A Multivariate Geostatistical Algorithm on delineation of Management Zones

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SPATIAL VARIABILITY

FIELD

PLANT GROWTH

PRODUCTION

QUALITY
SITE-SPECIFIC MANAGEMENT

MATCHING

MANAGED INPUTS  LOCAL ENVIRONMENTAL CONDITIONS

INCREASING FARMER’S INCOME
REDUCING ENVIRONMENTAL IMPACT
MANAGEMENT ZONES: homogeneous subfield regions with similar attributes affecting yield that can be uniformly managed

(Doerge, 1999)
Various authors have proposed criteria for the delineation of management zones based on:

- Topography, landscape position
- Soil Type
- Nutrient levels
- Yield
- EC (geo-electric sensors)
- Remote sensing and aerial photos
- Producer experiences

(Franzen et al., 2001; Basso et al., 2001; Johnson et al., 2003; Ferguson et al., 2004; Schepers et al., 2004, Chang et al., 2004; Fleming et al., 2004; Inman et al., 2005; Castrignanò et al., 2006; Bocchi & Castrignanò, 2007; Castrignanò et al., 2008; Morari et al., 2009)
DOES NOT INTERPRET
## CLUSTERING: CURRENT METHODS

### TYPE
- ISODATA
  *(Iterative self-organizing data analysis technique)*
- K or c means
  K or c fuzzy means
- Non-parametric multivariate density algorithm
- Ward’s minimum variance
- ....

### PROPERTIES
- Iterative Procedure
- Gaussian Distributions
- Similar Variances
- Iterative Process
  No previous requirements
- No requirement about distribution type
- ....

HOWEVER…
CLUSTERS ARE SUPPOSED TO BE **CRISPLY OR FUZZILY DELINEATED IN**

*ATTRIBUTE SPACE*

*GEOGRAPHIC SPACE*

BOTH SPACES
“Everything is related to everything else, but near things are more related than distant things”
MULTIVARIATE GEOSTATISTICS

INFORMATION

MULTI - SPATIAL

X₁, X₂.....

SPATIAL CORRELATION

MULTI - VARIATE

Z₁, Z₂....

DEPENDENCY BETWEEN THE PROPERTIES

ESTIMATE
FACTORIAL COKRIGING decomposes regionalized factors from raw variables.

MULTI-SCALE APPROACH

- Long Range
- Short Range
- Micro Range
OBJECTIVES

- STUDY SCALE - DEPENDENT CORRELATION STRUCTURE OF SOIL VARIABLES

- DELINEATE MANAGEMENT ZONES
STUDY CASE

Site: Grifalco farm, Ginosa (Taranto - ITALY) 40° 28' 48.40” N, 16° 47' 37.97” E.
Field size: 12 ha
Crop: Lettuce
Sampling Depth: 0.30 m
Data: coarse and fine sand contents (%), coarse and fine silt (%), clay contents (%), organic matter content (%) (OM), available Phosphorus concentrations (mg kg⁻¹), pH, electrical conductivity (mSm⁻¹) (EC), field capacity (%) (FC) and wilting point (%) (WP)
MULTI-GAUSSIAN GEOSTATISTICAL APPROACH

\[ Z = \Phi(Y) \]

\[ \Phi(Y) = \sum_{i=1}^{N} \Psi_i H_i(Y) \]

\( N = 30-100 \)

\( H_i(Y) = \text{Hermite Polynomials} \)
GEOSTATISTICAL ANALYSIS

FACTOR KRINGING ANALYSIS (FKA)

LINEAR COREGIONALIZATION MODEL

\[ \gamma_{ij}(h) = \sum_{u=1}^{N_S} b_{ij}^u g^u(h) \quad i, j=1,\ldots,n \]

\[ \Gamma(h) = \sum_{u=1}^{N_S} B^u g^u(h) \]
$B^u = Q^u \Lambda^u (Q^u)^T = A^u (A^u)^T$

$Q^u$ matrix of eigenvectors

$\Lambda^u$ matrix of eigenvalues
Regionalised factor estimation by cockrigin and mapping

\[ Z_i(x) = \sum_{u=1}^{N_S} \sum_{v=1}^{n} a_{iv}^u Y_v^u(x) \]

\[ Y_v^{u*}(x_0) = \sum_{i=1}^{n} \sum_{\alpha=1}^{N} \lambda_{\alpha i}^u Z_i(x_\alpha) \]
Multi-gaussian geostatistical approach

Flowchart

- Raw data
- Gaussian transform
- Gaussian data
- Variography
- Variogram of Gaussian variable
- Conditional estimation
- Conditional Raw estimation
- Inverse transform
- Conditional Gaussian estimation

Centre de Géostatistique - Ecole des Mines de Paris

Gaussian random function 35/58
## RESULTS

Basic statistics of the soil properties

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>Min.</th>
<th>Max</th>
<th>Mean</th>
<th>Median</th>
<th>Std. Dev.</th>
<th>CV</th>
<th>Skewness</th>
<th>Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC (%)</td>
<td>5.32</td>
<td>23.80</td>
<td>13.04</td>
<td>12.57</td>
<td>4.07</td>
<td>0.31</td>
<td>0.35</td>
<td>2.49</td>
</tr>
<tr>
<td>WP (%)</td>
<td>2.76</td>
<td>11.00</td>
<td>6.23</td>
<td>5.86</td>
<td>2.05</td>
<td>0.33</td>
<td>0.54</td>
<td>2.51</td>
</tr>
<tr>
<td>EC (mS m⁻¹)</td>
<td>141.30</td>
<td>518.00</td>
<td>240.23</td>
<td>230.50</td>
<td>75.95</td>
<td>0.32</td>
<td>1.30</td>
<td>5.07</td>
</tr>
<tr>
<td>Available P (mg Kg⁻¹)</td>
<td>28.00</td>
<td>120.00</td>
<td>65.57</td>
<td>65.63</td>
<td>18.76</td>
<td>0.29</td>
<td>0.33</td>
<td>3.10</td>
</tr>
<tr>
<td>O.M. (%)</td>
<td>0.19</td>
<td>0.68</td>
<td>0.38</td>
<td>0.39</td>
<td>0.11</td>
<td>0.29</td>
<td>0.32</td>
<td>2.81</td>
</tr>
<tr>
<td>Clay (%)</td>
<td>7.96</td>
<td>30.25</td>
<td>17.58</td>
<td>16.18</td>
<td>5.64</td>
<td>0.32</td>
<td>0.30</td>
<td>2.15</td>
</tr>
<tr>
<td>Coarse Silt (%)</td>
<td>4.92</td>
<td>12.45</td>
<td>8.62</td>
<td>8.37</td>
<td>1.51</td>
<td>0.17</td>
<td>0.43</td>
<td>3.06</td>
</tr>
<tr>
<td>Fine Silt (%)</td>
<td>0.51</td>
<td>7.48</td>
<td>5.07</td>
<td>5.37</td>
<td>1.61</td>
<td>0.32</td>
<td>-0.95</td>
<td>3.42</td>
</tr>
<tr>
<td>pH</td>
<td>7.00</td>
<td>8.15</td>
<td>7.63</td>
<td>7.67</td>
<td>0.32</td>
<td>0.04</td>
<td>-0.24</td>
<td>1.90</td>
</tr>
<tr>
<td>Coarse Sand (%)</td>
<td>21.47</td>
<td>45.36</td>
<td>32.93</td>
<td>34.32</td>
<td>6.14</td>
<td>0.19</td>
<td>-0.22</td>
<td>2.01</td>
</tr>
<tr>
<td>Fine Sand (%)</td>
<td>27.57</td>
<td>43.60</td>
<td>35.80</td>
<td>36.01</td>
<td>3.02</td>
<td>0.08</td>
<td>-0.29</td>
<td>3.51</td>
</tr>
</tbody>
</table>
## Correlation Matrix

The correlation coefficient >0.28 is significant at the 0.05 probability level.
Basic structures of the LMC:
1. Nugget effect;
2. Spherical model (range =68 m);
3. Exponential model (range=250 m).
<table>
<thead>
<tr>
<th>Variable</th>
<th>Nugget Effect</th>
<th>Model 1: Spherical Model</th>
<th>Model 2: Spherical Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>O.M (%)</td>
<td>Sill 0.007069</td>
<td>Range 50.00m Sill 0.001687</td>
<td>Range 248.20m Sill 0.00385</td>
</tr>
<tr>
<td>Fine Silt (%)</td>
<td>Sill 1.06843</td>
<td>Range 67.85m Sill 0.877644</td>
<td>-</td>
</tr>
<tr>
<td>Fine Sand (%)</td>
<td>Sill 1.03842</td>
<td>Range 58.53m Sill 7.9794</td>
<td>-</td>
</tr>
</tbody>
</table>

Variogram models
## Decomposition into regionalized factors

### Nugget effect

<table>
<thead>
<tr>
<th></th>
<th>gFC</th>
<th>gEC</th>
<th>gP</th>
<th>g WP</th>
<th>gClay</th>
<th>gCoarse Silt</th>
<th>gpH</th>
<th>gCoarseSand</th>
<th>Eigen Value</th>
<th>Var.Perc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor 1</td>
<td>0.2685</td>
<td>0.0033</td>
<td>-0.4677</td>
<td>0.0803</td>
<td>0.18</td>
<td>-0.4611</td>
<td>-0.6644</td>
<td>0.1279</td>
<td>0.4828</td>
<td>87.95</td>
</tr>
<tr>
<td>Factor 2</td>
<td>0.2389</td>
<td>0.0942</td>
<td>0.0557</td>
<td>-0.0758</td>
<td>-0.4246</td>
<td>-0.4342</td>
<td>0.0925</td>
<td>-0.7402</td>
<td>0.0362</td>
<td>6.59</td>
</tr>
<tr>
<td>Factor 3</td>
<td>0.1362</td>
<td>0.0703</td>
<td>-0.016</td>
<td>0.6723</td>
<td>-0.6341</td>
<td>0.2519</td>
<td>-0.1644</td>
<td>0.1783</td>
<td>0.03</td>
<td>5.46</td>
</tr>
</tbody>
</table>

### Cubic Model - Range = 68.00m

<table>
<thead>
<tr>
<th></th>
<th>gFC</th>
<th>gEC</th>
<th>gP</th>
<th>g WP</th>
<th>gClay</th>
<th>gCoarse Silt</th>
<th>gpH</th>
<th>gCoarseSand</th>
<th>Eigen Value</th>
<th>Var.Perc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor 1</td>
<td>0.4222</td>
<td>0.5104</td>
<td>0.311</td>
<td>0.459</td>
<td>0.3763</td>
<td>-0.0785</td>
<td>0.3143</td>
<td>-0.0855</td>
<td>1.4841</td>
<td>64.71</td>
</tr>
<tr>
<td>Factor 2</td>
<td>0.1994</td>
<td>-0.1505</td>
<td>0.2826</td>
<td>0.1306</td>
<td>0.2585</td>
<td>0.1048</td>
<td>-0.8412</td>
<td>-0.2352</td>
<td>0.4186</td>
<td>18.25</td>
</tr>
<tr>
<td>Factor 3</td>
<td>0.0746</td>
<td>-0.4657</td>
<td>-0.1018</td>
<td>0.271</td>
<td>0.3196</td>
<td>-0.5484</td>
<td>-0.012</td>
<td>0.5392</td>
<td>0.2846</td>
<td>12.41</td>
</tr>
<tr>
<td>Factor 4</td>
<td>0.4965</td>
<td>-0.1383</td>
<td>0.2032</td>
<td>-0.0184</td>
<td>-0.2944</td>
<td>0.5281</td>
<td>0.0233</td>
<td>0.5715</td>
<td>0.0856</td>
<td>3.73</td>
</tr>
<tr>
<td>Factor 5</td>
<td>-0.5897</td>
<td>0.1523</td>
<td>-0.0139</td>
<td>0.1609</td>
<td>0.482</td>
<td>0.4975</td>
<td>-0.0342</td>
<td>0.3492</td>
<td>0.0186</td>
<td>0.81</td>
</tr>
<tr>
<td>Factor 6</td>
<td>-0.1934</td>
<td>0.0913</td>
<td>-0.1851</td>
<td>0.7694</td>
<td>-0.5456</td>
<td>0.0017</td>
<td>-0.1739</td>
<td>0.0053</td>
<td>0.0021</td>
<td>0.09</td>
</tr>
</tbody>
</table>

### Spherical Model - Range = 250.00m

<table>
<thead>
<tr>
<th></th>
<th>gFC</th>
<th>gEC</th>
<th>gP</th>
<th>g WP</th>
<th>gClay</th>
<th>gCoarse Silt</th>
<th>gpH</th>
<th>gCoarseSand</th>
<th>Eigen Value</th>
<th>Var.Perc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor 1</td>
<td>0.3691</td>
<td>-0.3068</td>
<td>-0.4016</td>
<td>0.3831</td>
<td>0.3794</td>
<td>0.2672</td>
<td>0.2711</td>
<td>-0.4157</td>
<td>3.9668</td>
<td>90.99</td>
</tr>
<tr>
<td>Factor 2</td>
<td>-0.027</td>
<td>0.5538</td>
<td>-0.2114</td>
<td>-0.2842</td>
<td>0.0099</td>
<td>0.7515</td>
<td>-0.0409</td>
<td>-0.0248</td>
<td>0.3318</td>
<td>7.61</td>
</tr>
<tr>
<td>Factor 3</td>
<td>0.4522</td>
<td>0.0256</td>
<td>-0.0086</td>
<td>-0.152</td>
<td>-0.4072</td>
<td>-0.0079</td>
<td>0.7035</td>
<td>0.333</td>
<td>0.0611</td>
<td>1.4</td>
</tr>
</tbody>
</table>
Regionalized Factors
The resultant MZ map depicts three MZ of ~ 4 ha-size each one, characterised by different water retention properties: the southern zone, finer textured, with higher water retention, clay and OM (HIGH); the central zone, coarser textured, with smaller water retention and the northern part, with intermediate properties and larger heterogeneity (MEDIUM), where a sub-portion at the NE corner (~0.5 ha) looks quite similar to the central part (LOW).
1. MULTIVARIATE GEOSTATISTICAL APPROACH → MZ delineation

2. EACH MZ CHARACTERIZED BY DIFFERENT SOIL TEXTURAL AND RETENTION PROPERTIES "may affect" SITE-SPECIFIC IRRIGATION
For each MZ a simulation run was carried out by using the physically based model SWAP (Soil water Atmosphere Plant: van Dam et al. 2007) adopting the simple growth module option.

SWAP simulates water and solute in saturated and unsaturated soils solving the Richards equation.
Rosetta (M. Schaap) is a Windows program to estimate unsaturated hydraulic properties from surrogate soil data such as soil texture data and bulk density.

Rosette can be used to estimate the Water retention parameters, saturated hydraulic conductivity and unsaturated hydraulic conductivity parameters according to van Genuchten (1980) and Mualem (1976)

\[
S = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[1 + (\alpha h)^n \right]^{-m}
\]

\[
K = K_s S^{0.5} \left[1 - \left(1 - S^{1/m}\right)^m\right]^2
\]
Hydraulic Functions of MZ

Soil water pressure head ($h$: cm)

$$S = \frac{\theta - \theta_r}{\theta_s - \theta_r} = [1 + (\alpha h)^n]^{-m}$$

Soil water content ($\theta$)

Soil hydraulic conductivity ($K$: cm day$^{-1}$)

$$K = K_s S^{0.5} \left[ 1 - \left(1 - S^{1/m} \right)^m \right]^2$$

Soil water content ($\theta$)

Soil hydraulic conductivity (K: cm day$^{-1}$)
The hydraulic retention and conductivity functions for the low and medium MZ resulted in comparable and typical results for sandy soils, with high values for parameters $n$, $\alpha$, $K_s$ and low values of $\theta_s$ and $\theta_r$.

The resulting soil water retention for a profile of 70 cm calculated as difference between field capacity ($h=-300$ cm) and wilting point ($h=-15000$ cm) was 63, 65 and 99 mm, for low, medium and high MZ, respectively.

The hydraulic function of the third MZ was significantly different with lower values for $n$, $\alpha$ and $K_s$). $\theta_s$ and $\theta_r$ were considered similar to those of the other MZ.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LOW</th>
<th>MEDIUM</th>
<th>HIGH</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_r$</td>
<td>0.032</td>
<td>0.034</td>
<td>0.045</td>
</tr>
<tr>
<td>$\theta_s$</td>
<td>0.445</td>
<td>0.447</td>
<td>0.452</td>
</tr>
<tr>
<td>$\alpha$ (cm$^{-1}$)</td>
<td>0.062</td>
<td>0.055</td>
<td>0.029</td>
</tr>
<tr>
<td>$n$</td>
<td>1.45</td>
<td>1.39</td>
<td>1.33</td>
</tr>
<tr>
<td>$K_s$ (cm d$^{-1}$)</td>
<td>301.2</td>
<td>242.3</td>
<td>101.8</td>
</tr>
<tr>
<td>Soil water</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>retention (mm)</td>
<td>63.30</td>
<td>75.04</td>
<td>98.98</td>
</tr>
</tbody>
</table>
The top figure shows the time evolution of the average soil water content of the three MZs. Significant differences were found between the high MZ and the other ones with particular reference to irrigation management regarding the depth and time of irrigation. The seasonal irrigation depths were 77, 89 and 136 mm for low, medium and high MZ.
FUTURE IMPROVEMENTS

a) More variables of different types

b) More dynamic definition of MZ for scheduling irrigation

Remote Sensing  Infrared imaging  Proximal Sensing