3.28	0.29	2.86	2.20	0.56	35.4
	69	3.67	0.30	2.05	2.13	0.60	33.8
	104	3.40	0.26	2.14	2.12	0.54	33.2
P	0	3.43	0.27	2.48	2.13	0.58	33.2
	9	3.38	0.30	2.03	2.12	0.58	33.4
	18	3.53	0.29	2.54	2.21	0.54	35.6
K	0	3.77	0.31	1.78	2.24	0.66	32.0
	45	3.40	0.28	2.47	2.12	0.54	34.7
	90	3.17	0.27	2.81	2.10	0.50	35.8
With 44.8 Mg manure/ha							
N	35	3.47	0.39	5.62	2.03	0.47	42.6
	69	3.52	0.35	5.66	1.95	0.46	41.4
	104	3.65	0.40	5.26	2.18	0.51	41.2
P	0	3.81	0.39	5.62	2.08	0.49	41.4
	9	3.73	0.37	5.53	2.11	0.48	41.4
	18	3.17	0.38	5.40	1.98	0.46	42.3
K	0	3.74	0.40	5.55	2.17	0.52	41.9
	45	3.52	0.39	5.68	1.99	0.50	42.1
	90	3.45	0.35	5.31	2.00	0.42	41.4
Sufficiency range ^z	L	2.00	0.20	2.40	1.20	0.35	
	H	3.50	0.35	3.80	2.10	0.60	

^zFrom Bergmann (1988); L = lower limit and H = higher limit

plied, due presumably to a sampling stage different from norm and to site specificity (British sandy loam vs. Quebec organic soils) (Table 8). In contrast, DRIS and CND index diagnoses indicated treatment-dependent Ca shortage. Thus, CND PCs were instrumental in focusing diagnosis on K, Mg, and P, rather than on N or Ca.

CND PC diagnosis showed that mineral fertilizers alone failed to maintain nutrient balance in the carrot crop (Table 8). In contrast with CVA, CND PC diagnosis showed no apparent K or P excess in FYM-amended plots (Table 8). In the nine plots not receiving

FYM, K was generally deficient since we obtained a highly significant ($P < 0.01$) simple correlation coefficient ($r = -0.889$) between yield and PC ($\text{K} \cdot \text{Mg}^+$), whatever treatment was applied. In the FYM-amended plots, imbalance in PC ($\text{K} \cdot \text{Mg}^+$) almost totally disappeared. Thus, FYM increased yield essentially by improving K and, to a lesser extent, P supply to the crop.

Conclusions

Compared to diagnosis based on DRIS or CND nutrient in-

Table 6. Diagnosis and recommendation integrated system (DRIS) diagnosis of a fertilizer experiment on carrot crops grown on mineral soil at varied rates of manure, N, P, and K (adapted from Haworth et al., 1966).

Fertilizer	Rate	DRIS index					Order of
added	(kg·ha ⁻¹)	N	P	K	Ca	Mg	limitation ^z
Without manure							
N	35	2.2	-2.5	-4.1	-1.5	2.9	K>P>Ca
	69	4.4	-2.1	-8.7	-1.6	3.9	K>P>Ca
	104	3.7	-3.0	-7.3	-1.2	3.4	K>P>Ca
P	0	3.2	-3.1	-5.7	-1.6	3.5	K>P>Ca
	9	3.6	-1.9	-8.4	-1.3	3.8	K>P>Ca
	18	3.3	-2.4	-5.6	-1.4	2.7	K>P>Ca
K	0	5.0	-1.9	-11.5	-1.0	5.0	K>P>Ca
	45	3.1	-2.6	-5.6	-1.6	2.9	K>P>Ca
	90	2.3	-2.7	-3.9	-1.6	2.3	K>P>Ca>Mg
With 44.8 Mg manure/ha							
N	35	1.3	-1.0	1.2	-3.5	0.6	Ca>P>Mg
	69	1.8	-1.7	1.4	-3.8	0.7	Ca>P>Mg
	104	1.5	-1.0	0.4	-2.9	0.9	Ca>P
P	0	2.0	-1.2	0.9	-3.5	0.7	Ca>P
	9	1.9	-1.5	0.9	-3.2	0.7	Ca>P
	18	0.8	-0.9	1.1	-3.4	0.6	Ca>P>Mg>N
K	0	1.7	-1.1	0.7	-3.2	1.0	Ca>P
	45	1.4	-1.0	1.2	-3.8	1.0	Ca>P
	90	1.6	-1.4	1.0	-3.2	0.2	Ca>P

^zAmong negative DRIS indexes, from smallest value upward.

Table 7. Compositional nutrient diagnosis (CND) diagnosis of a fertilizer experiment on carrot crops grown on mineral soil at varied rates of manure, N, P, and K (adapted from Haworth et al., 1966).

Fertilizer	Rate	CND index					Order of
added	(kg·ha ⁻¹)	N	P	K	Ca	Mg	limitation ^z
Without manure added							
N	35	2.3	-2.1	-3.6	-1.6	2.3	K>P>Ca
	69	3.8	-1.7	-6.2	-1.6	2.8	K>P>Ca
	104	3.5	-2.3	-5.4	-1.2	2.5	K>P>Ca
P	0	3.1	-2.4	-4.5	-1.6	2.7	K>P>Ca
	9	3.1	-1.5	-6.1	-1.5	2.8	K>P=Ca
	18	3.3	-2.0	-4.5	-1.4	2.2	K>P>Ca
K	0	4.0	-1.5	-7.5	-1.2	3.3	K>P>Ca
	45	3.1	-2.1	-4.5	-1.6	2.3	K>P>Ca
	90	2.5	-2.3	-3.3	-1.6	1.9	K>P>Ca
With 44.8 Mg manure/ha							
N	35	1.6	-0.9	1.2	-3.8	0.6	Ca>P
	69	2.2	-1.5	1.5	-4.0	0.6	Ca>P
	104	1.9	-0.9	0.4	-3.3	0.9	Ca>P
P	0	2.3	-1.0	1.0	-3.8	0.7	Ca>P
	9	2.3	-1.3	1.0	-3.5	0.7	Ca>P
	18	1.0	-0.8	1.1	-3.7	0.7	Ca>P
K	0	2.0	-1.0	0.7	-3.5	0.9	Ca>P
	45	1.6	-0.9	0.7	-3.5	0.9	Ca>P
	90	2.1	-1.3	1.1	-3.4	0.2	Ca>P

^zAmong negative CND indexes, from smallest value upward.

dexes, CND PC diagnosis helps interpret nutrient status in carrot crops. CND also reduces the computational effort. Orthogonality among CND PCs allows the computation of euclidean distances using the Pythagorean theorem. CND PCs are freed from the bounded-sum constraint to 100%, from redundancy among nutri-

ent variates and from random effects of nonsignificant PCs. If sufficient data are available for conducting PCA over the high-yielding subpopulation, CND PCs become linear combinations of CND nutrient indexes. CND PC diagnosis is a multivariate approach providing a theoretical basis for further improvements in

Table 8. Multivariate diagnosis and recommendation integrated system (DRIS) and compositional nutrient diagnosis (CND) diagnoses of a fertilizer experiment on carrot crops grown on mineral soil at varied rates of manure, N, P, and K (adapted from Haworth et al., 1966).

Fertilizer	Rate	CND principal component (PC)					Yield
added	(kg·ha ⁻¹)	K-Mg ⁺	N-Ca ⁺	P ⁻	d ^z	NII ^y	(Mg·ha ⁻¹)
Without manure							
N	35	3.10	-2.60	1.93	4.48	13.2	35.4
	69	4.70	-3.79	1.76	6.29	20.7	33.8
	104	4.14	-3.42	2.35	5.86	18.6	33.2
P	0	3.80	-3.26	2.31	5.51	17.1	33.2
	9	4.59	-3.18	1.52	5.79	19.0	33.4
	18	3.46	-3.29	2.01	5.18	15.4	35.6
K	0	5.65	-3.71	1.70	6.97	24.4	32.0
	45	3.55	-3.25	2.02	5.22	15.8	34.7
	90	2.73	-2.76	2.08	4.40	12.8	35.8
With 44.8 Mg manure/ha							
N	35	-0.34	-2.93	0.56	3.00	7.6	42.6
	69	-0.45	-3.52	1.17	3.74	9.4	41.4
	104	0.27	-2.91	0.56	2.98	6.7	41.2
P	0	-0.15	-3.53	0.86	3.64	8.3	41.4
	9	-0.15	-3.37	1.12	3.55	8.2	41.4
	18	-0.28	-2.39	0.40	2.44	6.8	42.3
K	0	0.13	-3.08	0.79	3.18	7.7	41.9
	45	-0.16	-3.08	0.60	3.14	8.4	42.1
	90	-0.52	-3.22	1.02	3.42	7.4	41.4

^zCND euclidian distance.

^yDRIS nutrient imbalance index.

foliar diagnosis.

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