Assessment of Spatial Variability of Soil and Canopy Properties in a Cassava Field

キャッサバ畑における土壌や植生の不均一な圃場特性

Osama MOHAWESH¹⁾ Kazunari FUKUMURA²⁾ Tomoyasu ISHIDA²⁾
モハオシ オサマ 福村一成 石田朋靖
Kunihiko YOSHINO³⁾
吉野邦彦

1) *United Graduate School of Agricultural Science, Tokyo University of Agric. And Tech*
東京農工大学院連合農学研究科

2) *Faculty of Agriculture, Utsunomiya University*
宇都宮大学農学部

3) *College of Policy and Planning Science, Tsukuba University*
筑波大学社会学系

Site-specific crop management requires consideration of the spatial variability within the field. Spatial distributions of soil and canopy properties at the field may affect yield potential, hydrologic response, and solute transport. Thus, describing within-field variability is a fundamental first step toward determining the size of management zones. This study is being conducted at an arable flat cassava plantation area in northeast part of Thailand. Soil is generally *Rhodic Kandistox*, and its texture is clay. Dry bulk density, volumetric soil water content, Leaf area index (LAI) and plant height were measured at mesh points on site. Dry bulk density and volumetric water content were measured at depth 0-6 cm. Statistical and additional geostatistical analyses were applied on the measured properties. The correlation coefficient between LAI and plant height was significant. Spherical model best fitted all the experimental semivariograms. The range values of the measured properties were about 30 m. All the measured properties exhibited strong spatial continuity. Among the measured properties, LAI exhibited the strongest spatial correlation; plant height exhibited the weakest spatial correlation. The cross-validation showed the goodness of the fitted semivariogram models. The semivariogram model of the dry bulk density was used to estimate the distribution of soil hydraulic parameters in the field. Distribution of soil hydraulic properties across the field can be combined to give a useful input for numerical models to simulate water movement and distribution.

Key words : Dry bulk density, Soil hydraulic properties, Canopy structure, Spatial variability.

圃場内の土壌や作物キャノピーの空間分布特性は水文過程や溶質移動現象に大きな影響を与える。本論文では、圃場における水移動現象にかかわる土壌と植生の諸変数の空間分布特性を把握することを目的とした。対象地は、タイ国北東部に位置する平坦なキャッサバ畑で、土壌は *Rhodic Kandistox* に分類され、土性は粘土である。乾燥密度、体積含水率、LAI (葉面積指標)、植物高さをメッシュポイントで測定した。体積含水率、乾燥密度についてはメッシュポイントにおいて一つの深さ (0 - 6 cm) で測定した。圃場での測定値間の相関は LAI と植物高さで $r^2 = 0.35$ となったが、その他は相関が見られなかった。また測定値に空間統計学的手法を適用した結果、対象地の空間的不均一構造は、球形モデルによって最も適切に表され、そのレンジは、乾燥密度、体積含水率、LAI、植物高ともに 30 m 程度であった。さらに、測定値の空間依存性は LAI が最も強く、植物高さが最低であることがわかった。また、球形モデルで表されたセミバリオグラムを使いクリッキング手法により推定した分布は、クロス・バリデーション手法によって十分に満足できる精度であることが示された。こうして推定された乾燥密度の分布から土壌の水利特性の分布を求めることが示され、圃場における水分移動シミュレーションに有効に利用できる可能性が示唆された。

キーワード : 土壌水分移動特性、乾燥密度、キャノピー特性、空間統計

1) Saiwai-cho 3-5-8, Fuchu-shi, Tokyo, Japan 183-8509 〒183-8509 東京都府中市幸町 3-5-8

2) Mine-machi 350, Utsunomiya, Tochigi, Japan 321-8505 〒321-8505 栃木県宇都宮市峰町350

3) Tennodai 1-1-1, Tsukuba, Ibaraki, Japan 305-8577 〒305-8577 茨城県つくば市天王台 1-1-1

I. INTRODUCTION

Precision farming requires precise farm management through considering the spatial variability within the field. Site-specific crop management can be viewed as a cyclical process of within-field data collection, data analysis and optimum decision making, and evaluation. Crop status and soil properties are necessary data inputs to the system. Describing spatial variability of within-field properties is a fundamental first step toward determining the size of management zones and the inter-relationships between limiting factors for the development of management practices.

The wide use of water transfer models for management planning implies estimating the soil hydraulic properties at appropriate scale, which are very important in simulating the soil water regime (Witono and Bruckler, 1989)

At field level, the soil hydraulic properties vary in space. Previous studies have shown that this spatial variability should be taken into account (e.g., Bresler and Dagan, 1981; Russo *et al.*, 1989) However, measurements of soil hydraulic properties in the field are expensive and time consuming. As an alternative to their direct measurement, indirect methods are being developed which make use of easily available or measurable soil properties. Mohawesh *et al.* (2004) modified van Genuchten's and Mualem's models of soil water retention and hydraulic conductivity, respectively, by relating the models parameters to dry bulk density. Thus, it seems that by knowing the distribution of dry bulk density in the field, the distribution of soil hydraulic properties can be known.

Moreover, canopy properties like LAI and plant height, may also affected water and energy movements. LAI is one of the most important factors in the crop yield and water movement models (Ziaei and Sepaskhah, 2003) However, all the previous studies deal with an average value of LAI and plant height among the simulation area. No geostatistical field studies, to our knowledge, have been performed to assess the spatial variation in canopy structure. Therefore, appropriate estimation of

LAI and plant height may also results in greater precision in estimation of yield and water use.

Geostatistics, based on the theory of regionalized variables, is the primary tool of spatial variability analysis. It offers an alternative approach in that spatial correlations are quantified (Burgess and Webster, 1980; McBratney and Webster, 1983; Bos *et al.*, 1984) which is more adequate and informative tool to measure the structural variation and spatial dependency of the variables of interest.

The objectives of this work are therefore (1) assess spatial variability and pattern of soil and canopy properties in a field, and (2) describe spatial variability of field soil hydraulic properties.

II. MATERIAL AND METHODS

1. Description of study area

This study was conducted on a commercial arable flat area in northeast part of Thailand (N 14° 27' 56", E 102° 22' 45") The research site is a part of huge commercial Cassava plantation area with a uniform cultivation practices. Soil is generally *Rhodic Kandistox* (Typic Palehumults, Fine, kaolinitic, isohyperthermic) and its texture is clay (Clay 61%, Silt 21%, Sand 18%) The area has a tropical monsoon climate with a mean annual precipitation of 1636 mm and a mean temperature 26.4 oC. The research site is usually being ploughed two times before planting up to depth 0.15-0.20 m using disk plow.

2. Field measurements

Late September 2003, the field was surveyed and the sample locations were determined at the same time. An area (70 × 100 m) was established then divided into a mesh points (Fig. 1) Dry bulk density (ρ_d) volumetric soil water content (θ) leaf area index (LAI) and plant height (H) were measured at the mesh points on site. Location of each sample point was measured with a simple differential global positioning system (DGPS) to obtain latitude and longitude values (Saito *et al.*, 2004) These were converted to a metric coordinates. Crop residues were brushed aside prior to sampling. Soil

Fig. 1 Locations of sampling points. Dry bulk density (ρ_d), volumetric soil water content (θ), leaf area index (LAI) and plant height (h) were measured at the mesh points.

cores (5 cm i.d. $\times$ 5.1 cm long) were sampled right under the soil surface at depth 0–6 cm to evaluate dry bulk density using gravimetric method. Surface volumetric soil water content measured at the mesh points using Amplitude Domain Reflectometry (ADR) (ThetaProbe ML2X, Delta-T Device Ltd., UK) within 4 hours in a cloudy day. A 6 cm long coaxial hand probe with four 0.3 cm diameter rods was pushed vertically into the soil. A specific ADR-calibration was used to convert ADR measurements into values of θ (Mohawesh *et al.*, 2004). LAI and plant height were measured at the mesh points after soil properties measurements. LAI was measured using optical approaches (LI-COR LAI 2000 Plant Canopy Analyzer, Lincoln, Nebr.). Plant's height was measured at the mesh points using a measuring tape. An average of the surrounding plant's height was taken at each mesh point.

3. Statistical and Geostatistical Analysis

Data analysis were done in three steps: (i) normality tests were applied (normal probability plots); (ii) distributions were described with classical statistics (arithmetic means, standard deviation, coefficient of variation, minimum and maximum, median and skewness); (iii) Describe spatial variability of each variable using semivariograms, range, nugget, sill and nugget ratio values

were determined. Maps of variables were produced by kriging technique (Issaks and Srivastava, 1989).

In geostatistics, the concept of variance from classic statistics is extended to semivariance. A semivariogram, which graphs the semivariance between spatially separate data points as a function of the distance is well documented to illustrate the spatial relationship of soil properties (Warrick *et al.*, 1986; Buchter *et al.*, 1991).

Semivariance ($\gamma(h)$) at a given position was computed by means of the following equation:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2 \quad (1)$$

where $N(h)$ is the number of data pairs separated by the lag distance h , $Z(x_i)$ and $Z(x_i + h)$ are measurements of Z at x_i and $x_i + h$, respectively.

Certain features of semivariograms important for interpretation of spatial data from measured properties are shown in Fig. 2. The theoretical localized discontinuity or nugget, C_o , is defined by the y-intercept and is interpreted as variability due to experimental error, distributional effects below the sampling scale of the study, and other random effects. The range (A) is the lag distance beyond which samples are considered spatially independent. The corresponding value of the semivariance at this point is termed the sill ($C + C_o$) and represents the combination of a nugget effect and variability (C) attributable to spatial dependence.

Fig. 2 Generalized semivariogram showing the range of spatial dependence (A), nugget (C_o), variability associated with spatial dependence (C) and sill ($C + C_o$).

Geostatistical software (VARIOWIN, Springer, New York) was used to construct semivariograms and spatial structure analysis of variables and fitting them to different theoretical models. Models selection for experimental semivariogram was done on the basis of visual fitting and cross validation (Chiles and Delfiner, 1999) Geostatistical analysis was done for the measured properties.

III. RESULTS AND DISCUSSION

1. Classical statistical analysis

Descriptive statistics of the measured properties are presented in **Table 1**. The range of the coefficient of variations (CVs) obtained suggested different degrees of heterogeneity between the measured properties (**Table 1**) The values show that LAI exhibited the greatest variability followed by plant height, volumetric water content and dry bulk density. The average dry bulk density and CV were 1.325 mg m^{-3} and 7.0 percent, receptively. The CV value of dry bulk density is similar to the values of CV from a number of earlier studies (Buchter *et al.*, 1991; Nielsen *et al.*, 1973) The plot of dry bulk density versus normal standard deviates (μ) is almost linear as shown in **Fig. 3**. All other measured properties also reveal an approximately linear relationship with normal standard deviates, which promise the normal distribution of them.

A correlation tests between the measured prop-

Fig. 3 Fractile diagram of dry bulk density. Solid line is linear trend line.

erties were done. **Table 2** gives the coefficient of determination matrix between the measured properties. Except for the significant correlation between LAI and plant height ($r^2 = 0.35$) it is apparent that the measured properties are not correlated to each other. Anderson *et al.* (2004) showed that plant height is correlated with LAI for corn and soybean. The lack of correlation between LAI and water content was unexpected. These results may be due to heavy rain occurred two days before the measurements; the effect of LAI on soil wa-

Table 1 Summary statistics of measured dry bulk density (ρ_d) volumetric soil water content (θ) leaf area index (LAI) and plant height (H)

Parameter	Soil properties (0 - 6 cm)		Plant properties	
	ρ_d	θ	H	LAI
	(Mg m^{-3})	($\text{m}^3 \text{m}^{-3}$)	(m)	($\text{m}^2 \text{m}^{-2}$)
Observations	130	110	130	108
Mean	1.3250	0.3446	1.1211	1.3811
Median	1.3155	0.3422	1.1000	1.335
Skewness	0.3570	0.7048	0.5619	0.7632
Standard deviation	0.0926	0.0287	0.1541	0.4169
Maximum	1.5480	0.4336	1.80	2.88
Minimum	1.1110	0.2803	0.80	0.69
CV (%)	7.00	8.4	13.8	30.4

CV: coefficient of variation

Table 2 Correlation coefficients(r^2)between the measured properties.

Property	ρ_d (Mg m ⁻³)	θ (m ³ m ⁻³)	LAI (m ² m ⁻²)	H (m)
ρ_d	1.00			
θ	0.18	1.00		
LAI	0.00	0.01	1.00	
H	0.04	0.06	0.35*	1.00

* Significant at the 0.05 probability level.

ter depletion through evapotranspiration was not clear after short drying period. The correlation between water content and dry bulk density was relatively weak ($r^2 = 0.18$) Kilic *et al.* (2004)also found that dry bulk density and soil water content has a weak linear correlation.

2. Geostatistical analysis

Geostatistical analysis was done for the measured properties. Figs. 4 and 5 show the experimental and the modeled semivariograms. Semivariograms revealed the spatial structure for all studied properties.

Four isotropic models typically encountered in practice include linear, spherical, exponential, and Gaussian models. Here, a spherical model (Eq. 2) well fitted all our experimental variograms.

$$(h) = \begin{cases} C_o + C [1.5 (\frac{h}{A}) - 0.5 (\frac{h}{A})^3] & h \leq A \\ C_o + C & h > A \end{cases} \quad (2)$$

The parameters of the fitted semivariograms are shown in Table 3. Cambardella *et al.*, (1994)also found the spherical model best fit the experimental semivariograms of dry bulk density and water content.

The measured properties have non-zero nugget effect, which is caused by measurement error or micro-variability that can't be detected at the scale of sampling. To compare the relative size of the nugget effects among different properties and different models, the effect can be expressed as a ratio of nugget to sill ($NR = C_o/(C_o+C)$) This ratio NR (nugget ratio)has been used in qualitative assessment of the strength of the spatial Correla-

Fig. 4 Semivariograms of dry bulk density(left)and volumetric soil water content(right)at depth 0-6 cm. The marks and lines indicate the experimental and the modeled semivariograms, respectively.

Fig. 5 Semivariograms of leaf area index (left) and plant height (right) . The marks and lines indicate the experimental and the modeled semivariograms, respectively.

Table 3 Geostatistical model parameters of the measured properties.

property	depth (cm)	Model	Nugget (C_0)	Sill ($C_0 + C$)	Range (m)	NR	r^2
ρ_d (Mg m^{-3})	0-6	Spherical	0.00414	0.00972	31	0.43	0.84 *
θ ($\text{m}^3 \text{m}^{-3}$)	0-6	Spherical	0.000414	0.000972	24	0.43	0.76
LAI ($\text{m}^2 \text{m}^{-2}$)		Spherical	0.058	0.212	35	0.27	0.76
H (m)		Spherical	0.0159	0.0238	32	0.66	0.65

Gaussain model : $r^2 = 0.82$, Exponential model : $r^2 = 0.76$, Linear model : $r^2 = 0.77$.

tion within a field attribute (Cambardella *et al.*, 1994, Kilic *et al.*, 2004) A ratio of 0 indicates that the measurements error and short-range variability is negligible. A ratio $NR < 0.25$ means the spatial correlation of the variable is strong; between 0.25 and 0.75 has a moderate spatial correlation; ratio $NR > 0.75$ and less than 1 has a weak spatial correlation. Ratio of 1 exhibits pure nugget effect, indicating no spatial correlation at the scale of sampling.

Spatial correlation of dry bulk density was moderate ($NR = 0.43$) as shown in Table 3. Cambardella *et al.* (1994) showed that NR ranged from 0.36 to 0.24 for dry bulk density; suggested that dry bulk density possessed a moderate to strong spatial structure. Spatial correlation of volumetric soil water content was also moderate ($NR = 0.43$) Burden and Selim (1989) showed a moderate spatially correlation for volumetric soil water content.

LAI and plant height exhibit moderate spatial correlation; nugget ratio of plant height ($NR = 0.66$) was the highest among the measured properties and close to weak spatial correlation; lowest for LAI ($NR = 0.27$) which was close to strong spatial correlation.

The range values of the measured properties were around 30 m as shown in Table 3. The variability in this field is mainly caused by farming practices, as in and/or inter row spacing of plants, plough width, and so on. These scales are less than a few meters. Thus, the range of 30 m seems to be long comparing with these scales. The long ranges of the measured properties suggest strong spatial continuity.

The long range and small NR value suggest that the property's continuity and spatial correlation is strong; short range and large NR suggest weak spatial continuity and correlation. All the measured

properties exhibited strong spatial continuity. Among the measured properties NR of LAI was the smallest, which suggests relatively stronger spatial correlation. Plant height had the highest NR value, which suggests relatively weaker spatial correlation.

3. Kriging and its Validation

Semivariograms parameters were used for kriging and producing contour maps using surface mapping software (Surfer, Golden Software, 1997). Contour maps of dry bulk density, LAI and plant height are shown in Fig. 6 (a, b, c).

A semivariogram model is only an approximation of the spatial variability of the measured conditions. An indication of how well our semivariogram model approximates the experimental semivariogram is appraised by cross-validation technique (Vieira *et al.*, 1981). In this case one measured

point at a time is excluded and a kriged estimate is made and compared with measurements. Thus, if for every one of the locations where we have a measured value, z_i , we estimate a value, z_i^* , then we can calculate a set of estimation errors, $e_i = z_i^* - z_i$. The goodness of an estimation method is then expressed by two conditions on the estimation error: zero mean (no bias) and low variance (low dispersion) (Journel and Huijbregt, 1978).

The average and variance of the absolute error was calculated (Table 4). The results (low mean error and variance) verify the unbiased condition and low dispersion of the kriging estimation. This verifies the goodness of the fitted semivariogram models.

4. Estimation of soil hydraulic properties

Mohawesh *et al.*, (2004) modified van Genuchten's and Mualem's models to be a function of dry

Fig. 6 Estimated distributions of (a) dry bulk density (mg m^{-3}) (b) leaf area index ($\text{m}^2 \text{m}^{-2}$) (c) plant height (m) and (d) van Genuchten's model parameter, (m^{-1})

Table 4 Cross-validation parameters of the measured properties.

Parameter	ρ_d (Mg m ⁻³)	θ (m ³ m ⁻³)	LAI (m ² m ⁻²)	H (m)
Absolute average error	0.0416	0.0138	0.01720	0.0698
Absolute error variance	0.0010	0.0003	0.0180	0.3990

bulk density (Eqs. 3, 4)

$$\theta_r = \theta_s \frac{(\psi_s - \psi_r) - (\psi_s - \psi_r)}{[1 + (\psi_s - \psi_r)^n]^m} \quad (3)$$

$$K(\psi) = K_s [1 - (1 - \psi/\psi_s)^{1/m}]^m \quad (4)$$

where θ is volumetric soil water content (m³m⁻³), θ_s and θ_r are the saturated and residual soil water content (m³m⁻³) respectively, ψ is matric potential (m) (m⁻¹), n and m are shape parameters, K_s is saturated hydraulic conductivity (m s⁻¹), α is a fitting parameter, $\alpha = (\psi_s - \psi_r)/(\psi_s - \psi_r)$

Using the distribution of dry bulk density shown in Fig. 6(a) the distribution of the models parameters can be estimated at each location. Distribution of van Genuchten's model parameter (m⁻¹) as an example, is shown in Fig. 6(d) The distribution of all models parameters also can be known in the field.

These sets (Fig. 6) of soil and canopy properties distribution across the field can be combined to give useful input for numerical models to simulate the key processes at each location such as water movement and distribution.

IV. CONCLUSION

The distribution of the measured properties was found to be approximately normal. The measured properties were spatially correlated. Spherical model well fitted all our experimental semivariograms.

Range values of the measured properties were about 30 m which suggested a strong spatial continuity. Nugget ratio ranged from small to large values suggested a range of strong to weak spatial correlation. LAI exhibited relatively the strongest spatial correlation; plant height exhibited relatively the weakest spatial correlation. These results are important implications for how site-specific management information should be collected and ex-

plained.

The cross-validation with low mean error and variance shows the goodness of the fitted semivariogram models in this study.

Distribution of soil hydraulic parameters was estimated using the distribution of dry bulk density. In an ongoing research, these distributions of soil hydraulic properties across the field will be combined to give useful input for numerical models to simulate the key processes at each location such as water movement and distribution.

ACKNOWLEDGEMENTS : The authors would like to thank Prof. M. Aoki from Tokyo University of Agri. and Tech. for his assistance. Likewise Prof. S. Boonyawat and Mr. P. Tongdeenok from Kasetsart University, Thailand for the valuable support and useful help they provided in the fieldwork.

REFERENCES

- Anderson, M. C., Neale, C. M. U., Li, F., Norman, J. M., Kustas, W. P., Jayanthi, H. and Chavez, J. (2004): Upscaling ground observations of vegetation water content, canopy height, and leaf area index during SMEX02 using aircraft and landsat imagery, *Remote Sensing of Environment*, **92**, pp. 447-464.
- Bresler, E. and Dagan, G. (1981): Convective and pore scale dispersive solute transport in unsaturated heterogeneous fields, *Water Resour. Res.*, **17**, pp. 1683-1693.
- Bos, J., Collins, M. E., Gensheimer, G. J. and Brown, R. B. (1984): Spatial variability for one type of phosphate mine land in central Florida, *Soil Sci. Soc. Am. J.*, **48**, pp. 1120-1125.
- Buchter, B., Aina, P.O., Azari, A. S. and Nielsen, D. R. (1991): Soil spatial variability along transects, *Soil Technology*, **4**, pp. 297-314.
- Burrough, P. A. (1993): Soil variability: a late 20th century view, *Soils and Ferti.*, **56**, pp. 529 - 562.
- Burgess, T. M. and Webster, R. (1980): Optimal interpolation and isarithmic mapping of soil properties. I. The semivariogram and punctual kriging, *Soil Sci.*, **31**, pp. 315-331.
- Burden, D. S. and Selim, H. M. (1989): Correlation

- of spatially variable soil water retention for a surface soil, *Soil Sci.*, **148**(6), pp. 436-447.
- Cambardella, G. A., Moorman, T. B., Nowak, J. M., Parkin, T. B., Karlen, D. L., Turco, R. F. and Konopka, A. E. (1994): Field-scale variability of soil properties in central Iowa soils, *Soil Sci. Soc. Am. J.*, **58**, pp. 1501-1511.
- Chiles, J. P. and Delfiner, P. (1999): Geostatistics: modeling spatial uncertainty, Wiley Inc., pp. 104-115.
- Gajem, Y. M., Warrick, A. W. and Myer, D. E. (1981): Spatial structure of physical properties of a Typic Torrifluent soil, *Soil Sci. Soc. Am. J.*, **45**, pp. 709-715.
- Isaaks, E. H. and Srivastava, R. M. (1989): An introduction to applied geostatistics, Oxford University.
- Journel, A. G. and Huijbregts, Ch. J. (1978): Mining geostatistics, pp. 49-50, Academic Press, London.
- Kilic, K., Ozago, E. and Akbas, F. (2004): Assessment of spatial variability in penetration resistance as related to some soil physical properties of two fluvents in Turkey, *Soil Till. Res.*, **76**, pp. 1-11.
- Liss, H. F. (1983): Spatial and temporal variability of water soluble organic carbon for a cropped soil, ph. D. Dissertation, Univ. Of California, Davis.
- McBratney, A. B. and Webster, R. (1983): How many observations are need for regional estimation of soil properties, *Soil Sci.*, **135**(3), pp. 177-183.
- Mohawesh, O., Fukumura, K. and Ishida, T. (2004) Soil hydraulic properties in a cassava field as a function of soil dry bulk density, *J. Japan Soc. Hydro. and Water Resour.*, **18**(2), pp. 156-166.
- Nielsen, D. R., Biggar, J. W. and Erh, K. T. (1973) Spatial variability of field-measured soil-water properties, *Hilgardia*, **42**, pp. 215-259.
- Russo, D., Jury, W. A. and Butters, G. L. (1989): Numerical analysis of solute transport during transient irrigation: 1. The effect of hysteresis and profile heterogeneity, *Water Resour. Res.*, **25**, pp. 2109-2118.
- Saito, H., Yoshino, K., Ishida, T., Nagano, T., Siri-chuaychoo, W., Jongskul, A., Haraguchi, N. (2004): Geostatistical estimation of tropical peat-soil volume at Bacho, Thailand: impact of spatial support size and censored information, *Geoderma*, **125**, pp. 235-247.
- Vieira, S. R., Nielsen, D. R. and Biggar, J. W. (1981) Spatial variability of field-measured infiltration rate, *Soil Sci. Soc. Am. J.*, **45**, pp. 1040-1048.
- Warrick, A. W., Myers, D. E. and Nielsen, D. R. (1986): Geostatistical methods applied to soil science, In: Klute, A. (ed.) *Methods of Soil Analysis*, Part 1, 2nd ed., pp. 53-73, Agron. Monogr. 9. ASA and SSSA, Madison, WI.
- Witono, H. and Bruckler, L. (1989): Use of remotely sensed soil moisture content as boundary conditions in soil-atmosphere water transport modeling, *Water Resour. Res.*, **25**, pp. 2423-2435.
- Ziaei, A. N. and Sepaskhah, A. R. (2003): Model for simulation of winter wheat yield under dryland and irrigated conditions, *Agri. water management*, **58**, pp. 1-17.

(Received : Nov. 18, 2004, Accepted : Feb. 22, 2005)