The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

1867-35

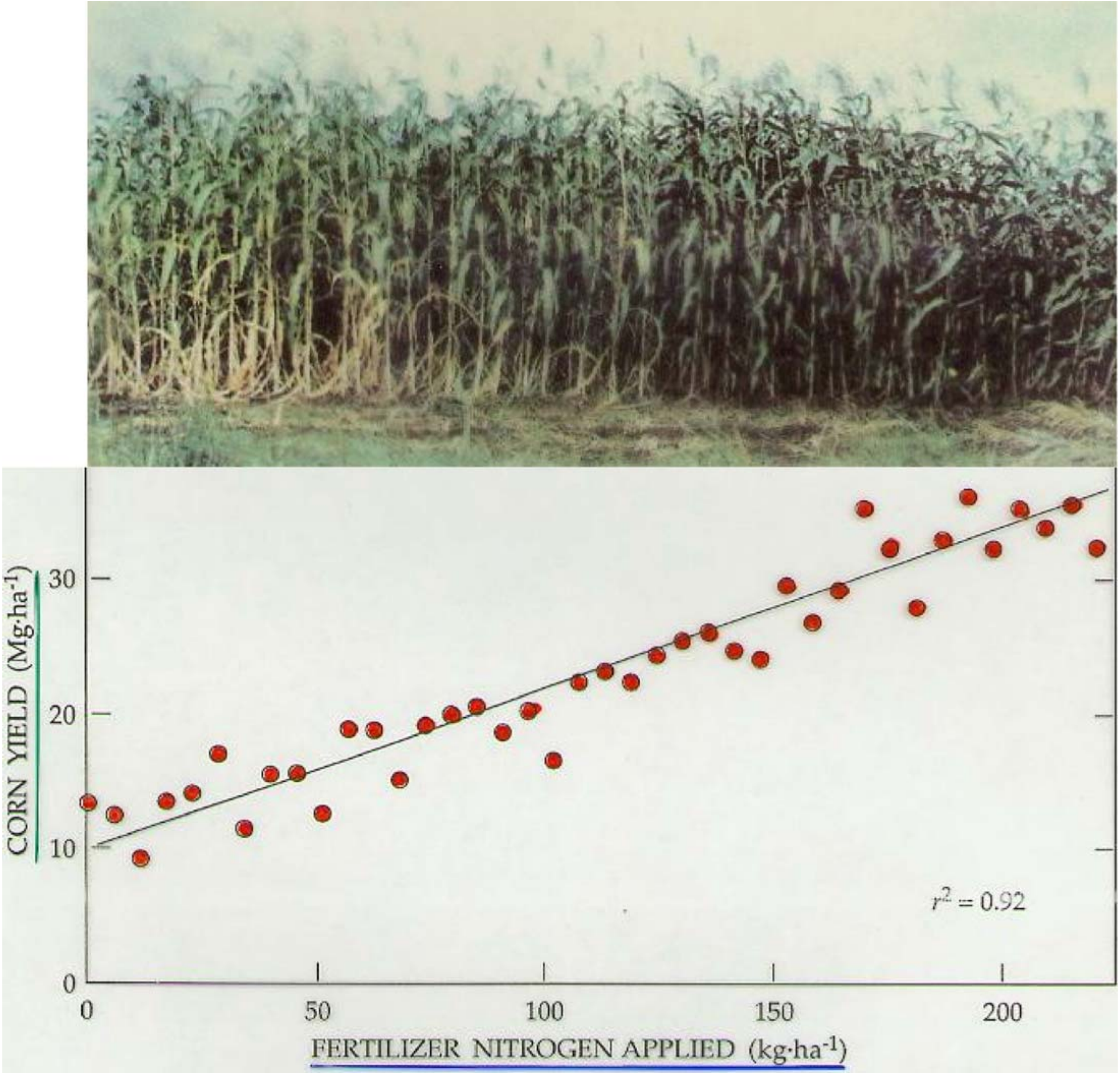
College of Soil Physics

22 October - 9 November, 2007

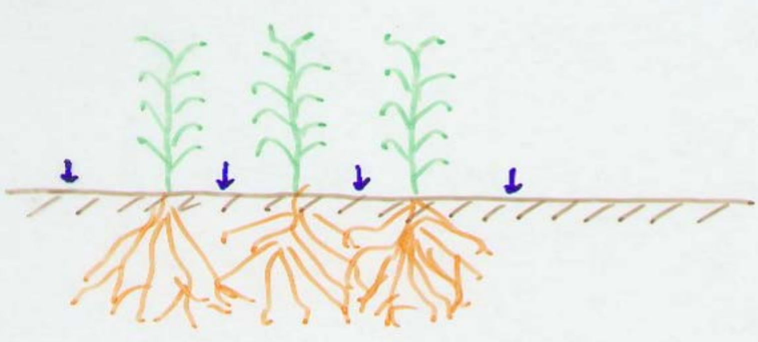
Sampling soils and their vegetation

Donald Nielsen
University of California, Davies
USA

Corn versus N



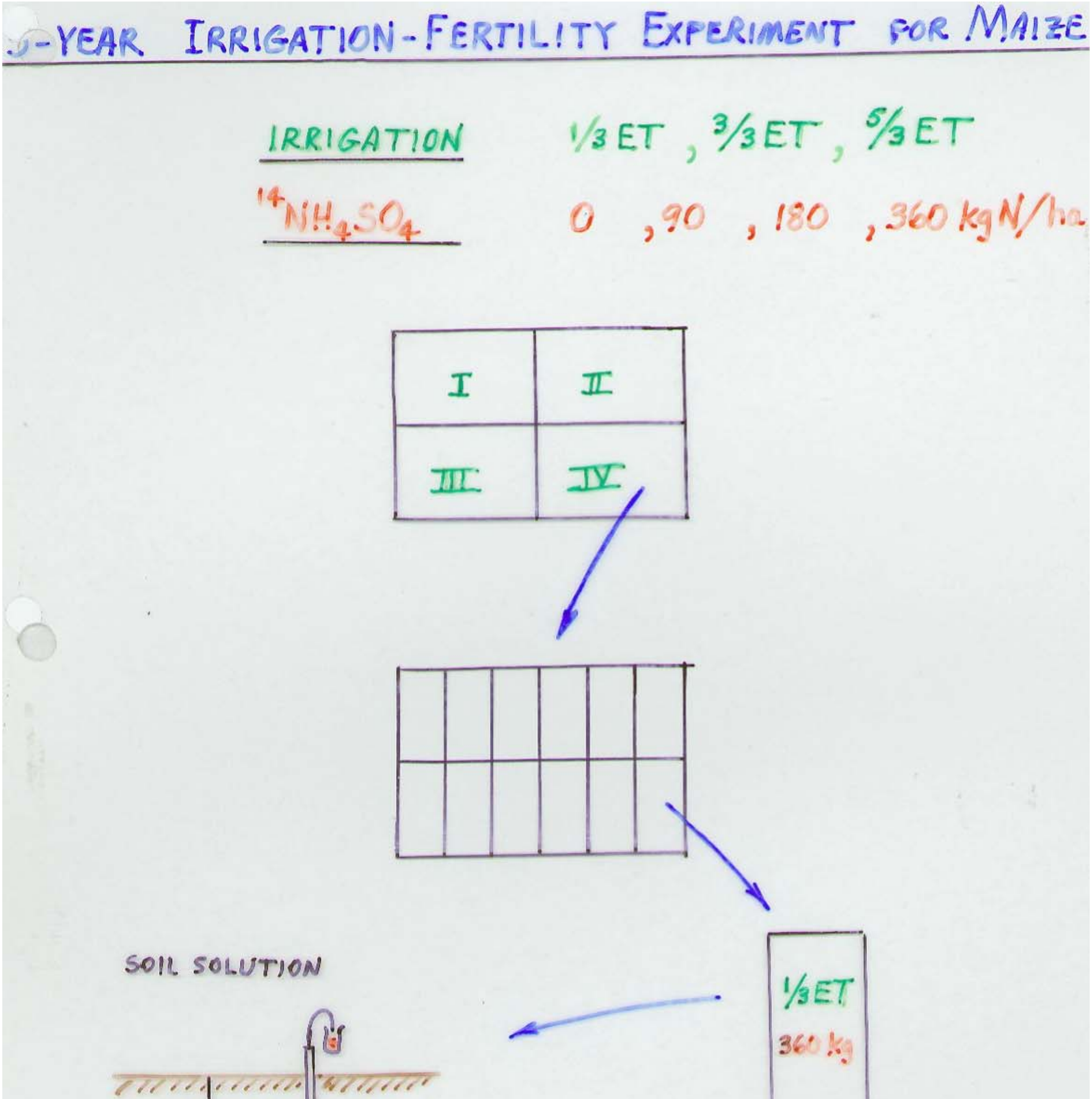
LEACHING BELOW AGRICULTURAL FIELDS



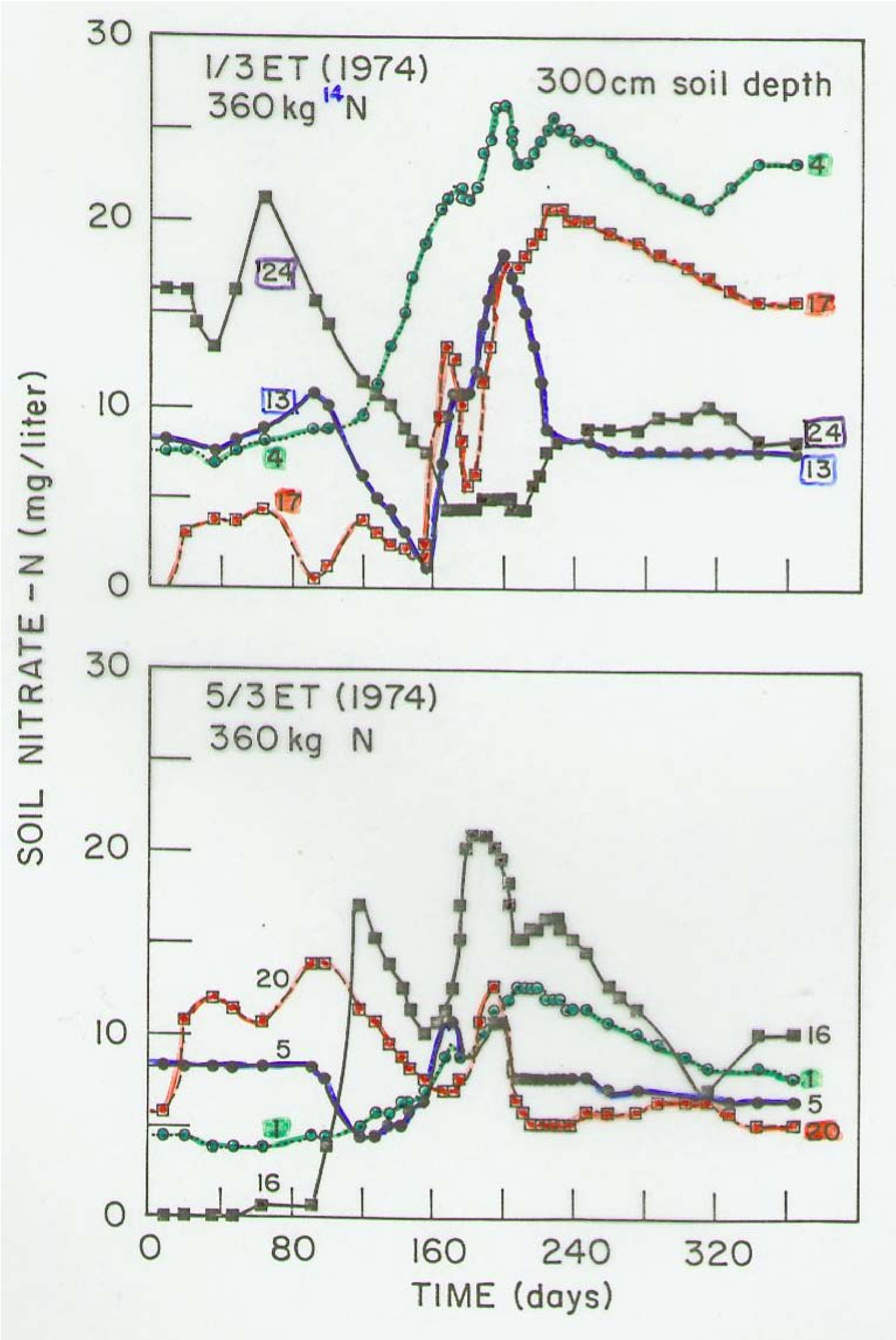
$$\downarrow J_W \times c_{NO_3^-} = J_{NO_3^-} \downarrow$$

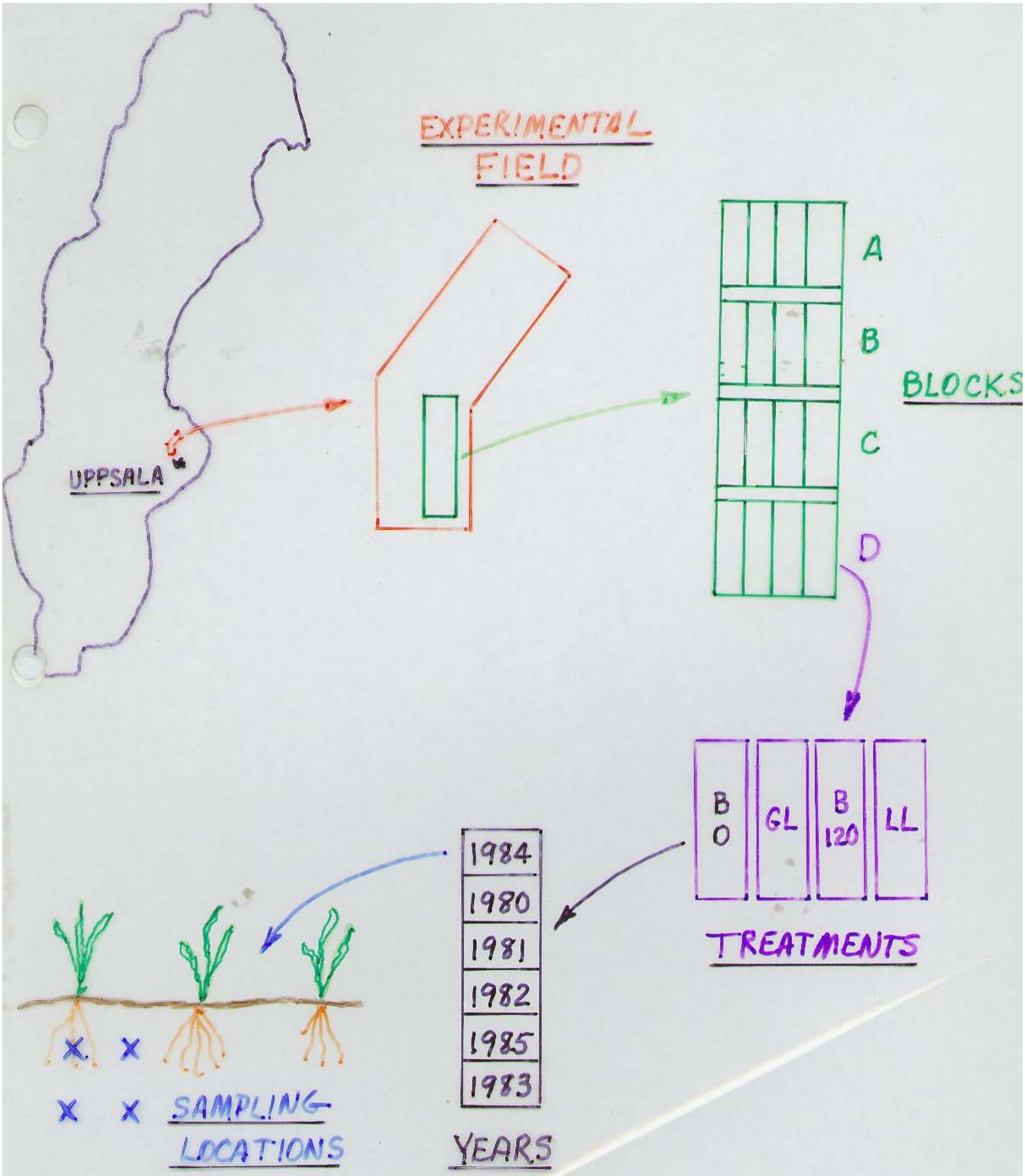
^{15}N-FERTILIZER TO TRACE NITROGEN IN ENVIRONMENT

Irrigation-fertility expt



Soil nitrate conc





EXPERIMENTAL FIELD
UPPSALA
A
B
BLOCKS
C
D
B O
GL
B 120
LL
TREATMENTS
1984
1980
1981
1982
1985
1983
YEARS
SAMPLING LOCATIONS

We talk

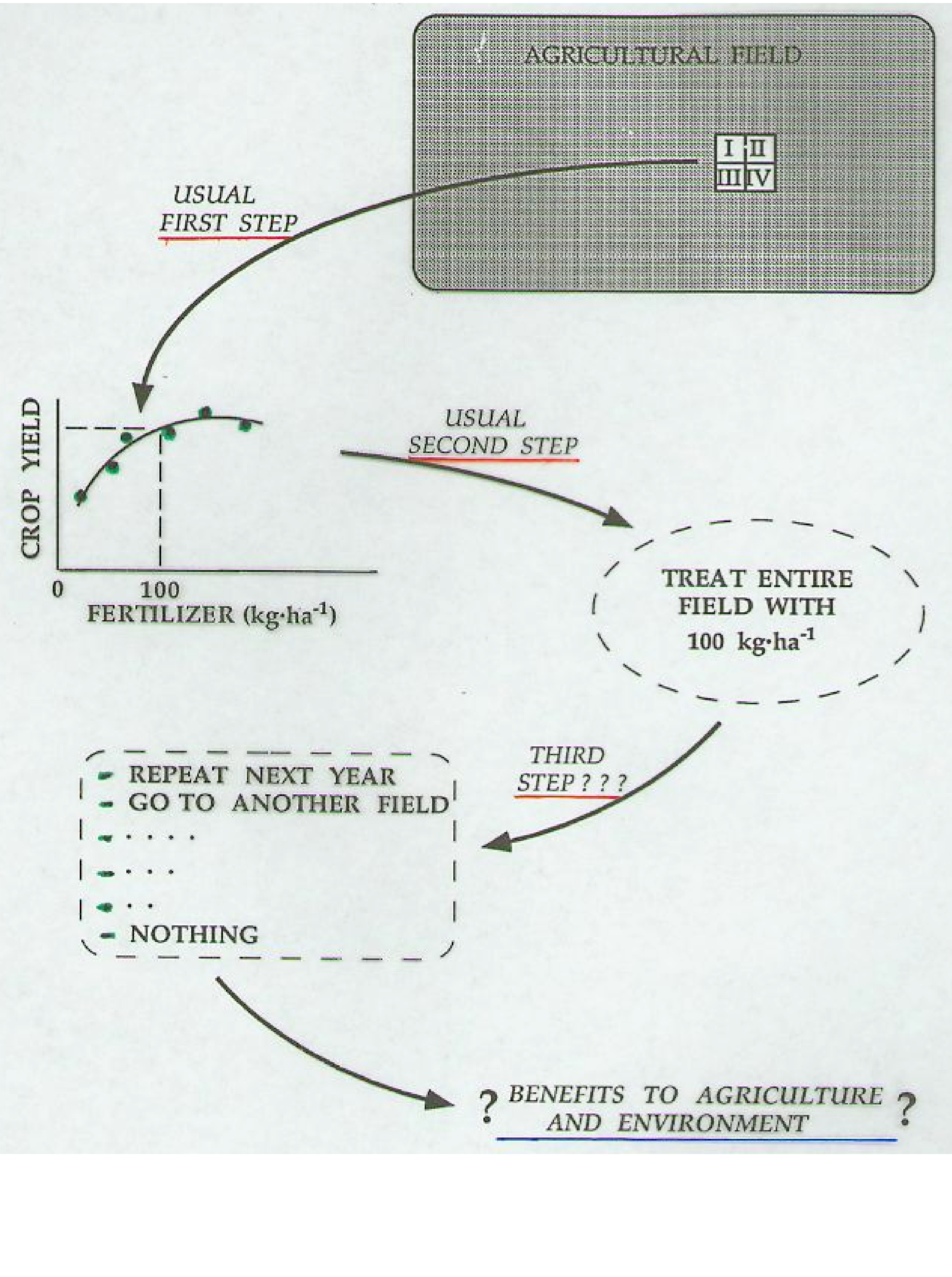
WE TALK ABOUT IMPROVING THE ENVIRONMENT, INCREASING AGRICULTURAL PRODUCTION AND SOLVING ENVIRONMENTAL PROBLEMS, BUT WE STILL USE SMALL PLOTS ON SELECTED SITES TO CONDUCT OUR RESEARCH! WE DO NOT KNOW HOW TO QUANTITATIVELY MAKE ASSESSMENTS ACROSS THE LANDSCAPE!

WE RESTRICT OUR RESEARCH BY IMPOSING TREATMENTS WITHIN GLASSHOUSES, ON SMALL PLOTS AND ON LYSIMETERS.

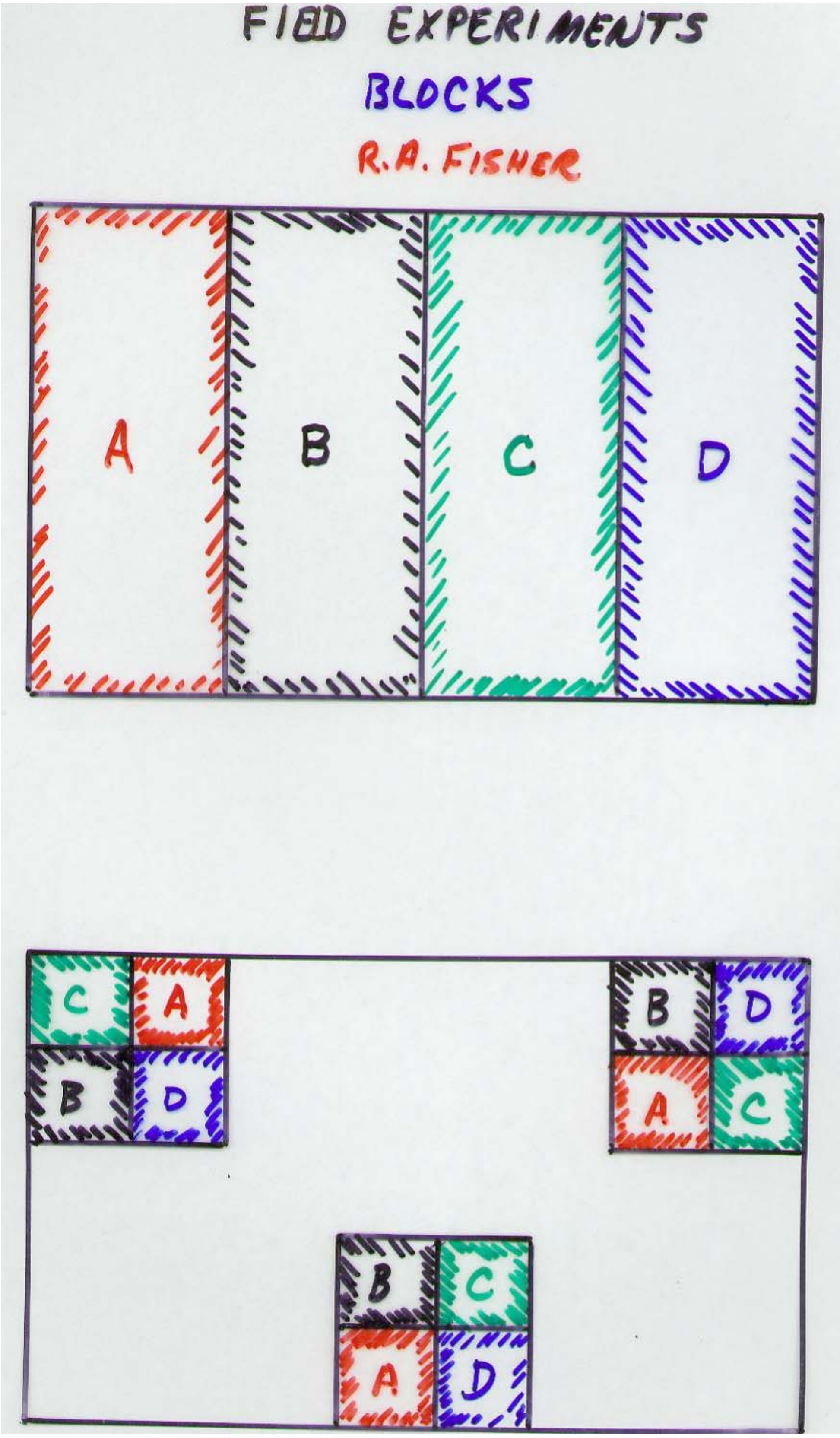
- CROP PRODUCTION - FERTILIZERS
- PEST MANAGEMENT - PESTICIDES
- EROSION CONTROL - SOIL SURFACE GEOMETRIES
- TRANSPIRATION - IRRIGATION SCHEDULES

WE STILL USE THE SAME STATISTICAL METHODS DESIGNED 75 YEARS AGO BY FISHER WHEN ONLY A PAPER & PENCIL, SLIDE RULE AND ABACUS WERE AVAILABLE FOR MATHEMATICAL CALCULATIONS.

Present-day research



Fisher blocks



Classical Eq.

MEAN

$$\bar{z} = \frac{1}{n}\sum_{i=1}^{n} z_i$$

VARIANCE

$$s^2 = \frac{1}{n}\sum_{i=1}^{n}(z_i - \bar{z})^2$$

NORMAL DISTRIBUTION

$$N = \frac{n\Delta z}{s\sqrt{2\pi}} exp\left[-\frac{(z-m)^2}{2s^2}\right]$$

LOG-NORMAL DISTRIBUTION

$$N = \frac{n\Delta z}{z s_{ln}\sqrt{2\pi}} \exp\left[-\frac{(\ln z - m_{ln})^2}{2s_{ln}^2}\right]$$

COVARIANCE

$$cov_{yz} = \frac{1}{n-1}\sum_{i=1}^{n}(y_i - \bar{y})(z_i - \bar{z}).$$

CORRELATION COEFFICIENT

$$r_{yz} = \frac{cov_{yz}}{s_y s_z}$$

LINEAR REGRESSION

$$\hat{y} = az + b$$

$$\begin{vmatrix} z & \hat{y} & 1 \\ \sum z_i & \sum y_i & n \\ \sum z_i^2 & \sum z_i y_i & \sum z_i \end{vmatrix} = 0$$

Questions to ask

FOR A SMALL PLOT, A FIELD, AN ENSEMBLE OF FARMS OR A GEOGRAPHICAL REGION, WE SHOULD KNOW THE ANSWERS TO THESE QUESTIONS:

- HOW MANY SAMPLES?
- WHEN TO TAKE SAMPLES?
- WHERE TO TAKE SAMPLES?
- WHAT SIZE OF A DOMAIN DOES A SAMPLE REPRESENT?
- UTILITY OF A SAMPLE IN RELATION TO A CONCEPTUAL MODEL?
- UTILITY OF A CONCEPTUAL MODEL IN RELATION TO A SAMPLE?

Optimal Freq&tim

AN OPTIMAL FREQUENCY IN TIME AND SPACE FOR
MAKING OBSERVATIONS
OF A SOIL ATTRIBUTE
REMAINS AN ENIGMA FOR ALL SOIL SCIENTISTS

The Enigma

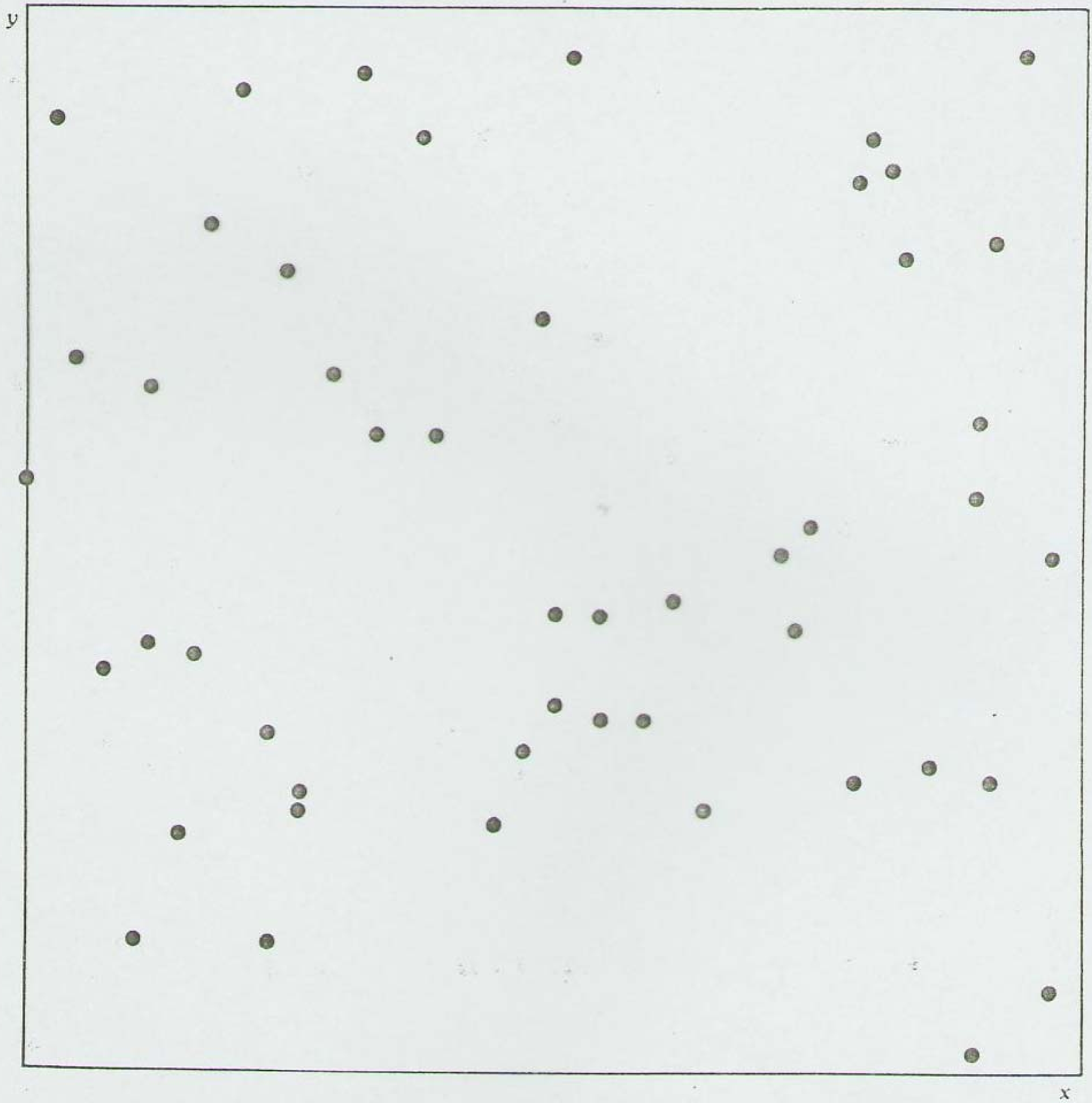
THE ENIGMA

Proven concepts and strategies to interpret the cause of spatial crop patterns do not exist, and we are unable to reliably predict and achieve yield patterns.

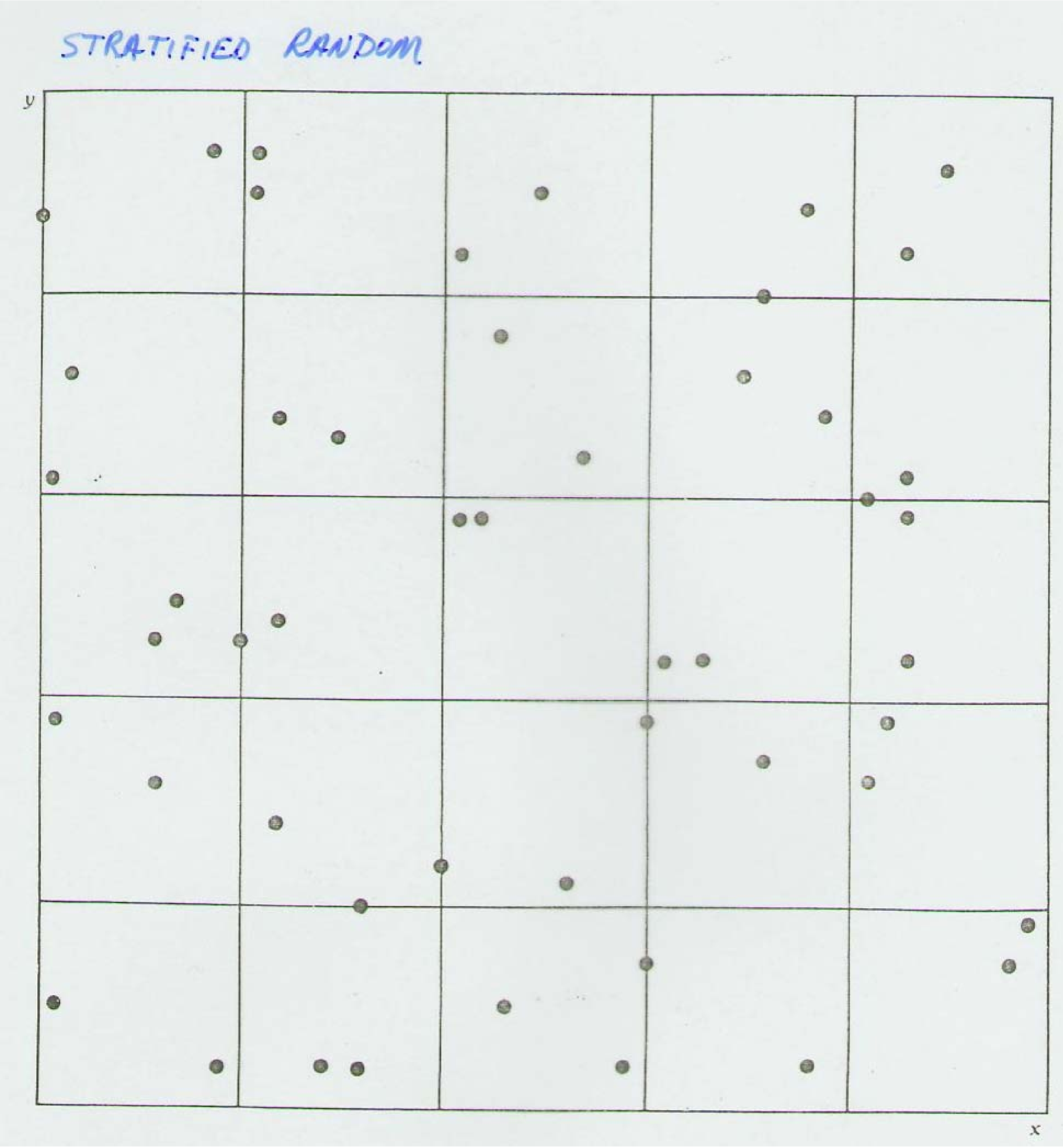
The enigma persists owing to the propensity of agronomists limiting their research to classical randomized block field experiments having different treatments thought to have an impact on crop growth.

And the enigma will not readily be solved by merely importing tremendous amounts of field data into geographic information systems to produce spatial distribution maps that remain open to question because underlying assumptions are neither met nor sufficiently examined.

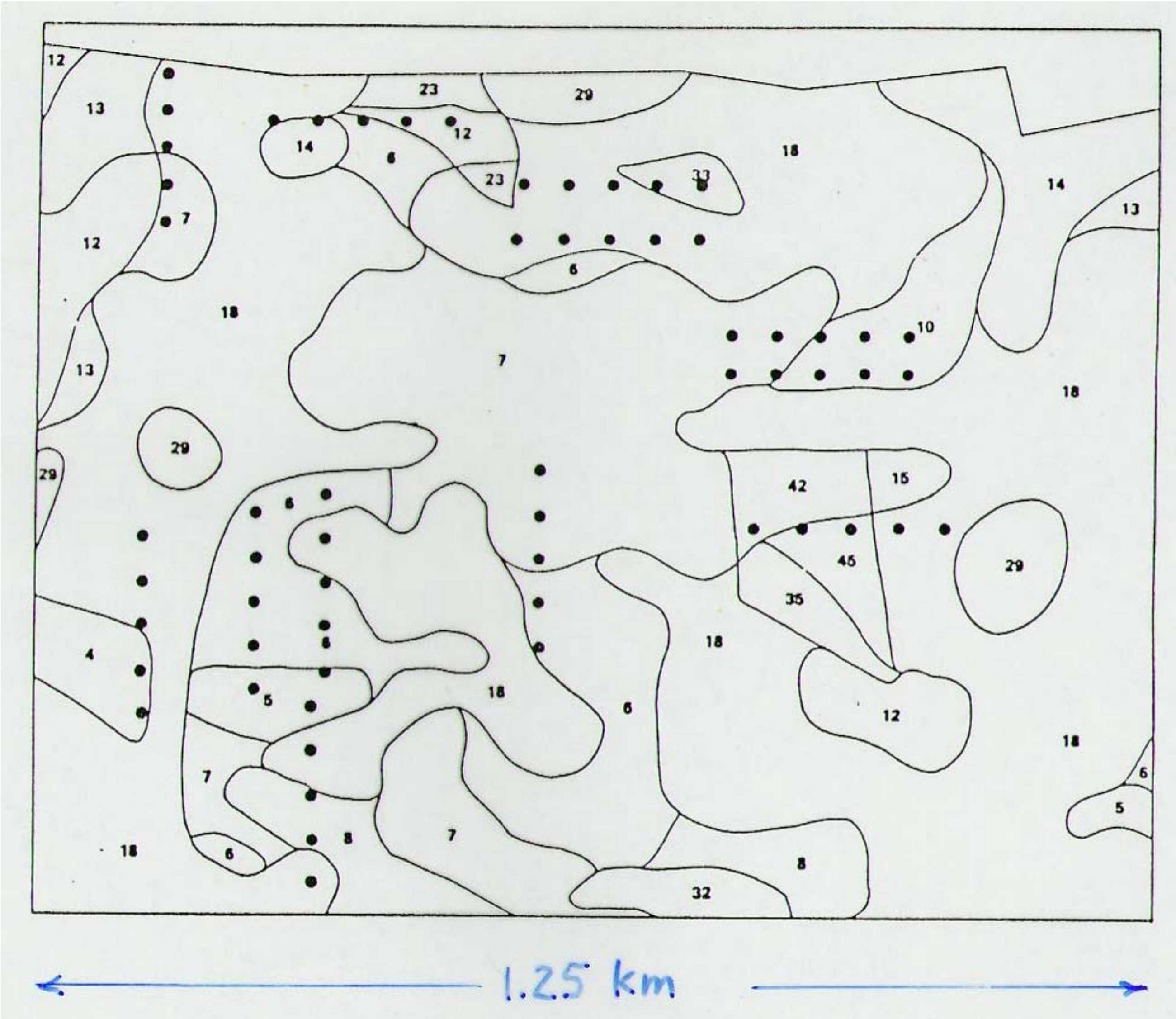
SIMPLE RANDOM



Stratified random



Dutch sampling

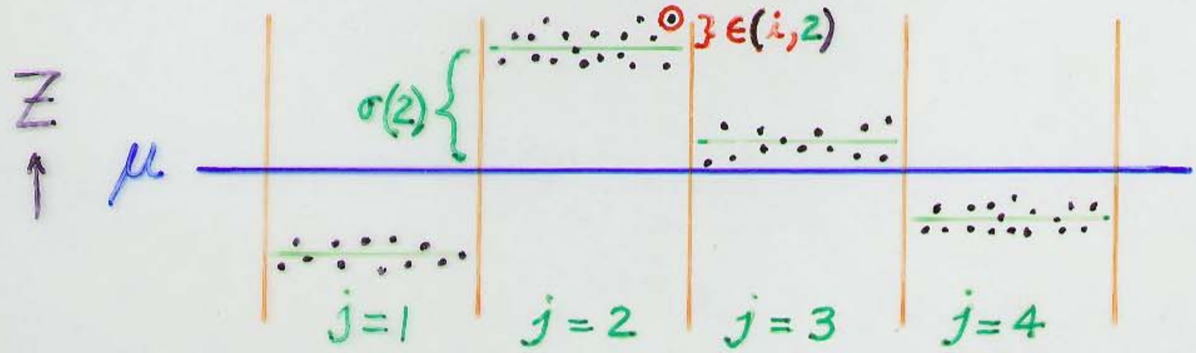


ANOVA

ANALYSIS OF VARIANCE

$$Z(i,j) = \mu + \sigma(j) + \epsilon(i,j)$$

observation — mean — class deviation — error

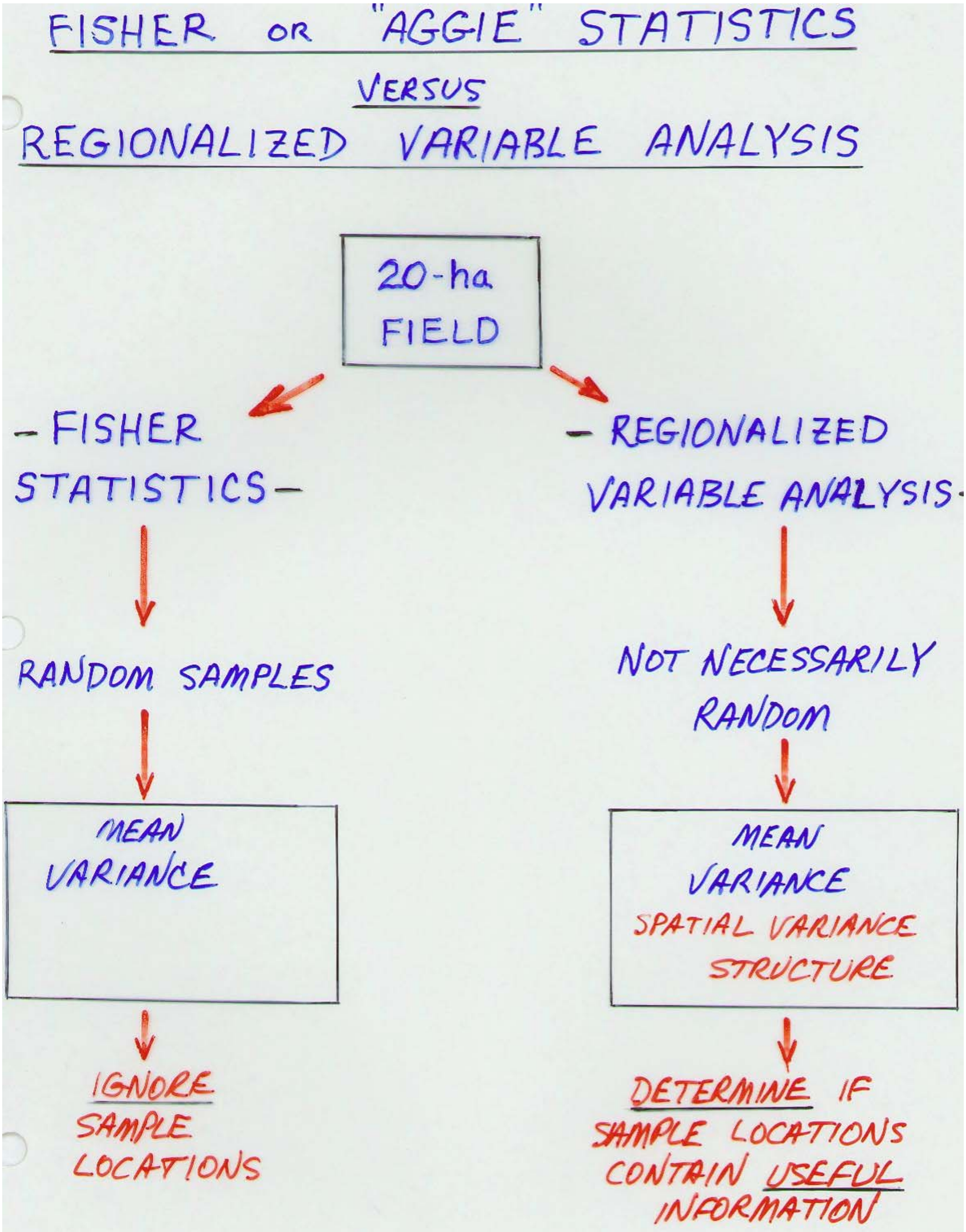


GEOGRAPHIC LOCATIONS OF OBSERVATIONS ARE IGNORED!

ALTHOUGH 50 YEARS OF USING ANOVA HAS BEEN HIGHLY BENEFICIAL, IT HAS UNFORTUNATELY LEAD TO:

- UNNECESSARILY IMPOSING "TREATMENTS" TO MOST EXPERIMENTS
- SELECTING "TYPICAL" OR "REPRESENTATIVE" SITES
- TAKING "RANDOM" SAMPLES TO "AVOID BIAS"
- AVOIDING SPATIALLY VARIABLE LOCATIONS
- ASSUMING VARIABILITY IS "BAD"
- ASSUMING VARIABILITY IS "ERROR"
- NOT TRUSTING ONLY ONE SAMPLING
- NOT TRUSTING ONLY ONE YEAR'S RESULTS

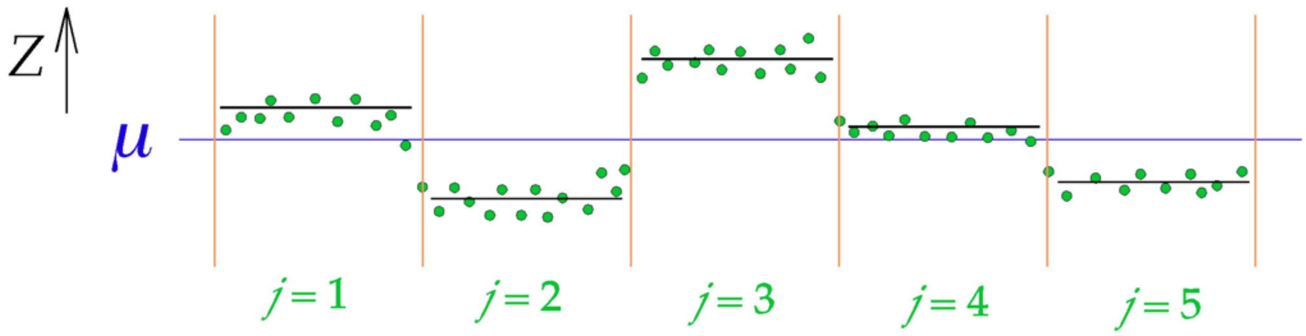
Aggie vs regionalized



Fisher ANOVA

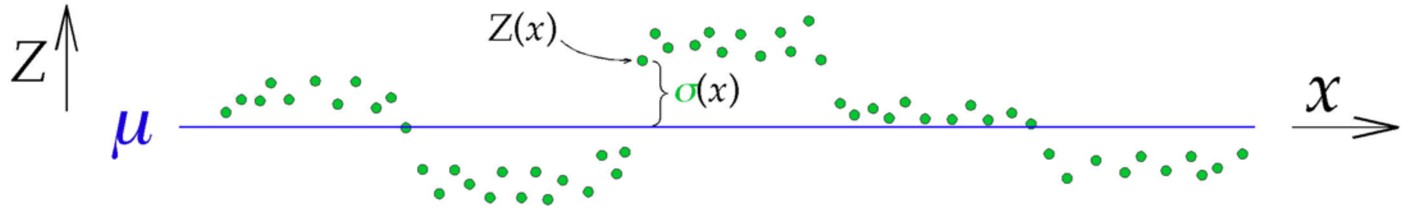
FISHER ANALYSIS OF VARIANCE

$$Z(i, j) = \mu + \sigma(j) + \varepsilon(i, j)$$



REGIONALIZED VARIABLE ANALYSIS

$$Z(x) = \mu + \sigma(x)$$



Opportunities

OPPORTUNITIES

- CORRELOGRAMS
- VARIOGRAMS
- KRIGING
- SPECTRAL ANALYSIS
- COHERENCY
- STATE-SPACE ANALYSIS
- MONTE CARLO SIMULATIONS
- KINEMATIC WAVE EQUATIONS
- NONLINEAR KALMAN FILTERING
- FRACTAL DISTRIBUTIONS
- AUTOREG. MOVING AVERAGES

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•
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- CROSS-CORELLOGRAMS
- CO-VARIOGRAMS
- CO-KRIGING
- CO-SPECTRAL ANALYSIS
- SPLIT MOVING WINDOWS
- MARKOV PROCESSES
- TRANSFER FUNCTIONS
- FUZZY SETS
- STOCHASTIC EQUATIONS
- SCALING CONCEPTS

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Lecture content

- INTRODUCTION
  - Review of agricultural research experiments with small field plots
  - Disadvantages of present-day experiments and statistical analyses
  - Need for improved technology applicable to a farmer's entire field
  - Need for improved technology applicable to an ensemble of fields
- CONCEPT OF A REGIONALIZED VARIABLE
  - Autocorrelation
  - Crosscorrelation
  - Examples
- GEOSTATISTICAL METHODS
  - Variograms and covariograms
  - Kriging and cokriging
  - Examples
- APPLIED TIME SERIES ANALYSIS
  - Spectral and cospectral analyses
  - Coherency
  - Examples
- STATE-SPACE ANALYSIS
  - Autoregressive functions
  - Nonlinear Kalman filtering
  - Examples
- NEAREST NEIGHBOR ANALYSIS
  - Example
- FUTURE RESEARCH OPPORTUNITIES

Objectives

- IDENTIFY ANALYTICAL METHODS NOT NORMALLY USED IN FIELD STUDIES OF SOILS AND AGROECOLOGY
- PROVIDE EXAMPLES OF A POTENTIAL NEW FIELD TECHNOLOGY FOR DESCRIBING, ANALYZING AND MANAGING OUR SOIL RESOURCES

Taking advantage of variability

TAKING ADVANTAGE OF
SPATIAL VARIABILITY
RATHER THAN IGNORING IT
WHEN
ANALYZING FIELD SOILS

Title of autocorrelation

SPATIAL OR TEMPORAL

AUTOCORRELATION

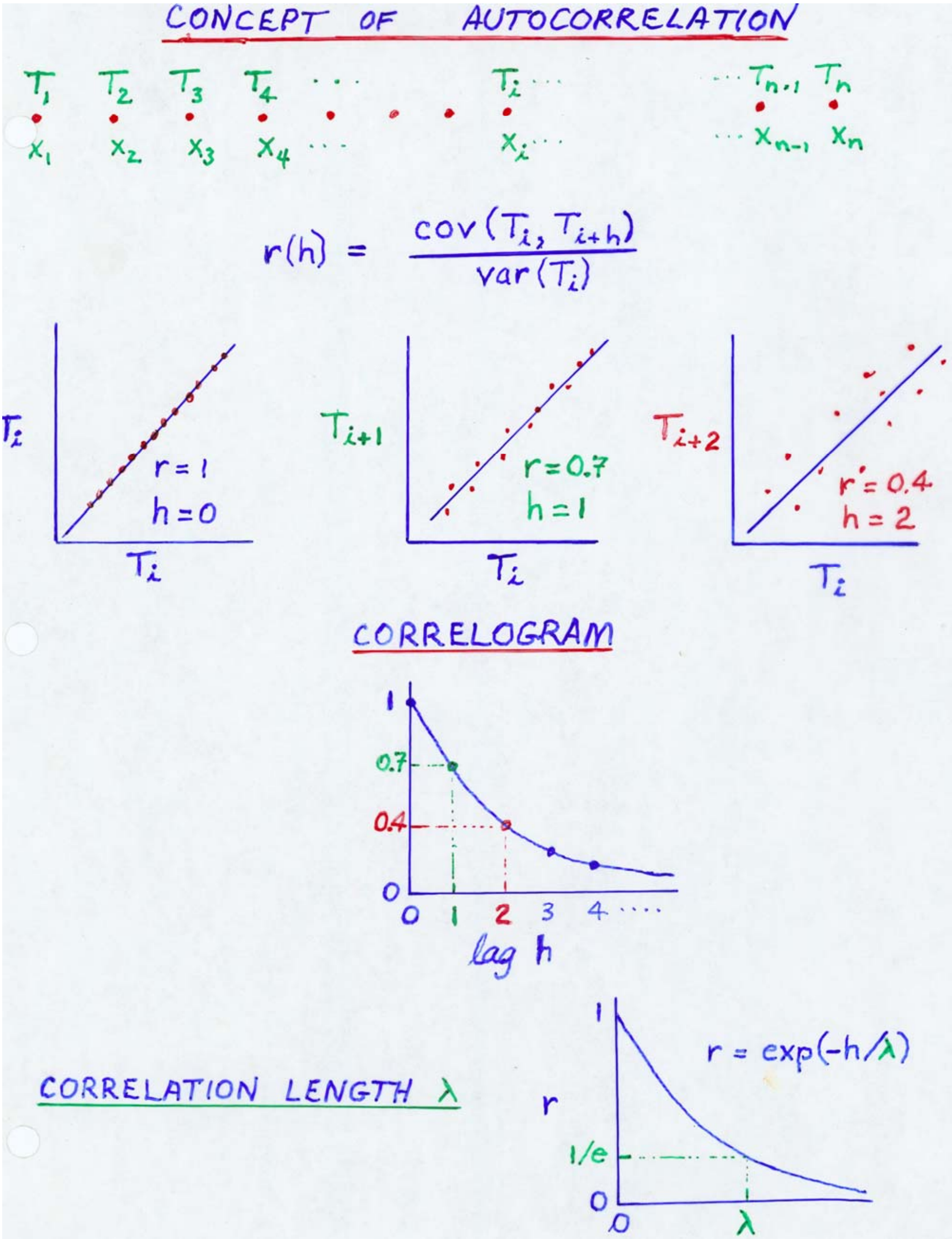
Questions for autocorrel

QUESTIONS FOR AUTOCORRELATION

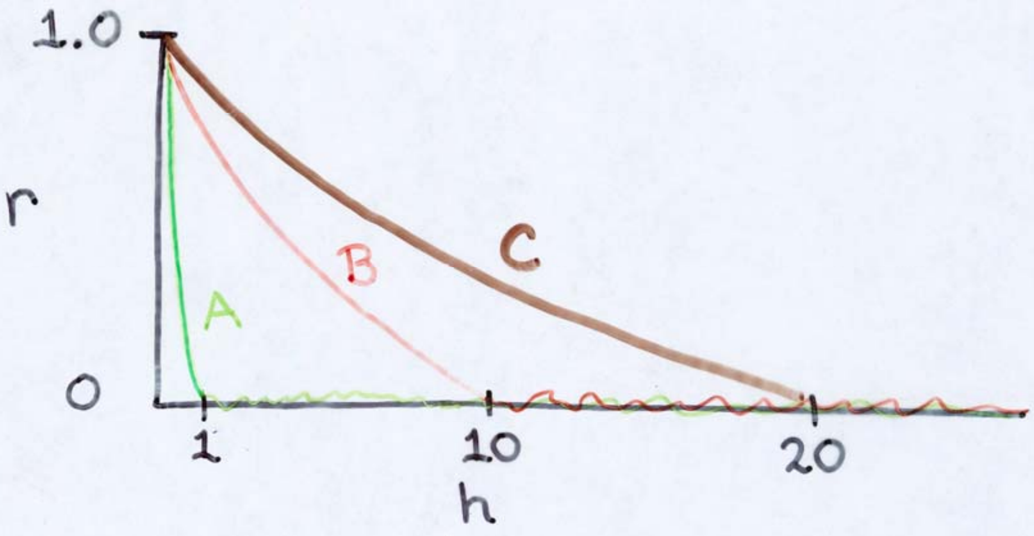
- HOW FAR APART SHOULD I TAKE SAMPLES?
- WHAT SIZE SAMPLE SHOULD I TAKE?
- HOW OFTEN SHOULD I TAKE SAMPLES?
- WHAT IS THE AREA REPRESENTED BY A SAMPLE?
- WHAT IS THE LENGTH OF TIME REPRESENTED BY A SAMPL

"CORRELATION LENGTH" VERSUS SAMPLE DIMENSION

Concept of autocorrel



ACF fields a,b,c

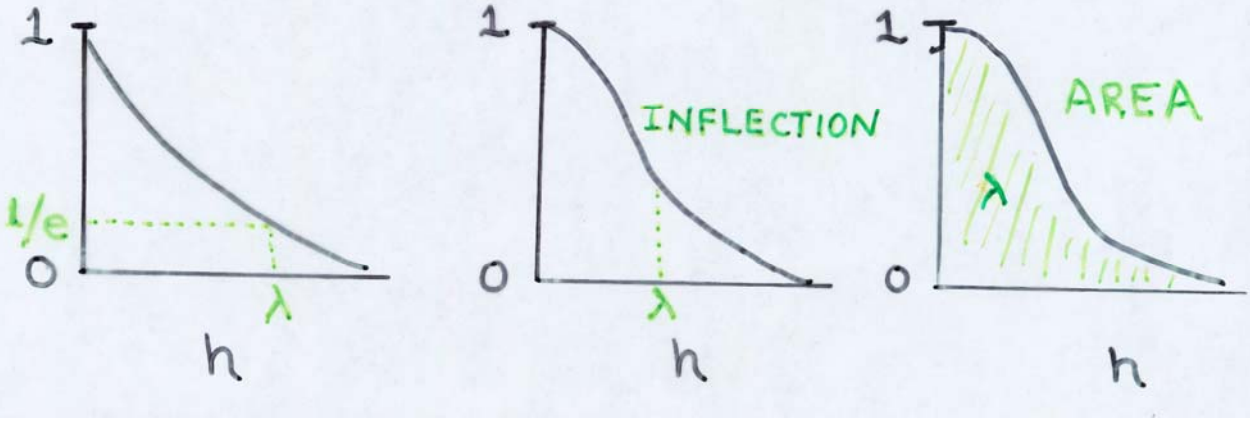


IF FOR h = 1 , r → 0 : FISHER STATISTICS

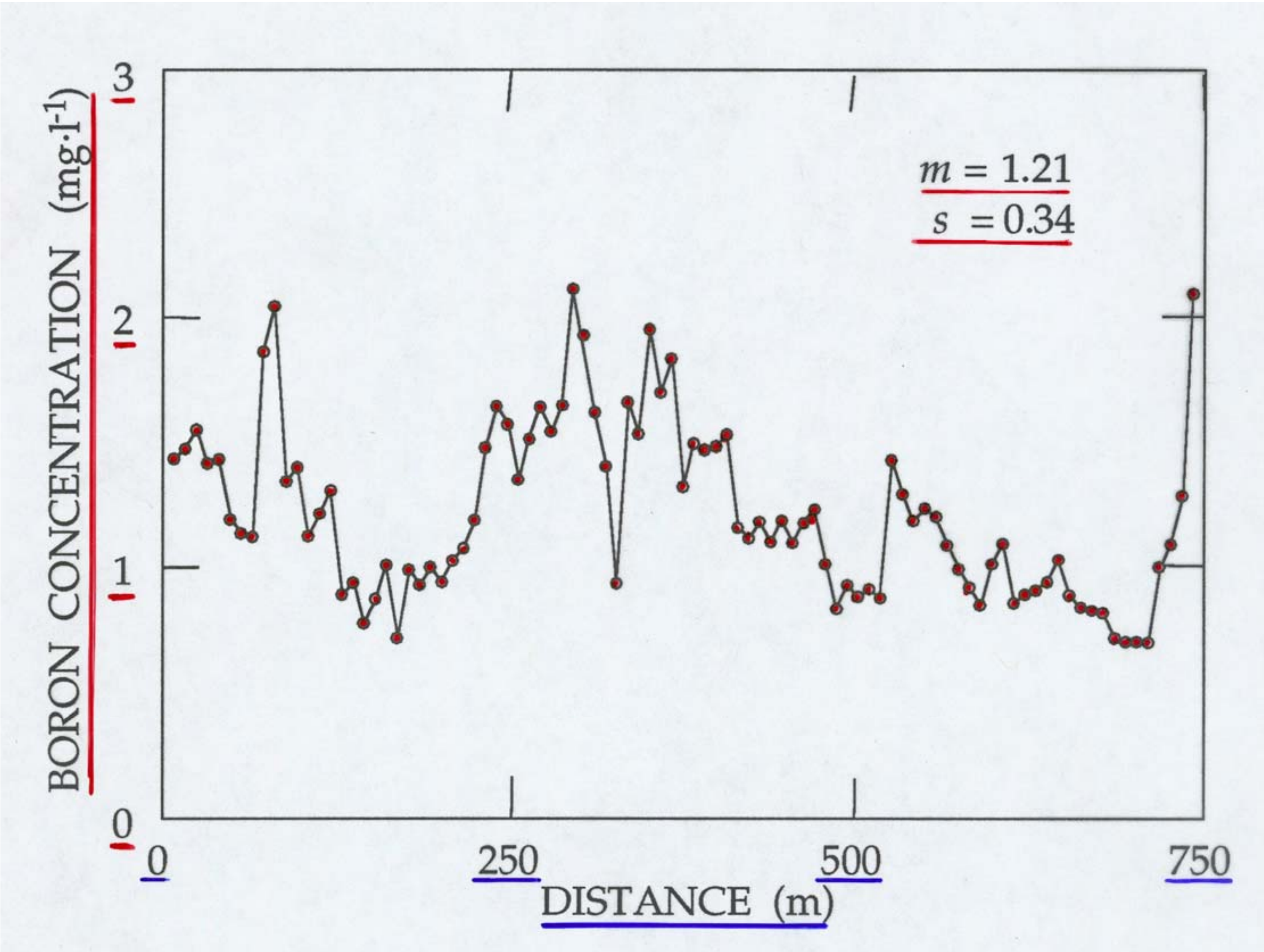
IF FOR h > 1 , r ≠ 0 : GEOSTATISTICS

AUTOCORRELATION LENGTH

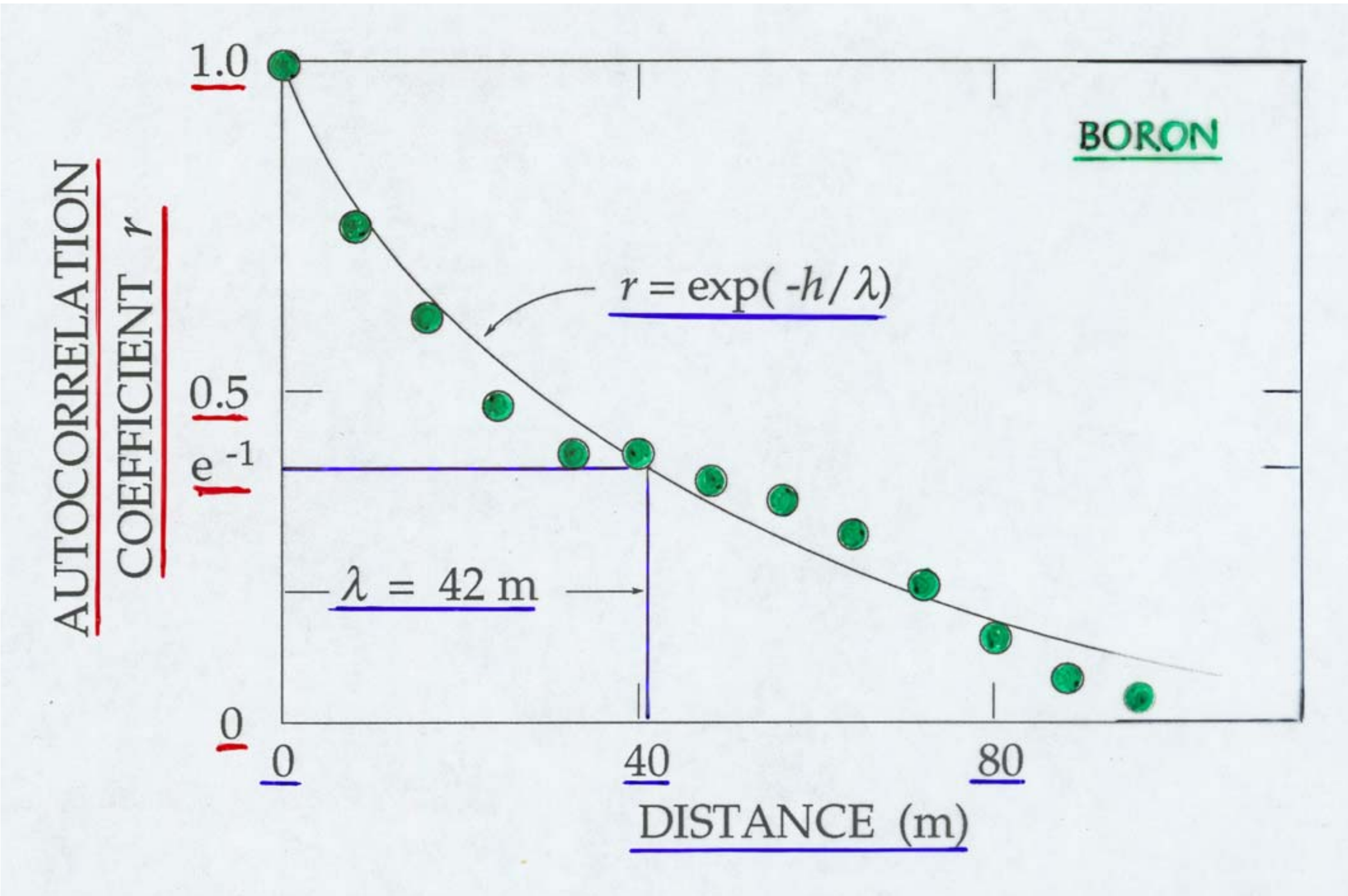
– DISTANCE ACROSS THE LANDSCAPE CHARACTERIZED BY A SINGLE OBSERVATION WITHIN THE FIELD



Boron versus distance

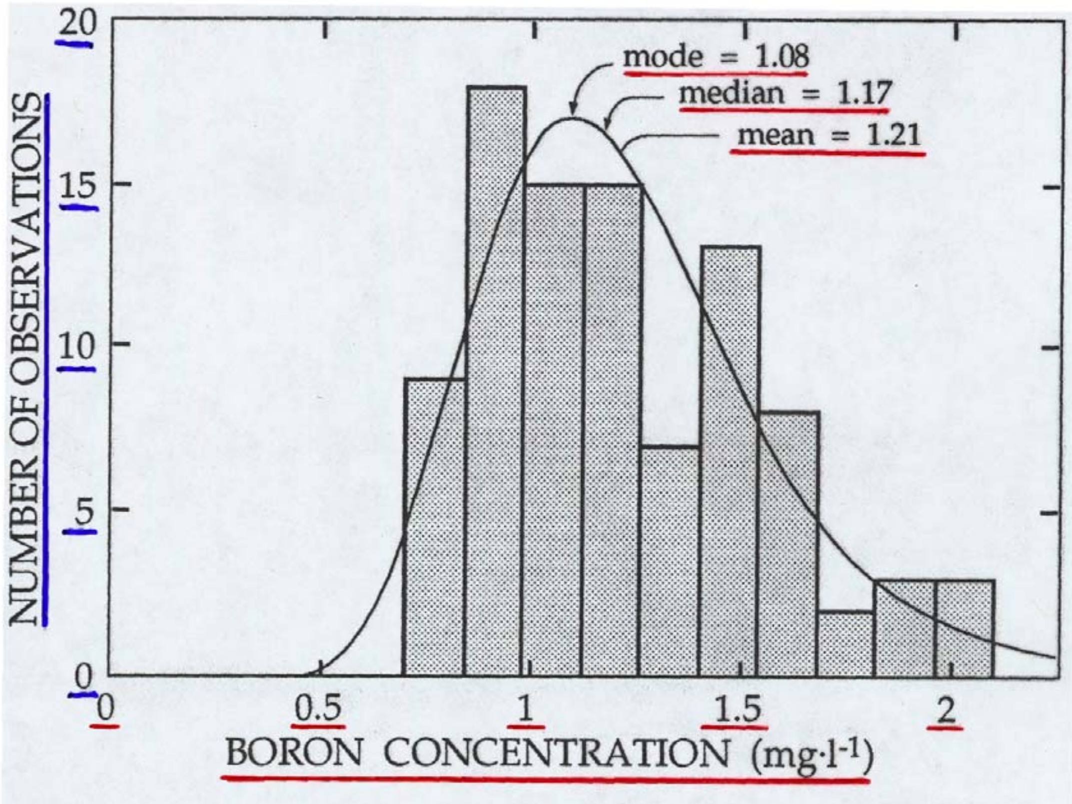


ACF Boron



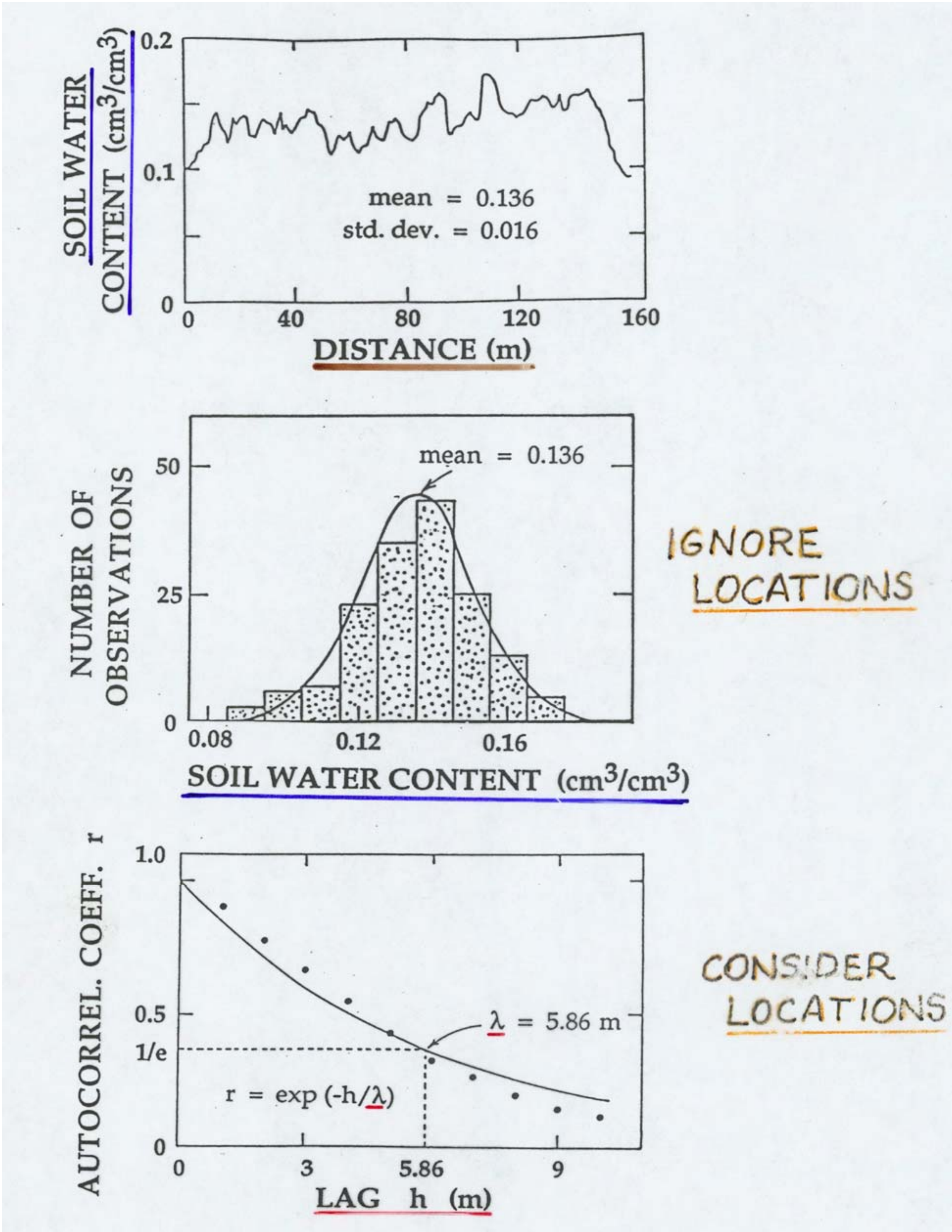
BORON
AUTOCORRELATION COEFFICIENT r
1.0
0.5
e -1
0
0
40
80
DISTANCE (m)
r = exp(-h / λ)
λ = 42 m

Boron

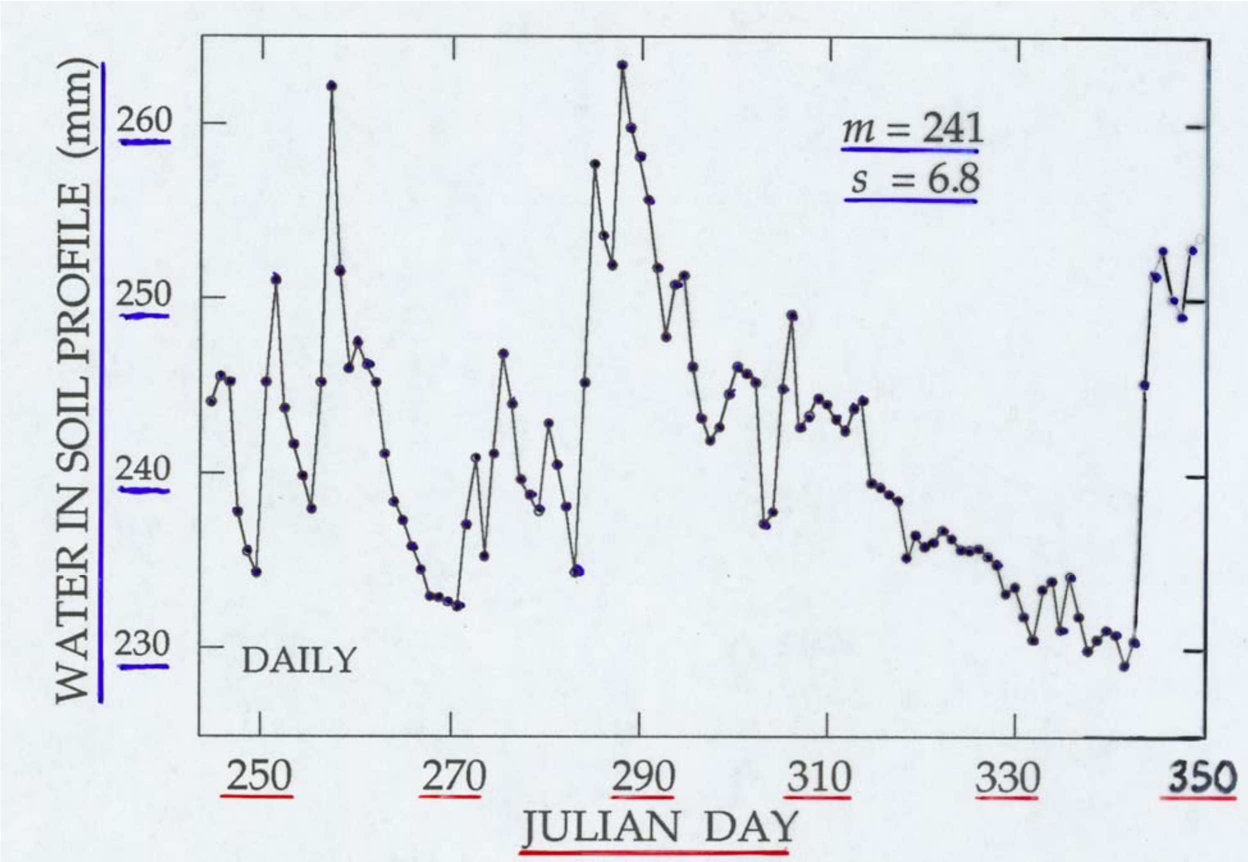


NUMBER OF OBSERVATIONS
20
15
10
5
0
mode = 1.08
median = 1.17
mean = 1.21
0
0.5
1
1.5
2
BORON CONCENTRATION (mg·l-1)

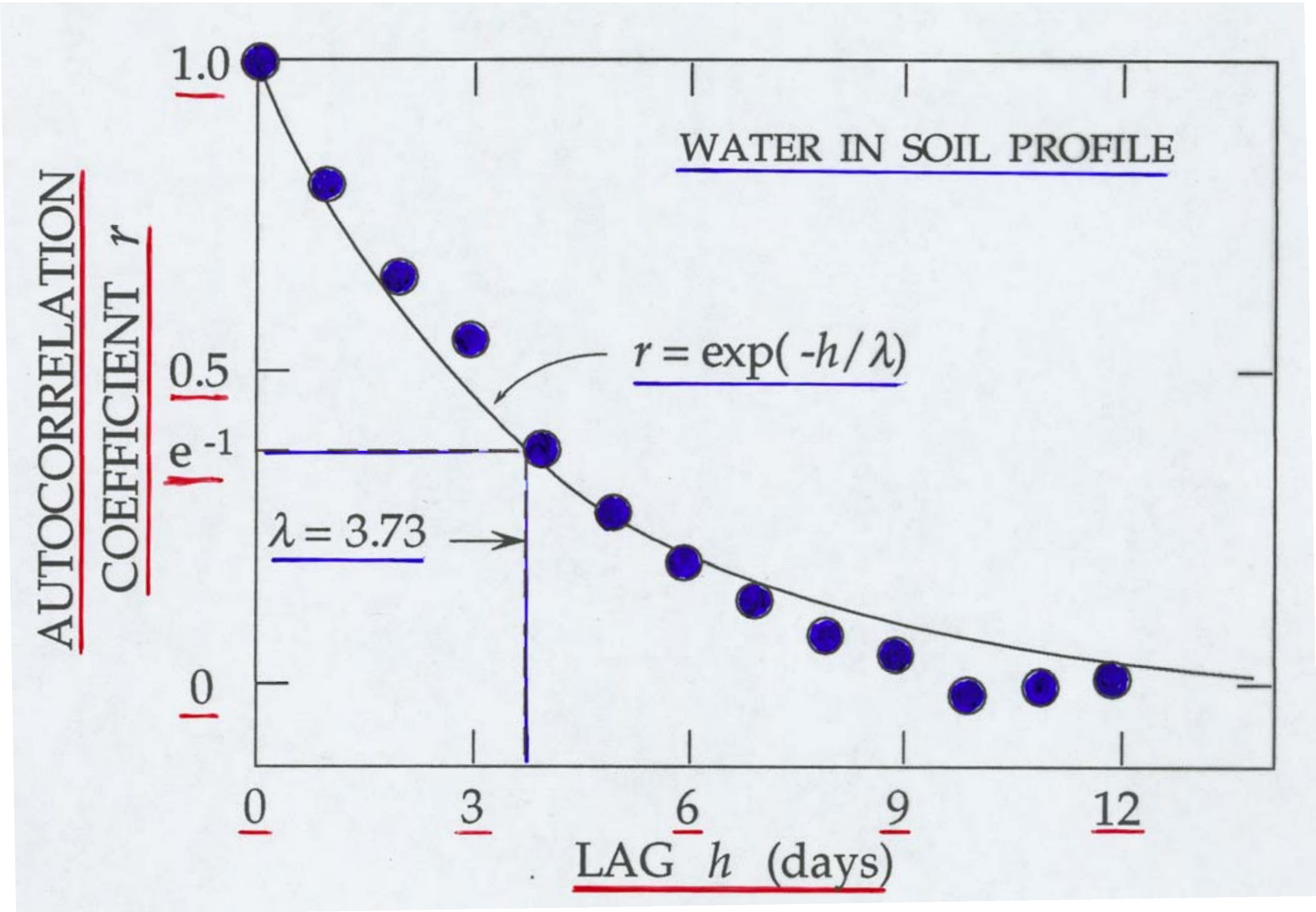
Soil water content



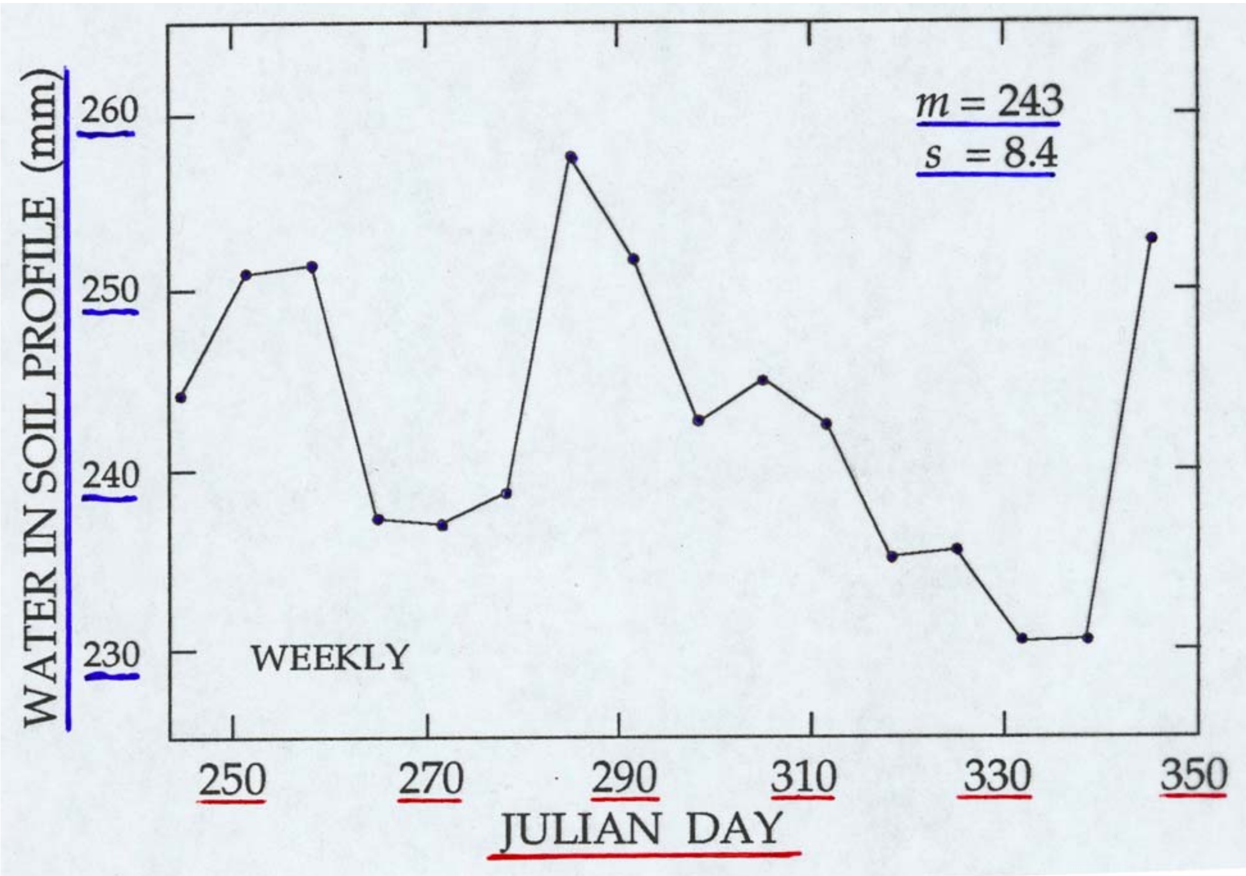
Daily soil water



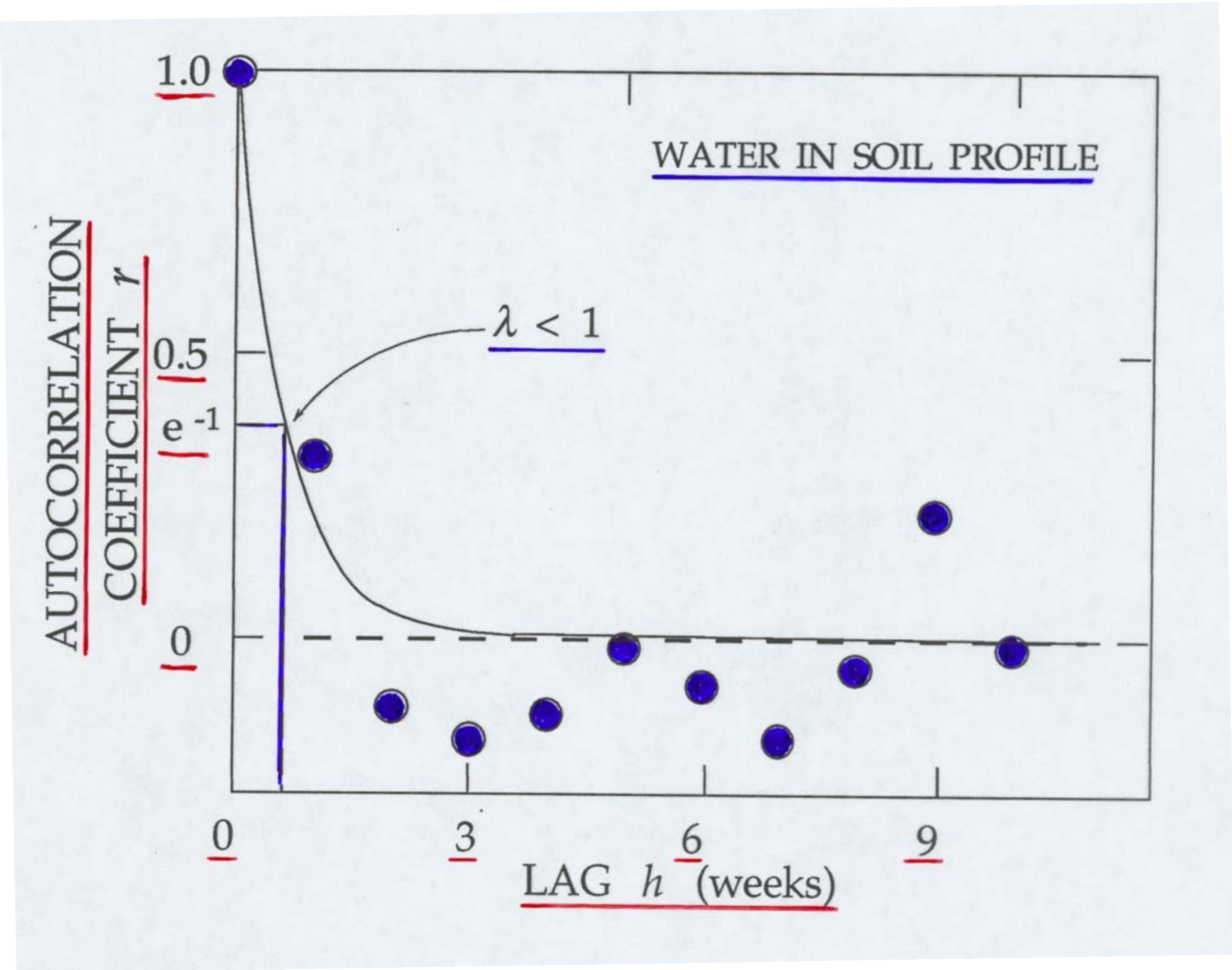
ACF Daily water



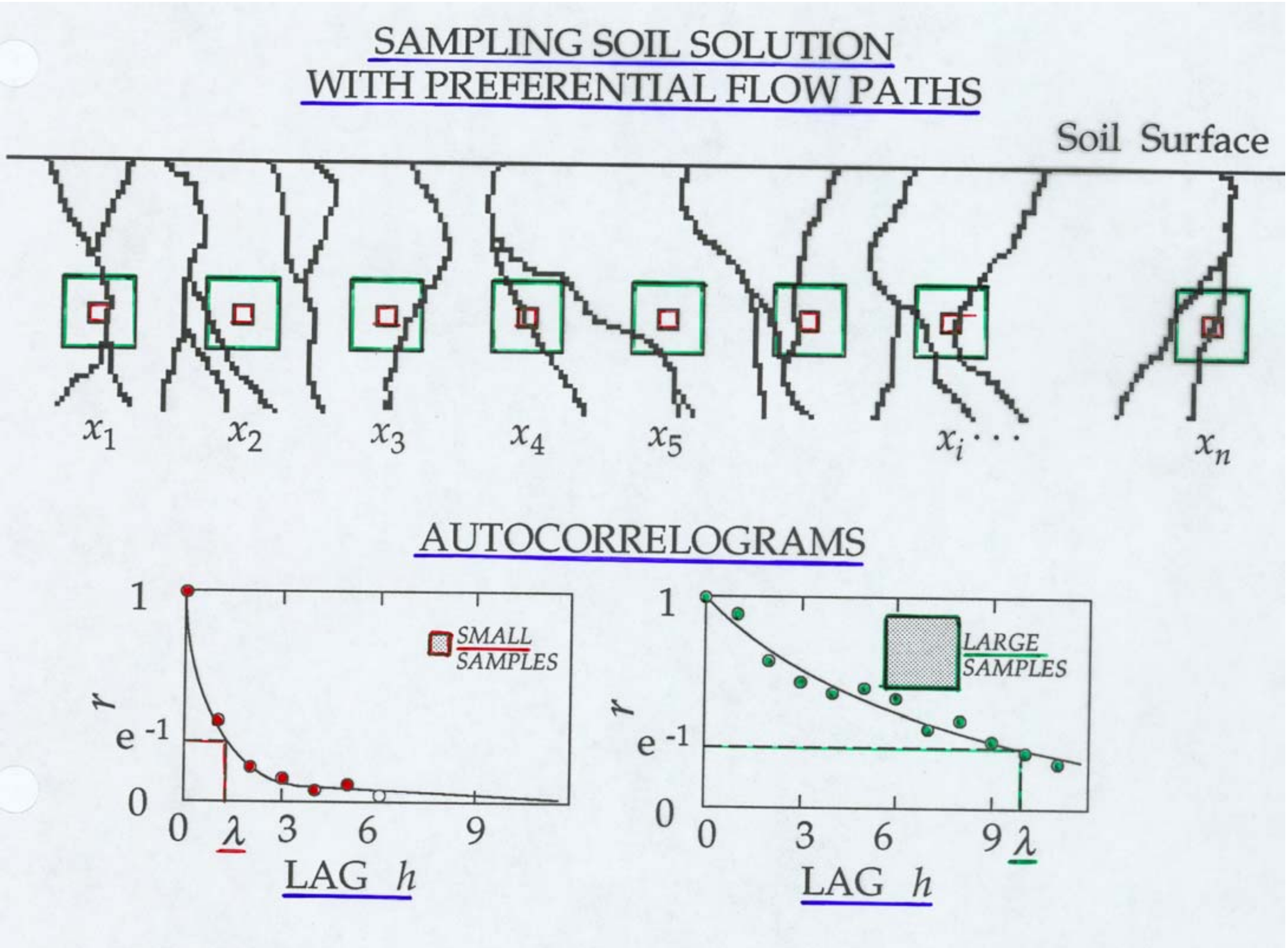
Weekly soil water



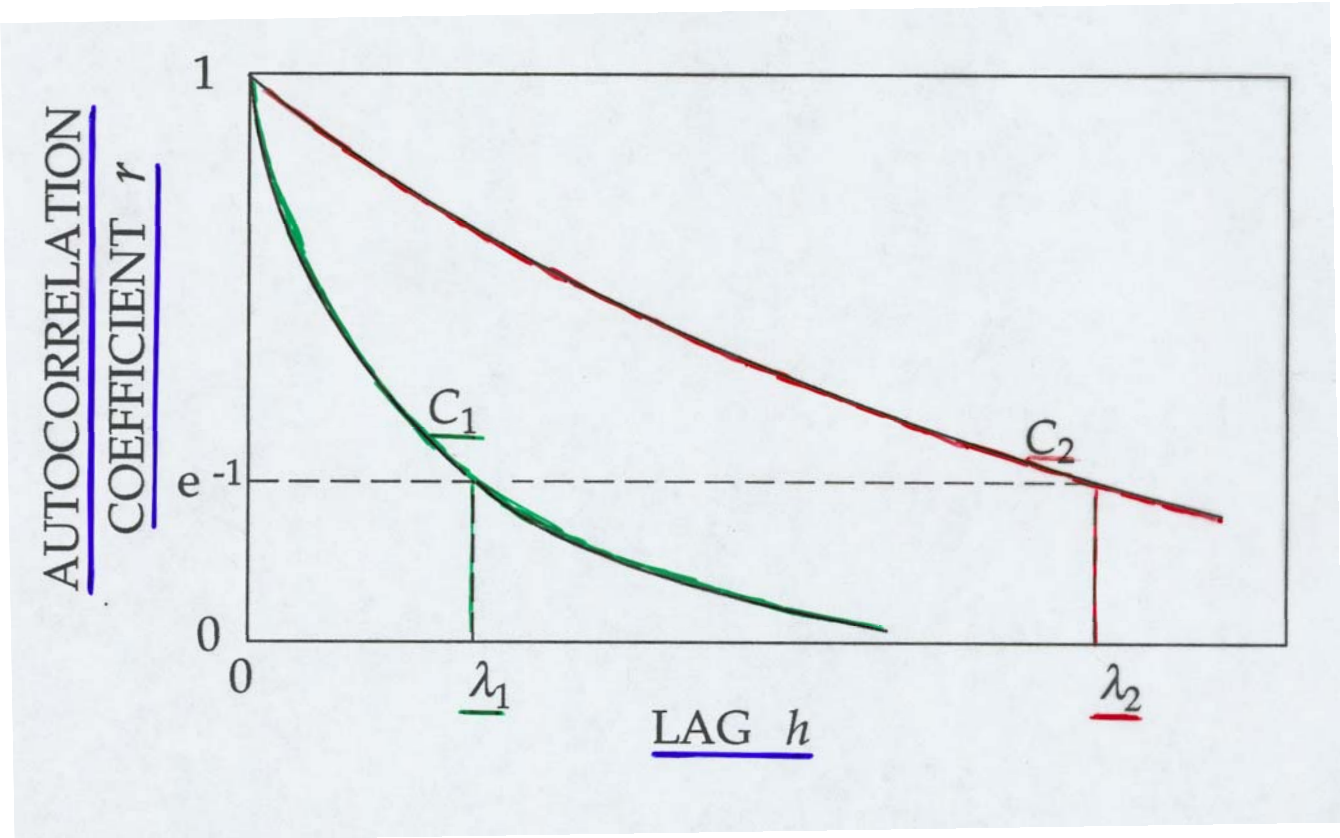
ACF Weekly soil water



Sampling preferential flow



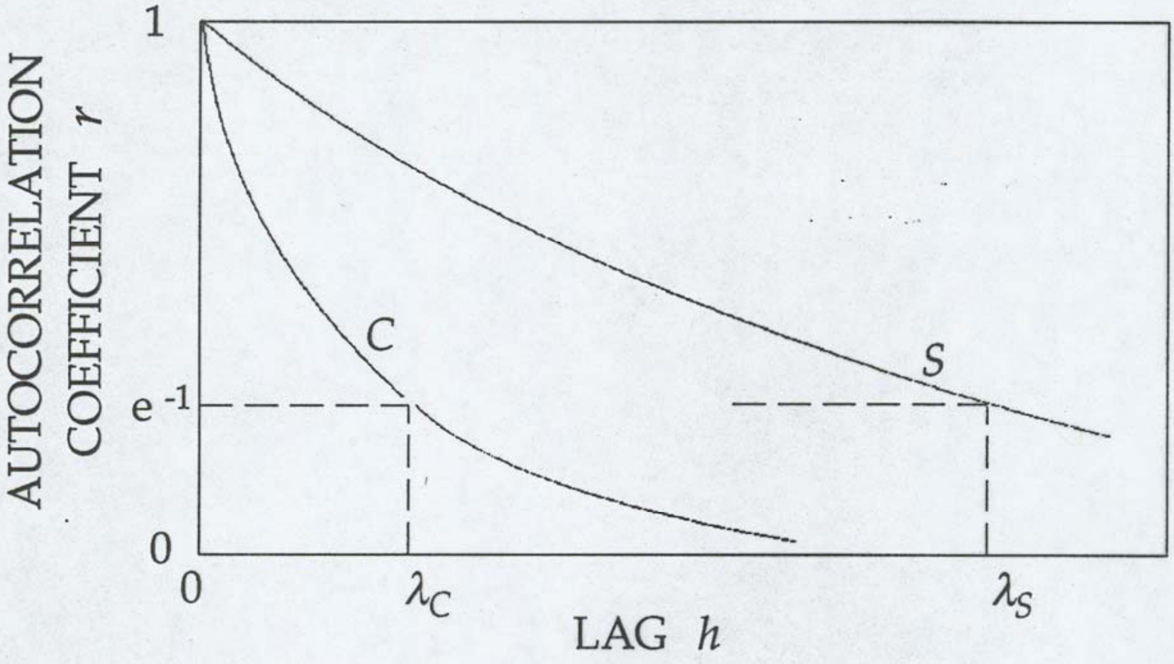
ACF C1 and C2



ACF C&S NH4

IF $\lambda_C = \lambda_S$ $\quad S = RC$ or $f(C)$

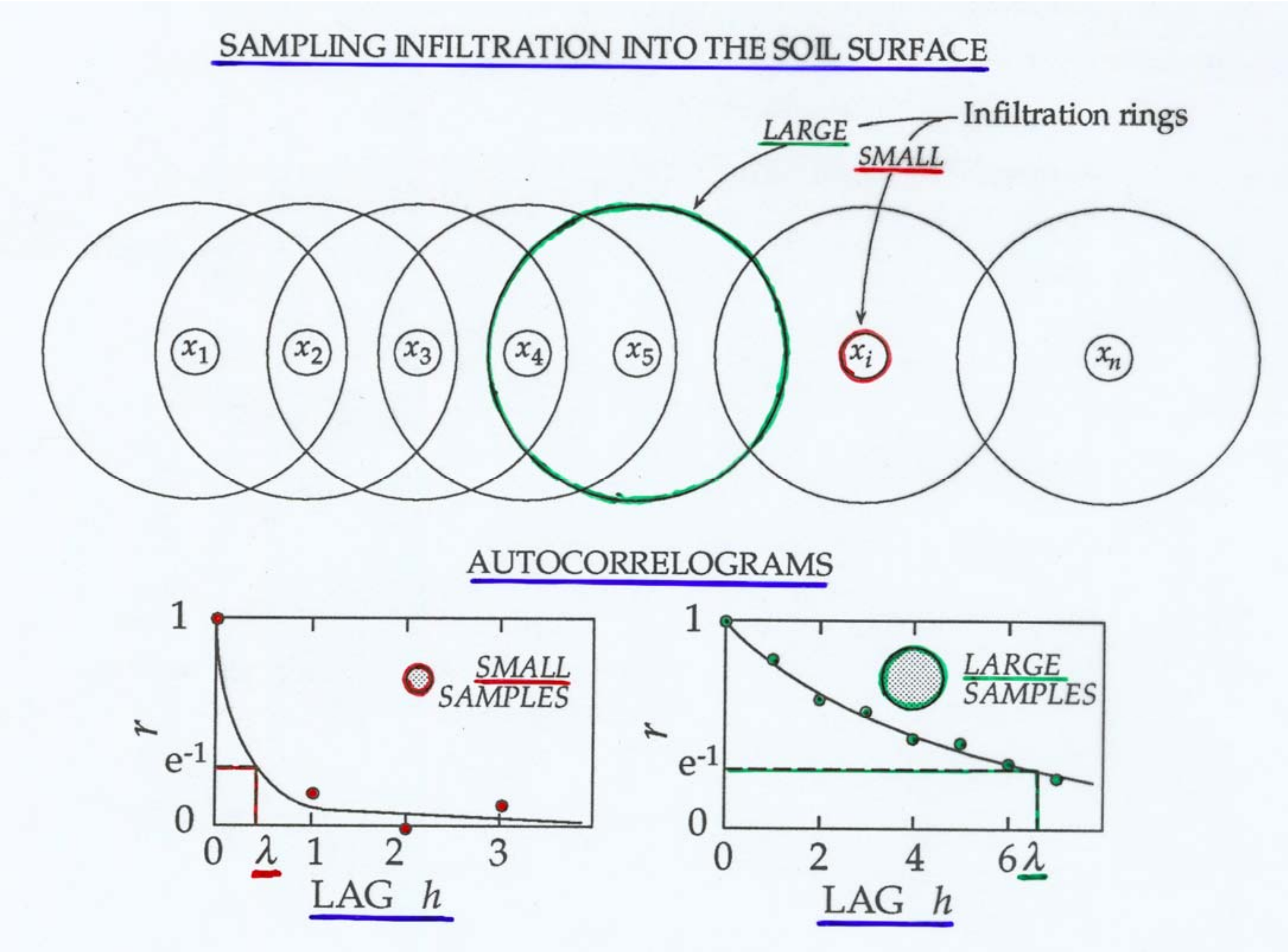
$\lambda_C \neq \lambda_S$ $\quad S \stackrel{?}{=} RC$ or $f(C)$?



$$q_{\text{solute}} \stackrel{?}{=} -D\,\nabla C$$

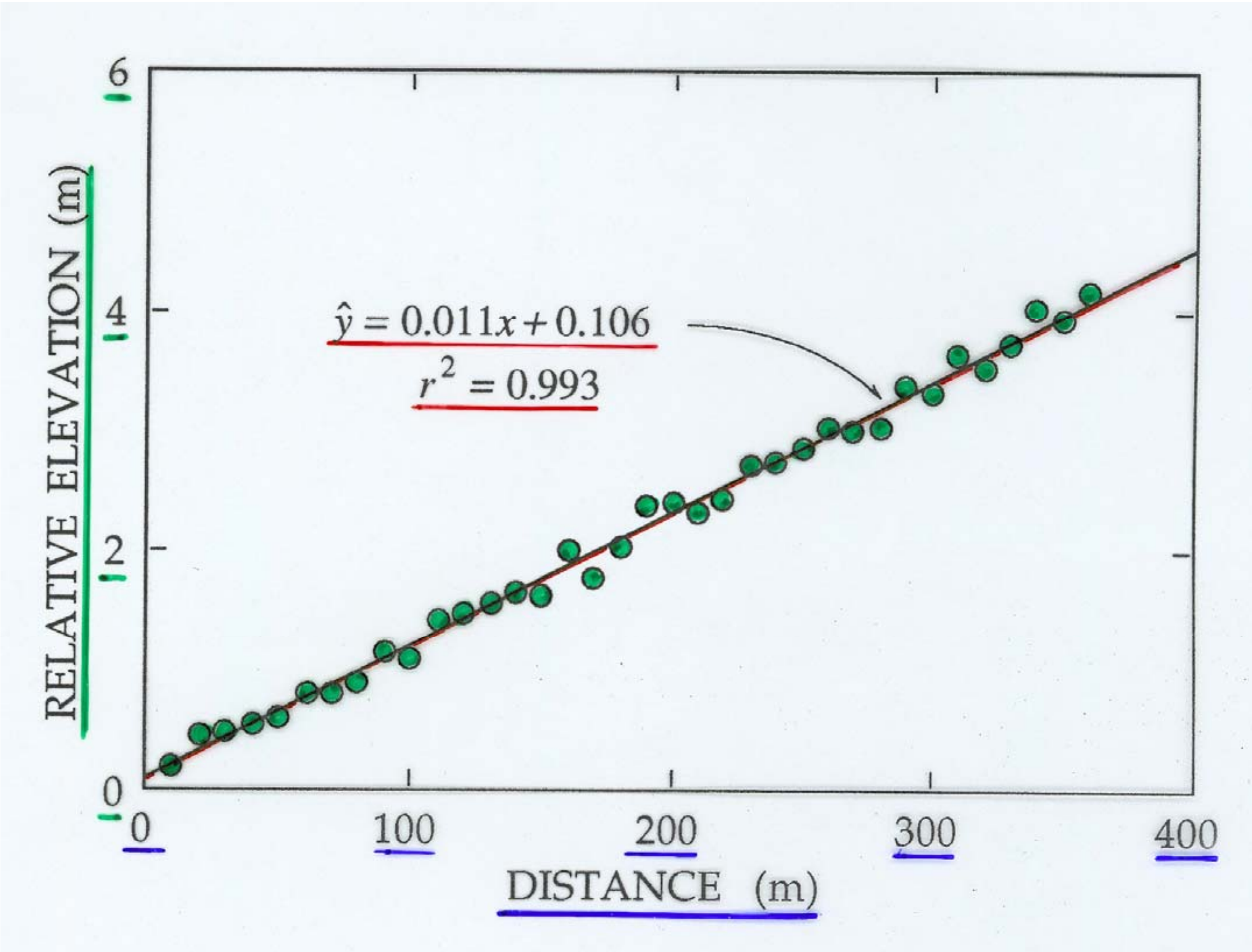
$$q_{\text{water}} \stackrel{?}{=} -K\,\nabla H$$

Sampling infiltration rings

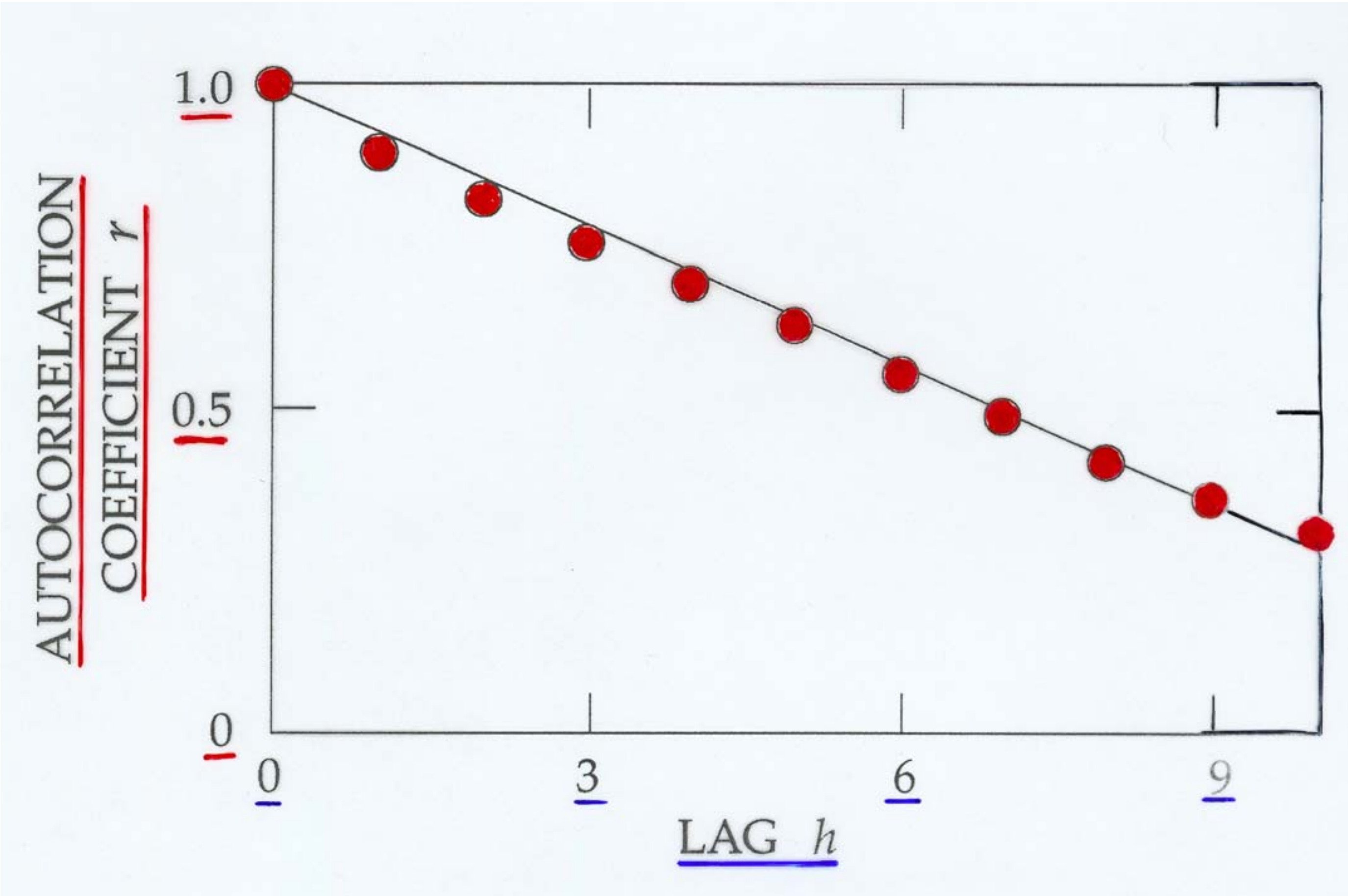


IMPACT OF DETERMINISTIC TREND

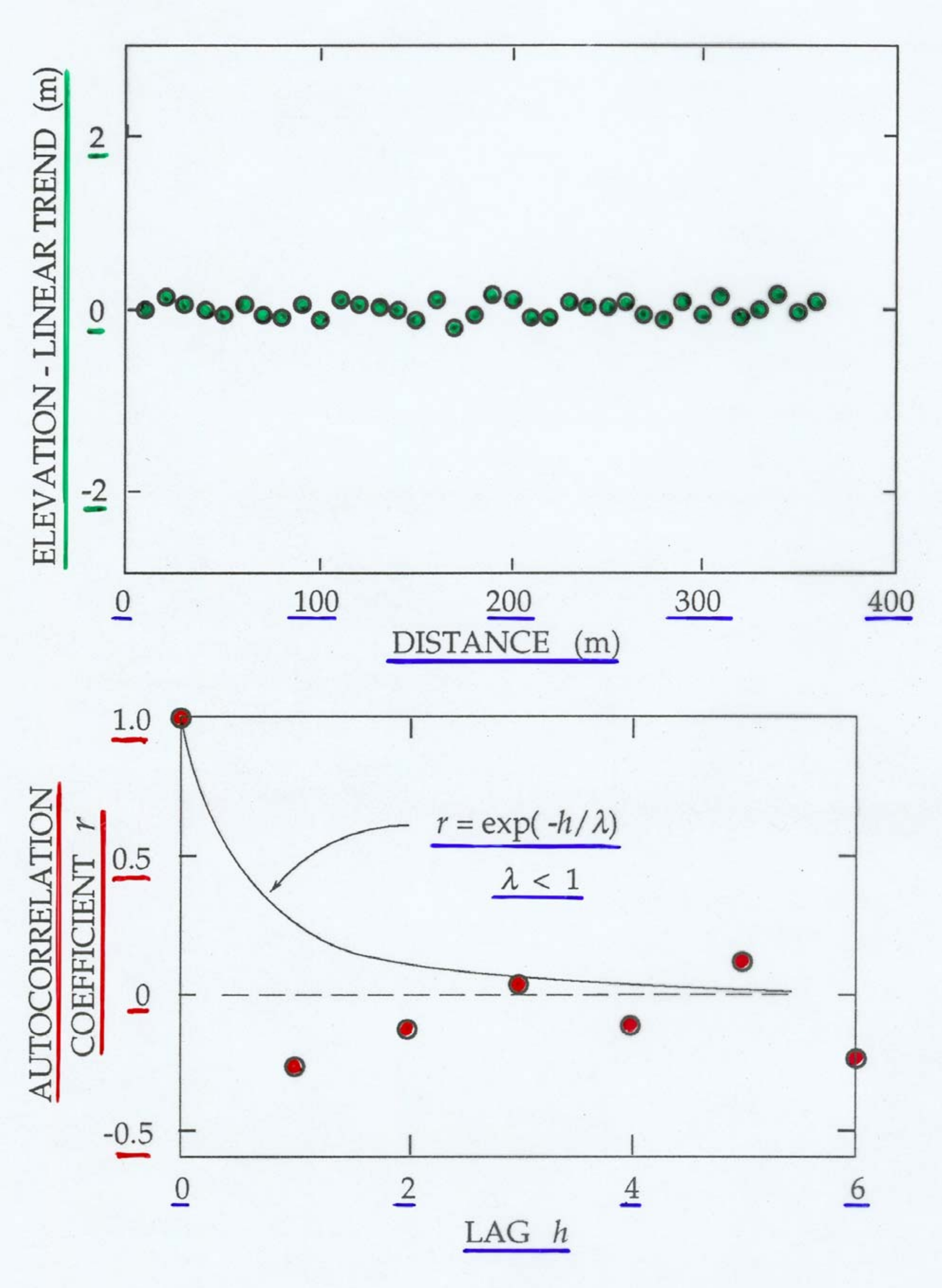
Linear elevation vs distance



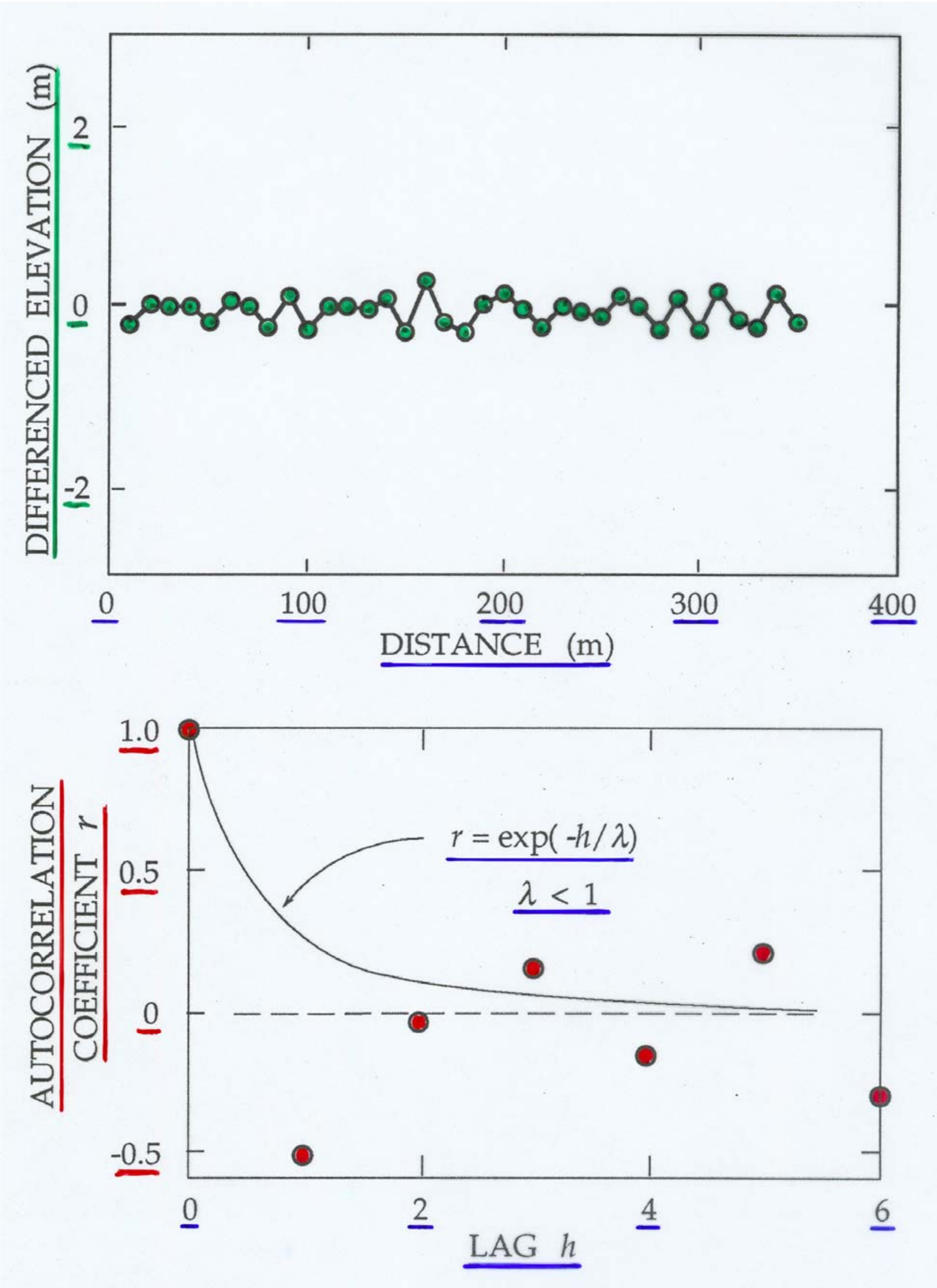
ACF linear elevation



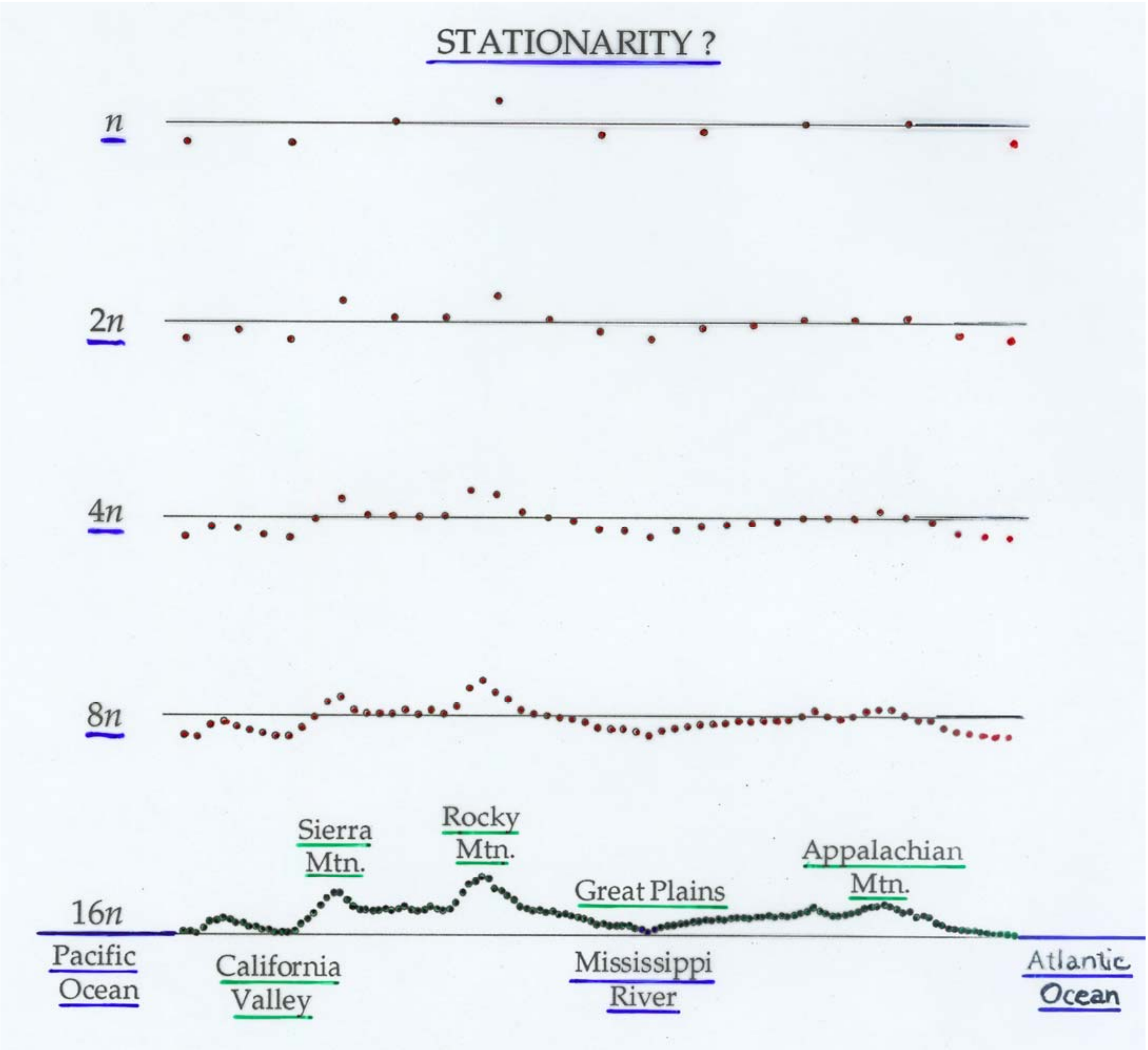
Elevation minus linear



Differenced elevation

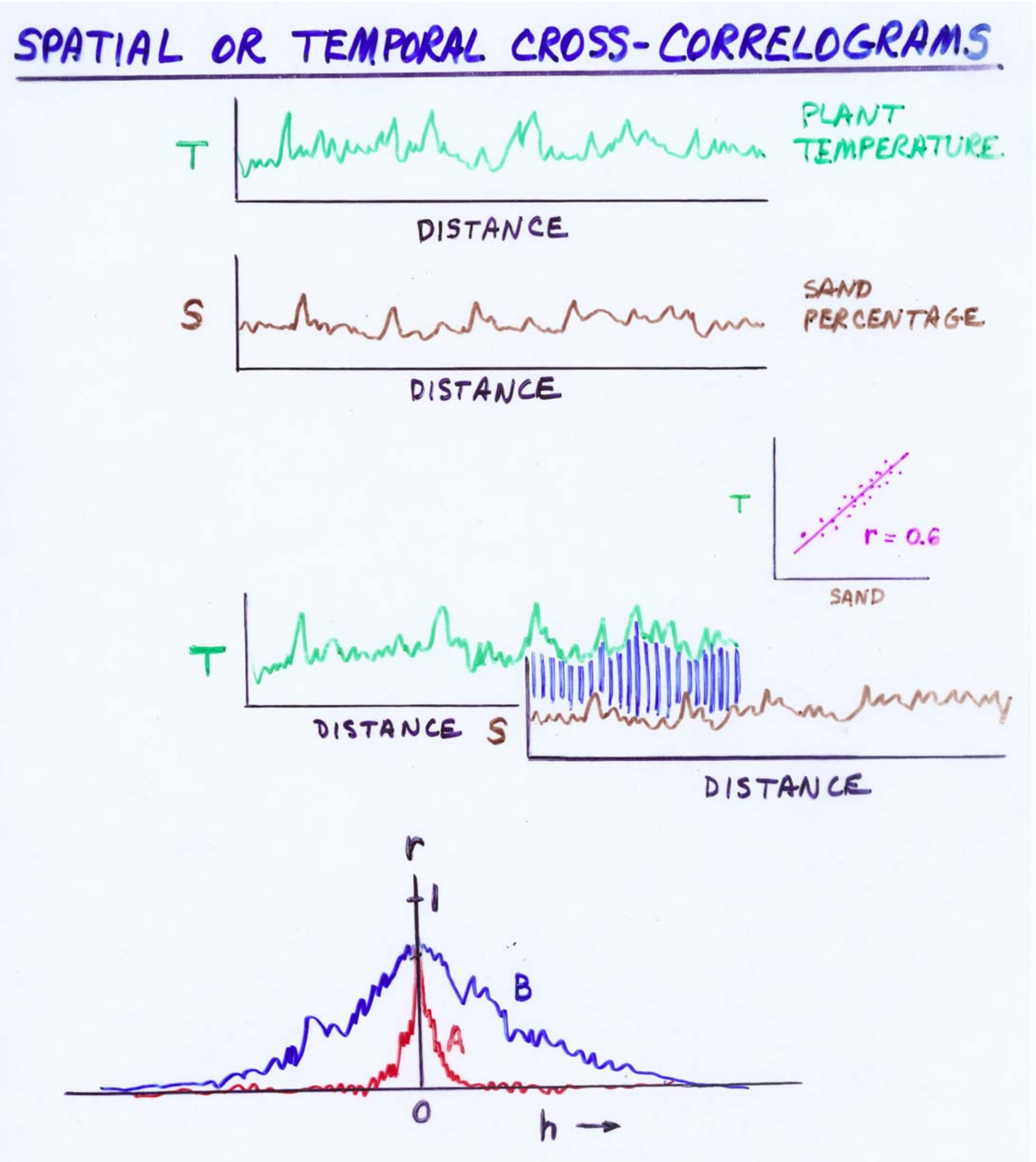


Stationarity?

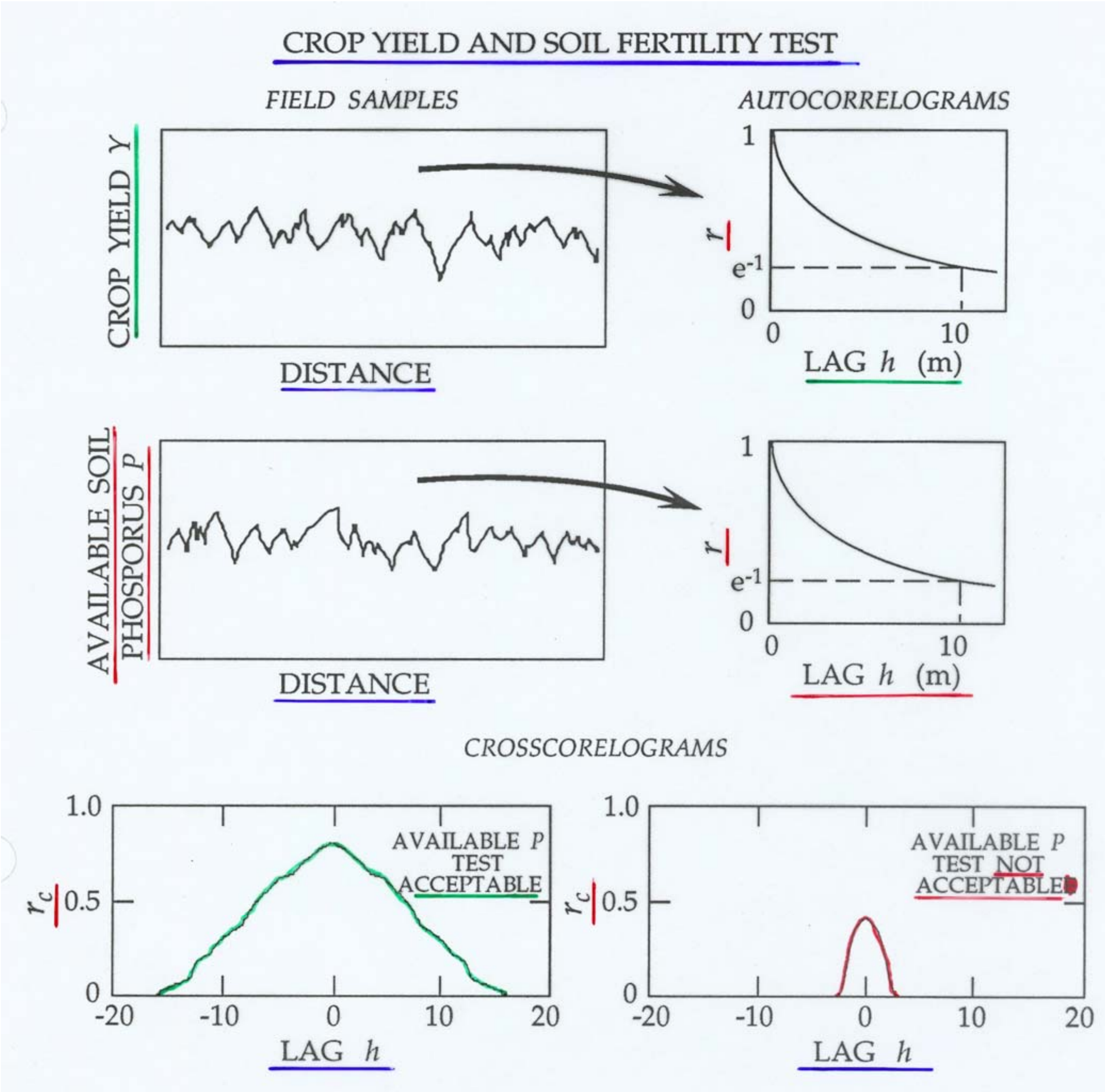


SPATIAL OR TEMPORAL CROSS CORRELATION

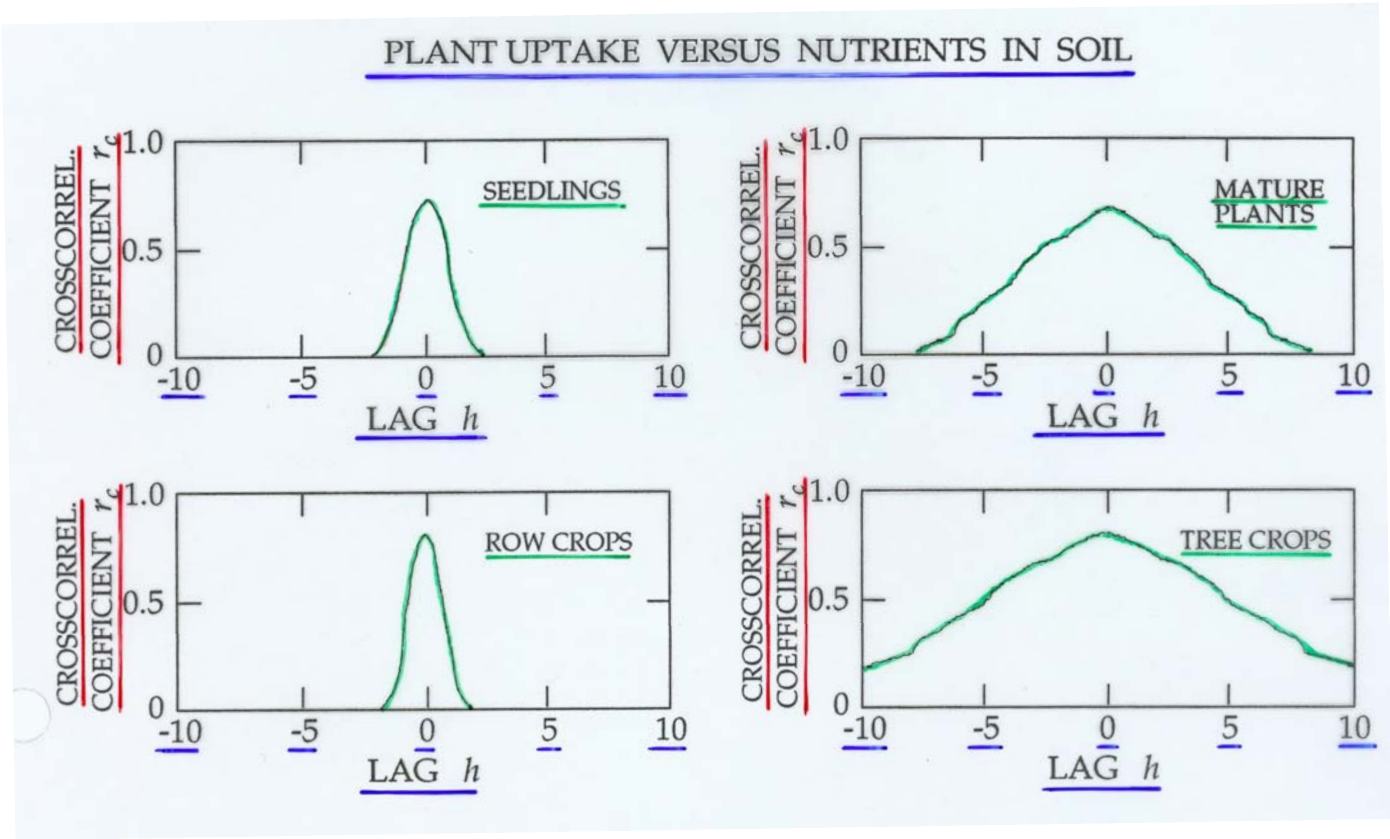
Crosscorrelation diagram



Yield&fertility CCF

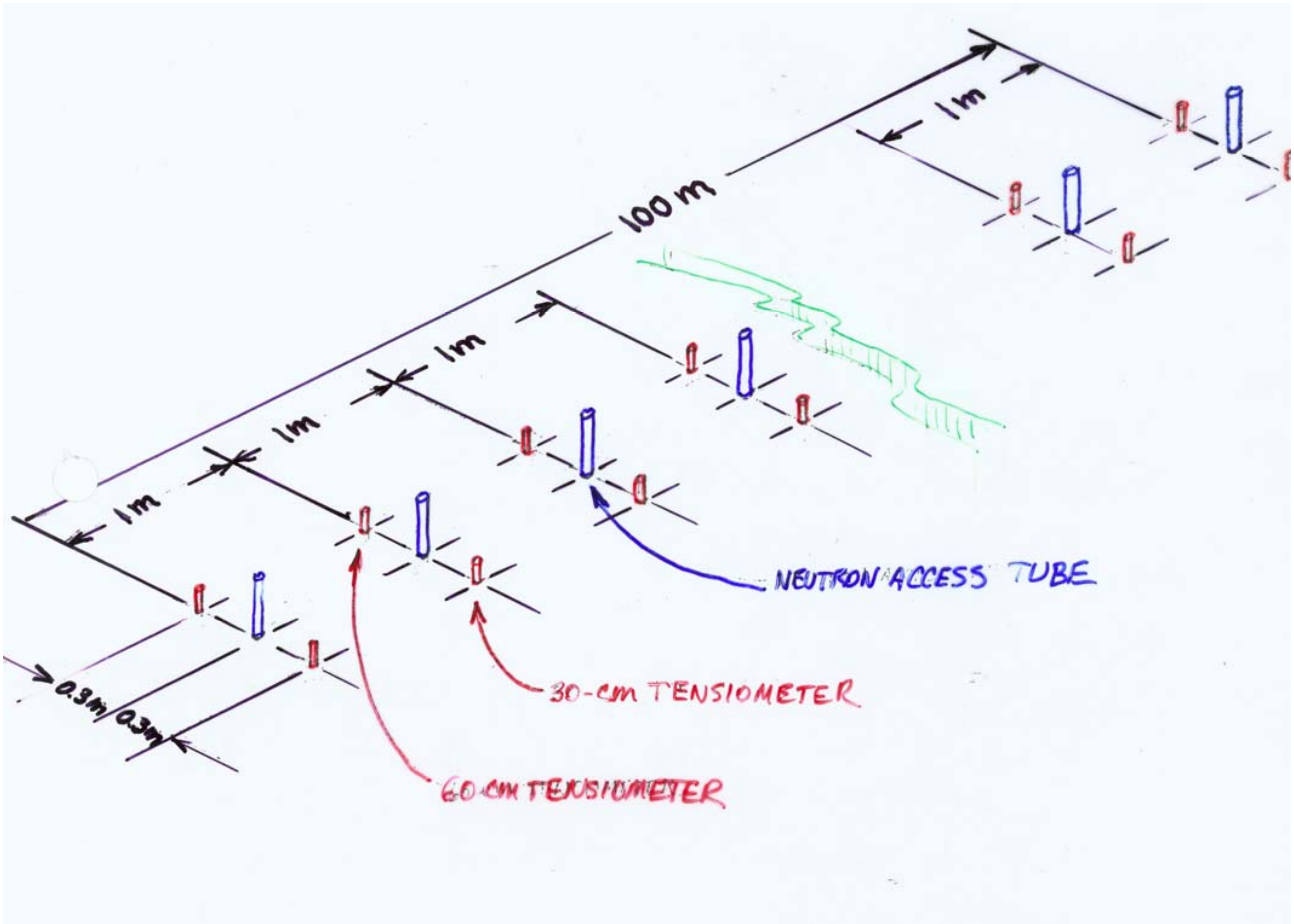


Plant uptake&nutrients

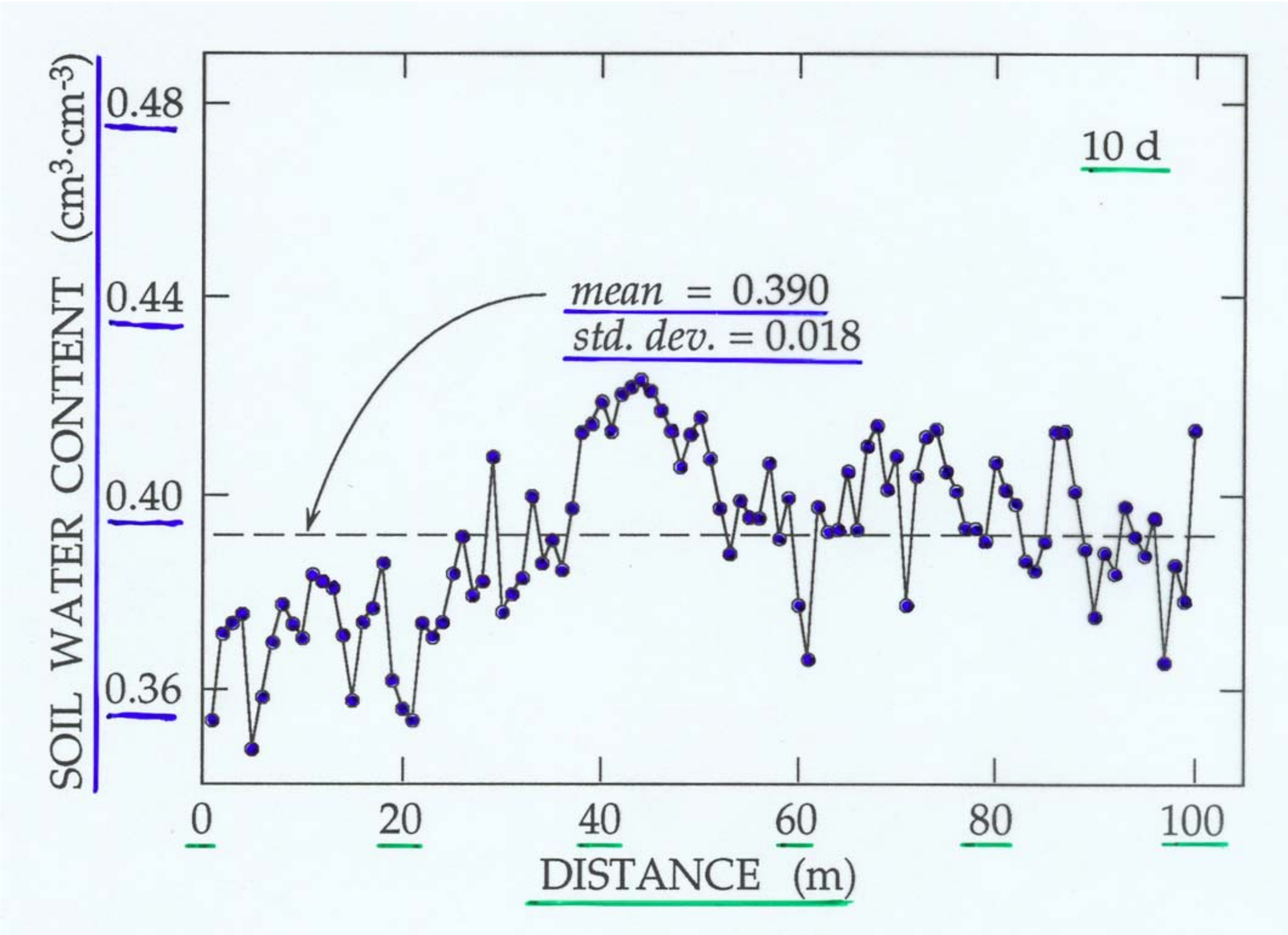


TWO SETS OF PHYSICALLY RELATED MEASUREMENTS

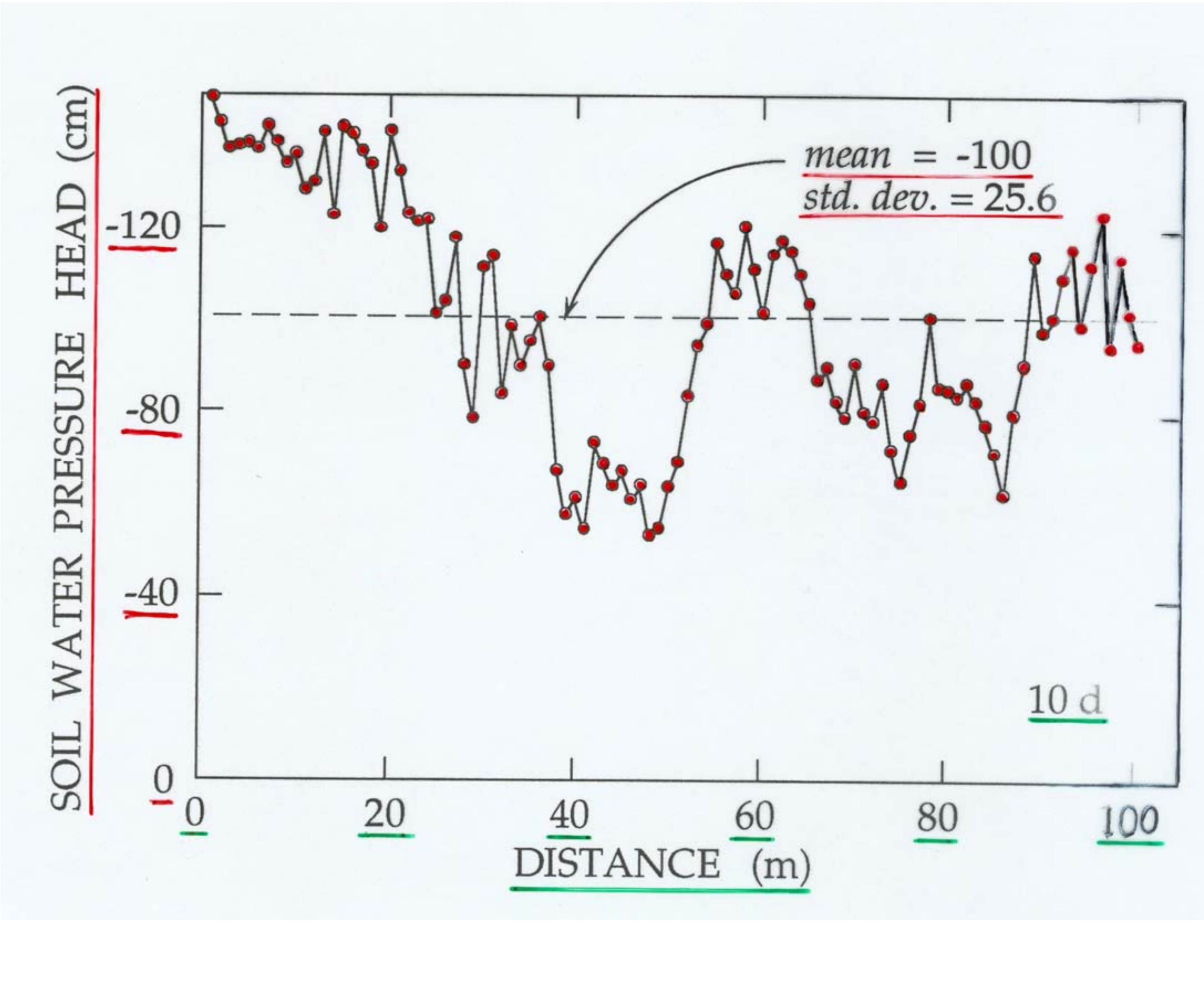
Tension-neutron placement



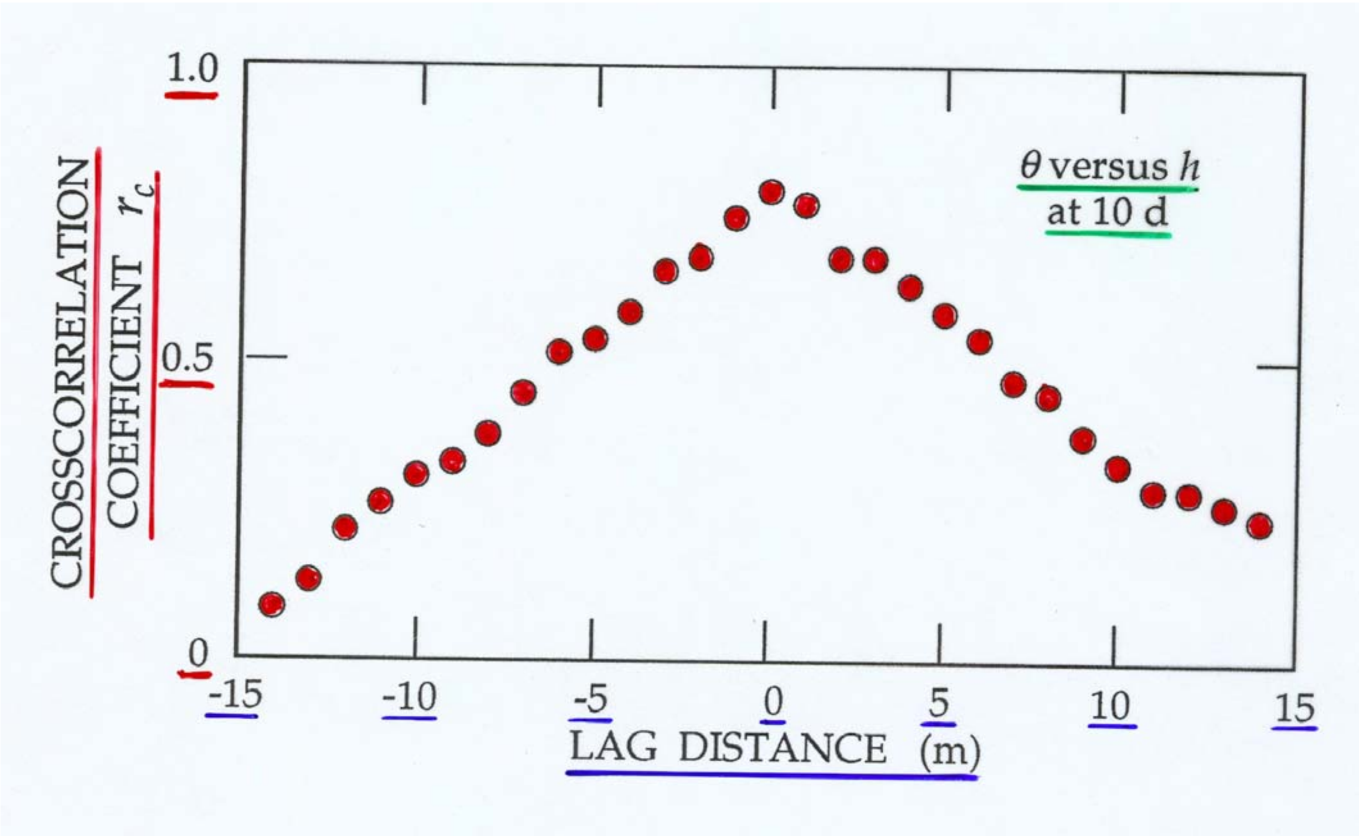
Theta vs distance



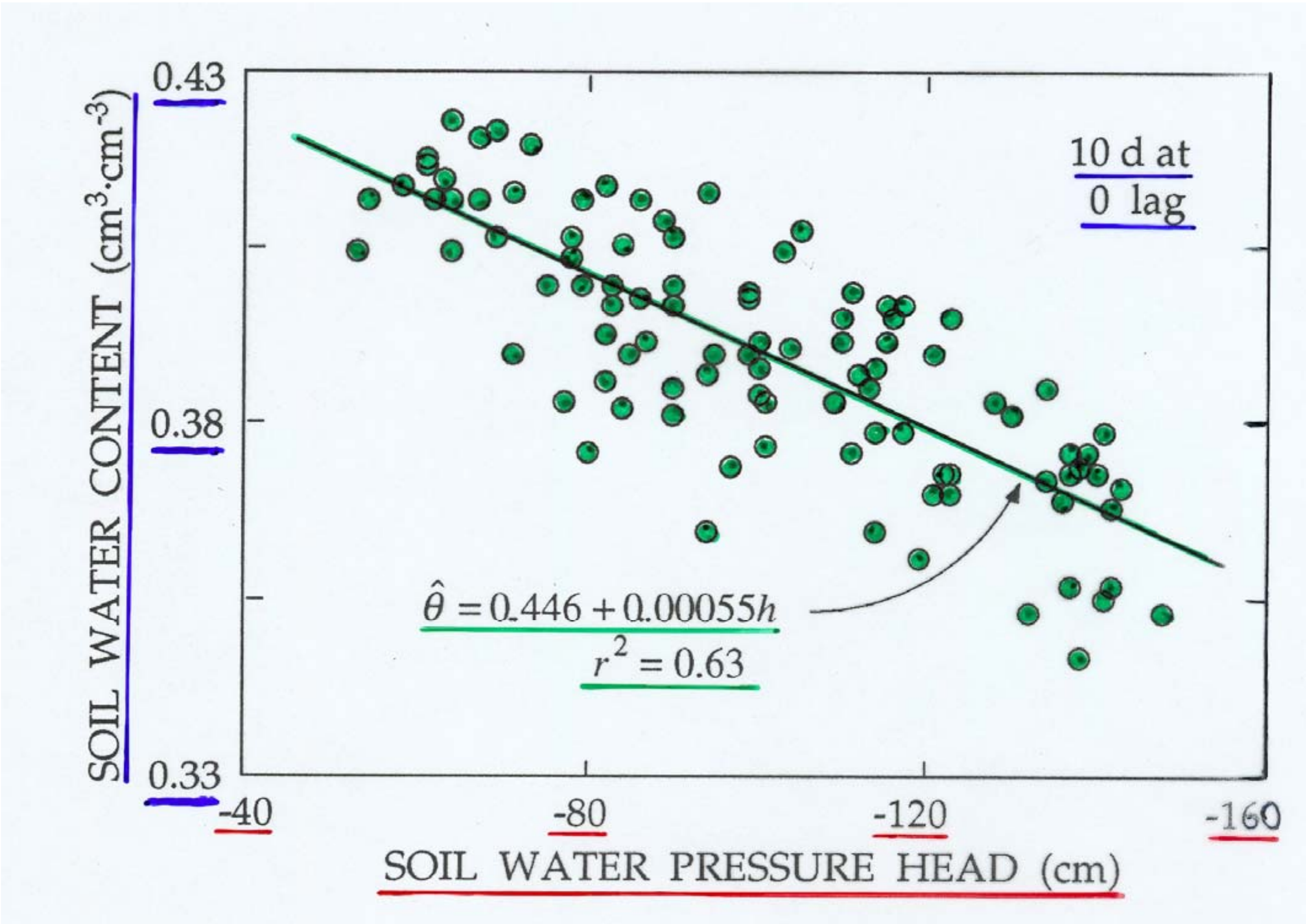
h vs distance



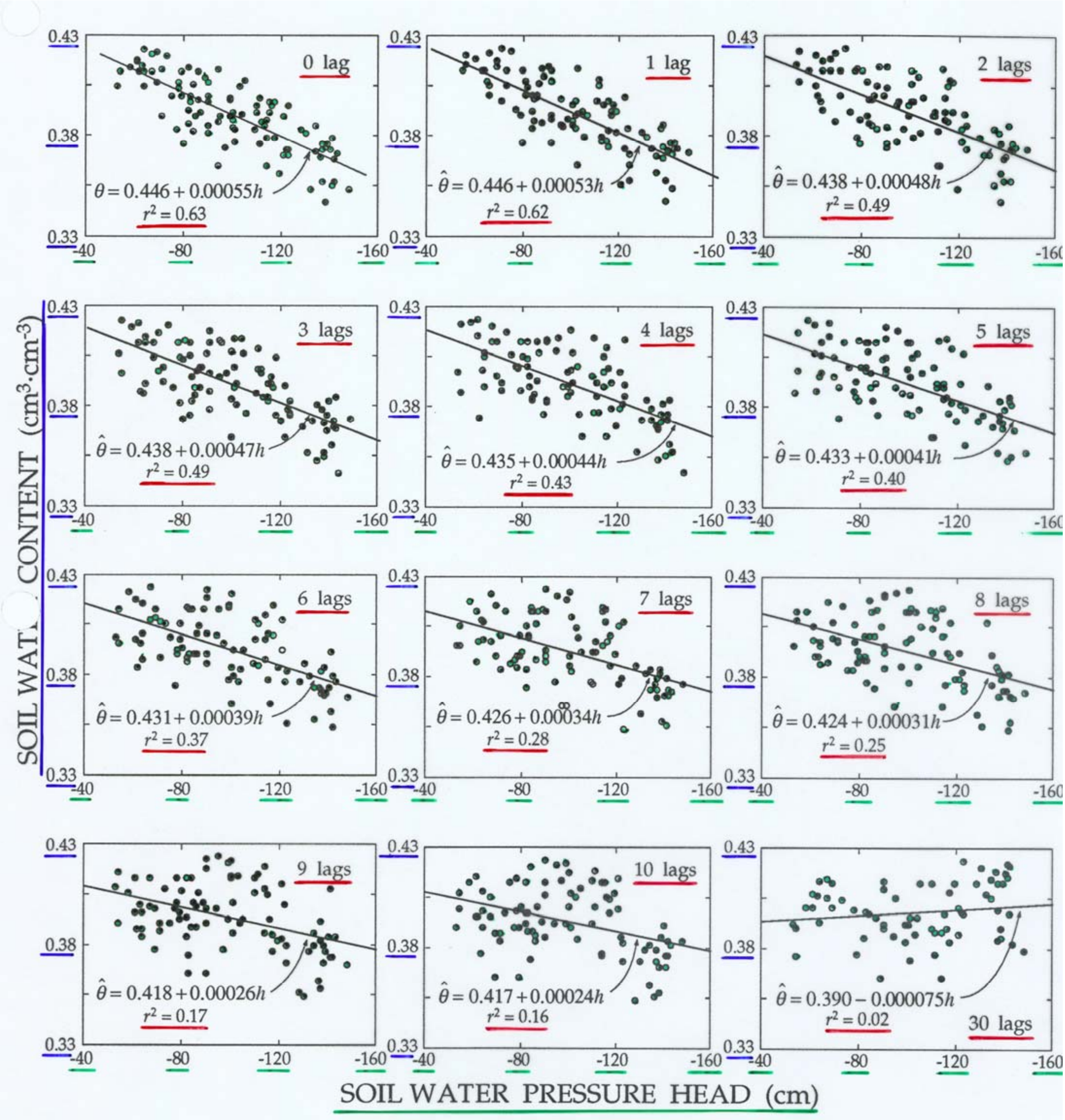
CCF theta-h at 10 days



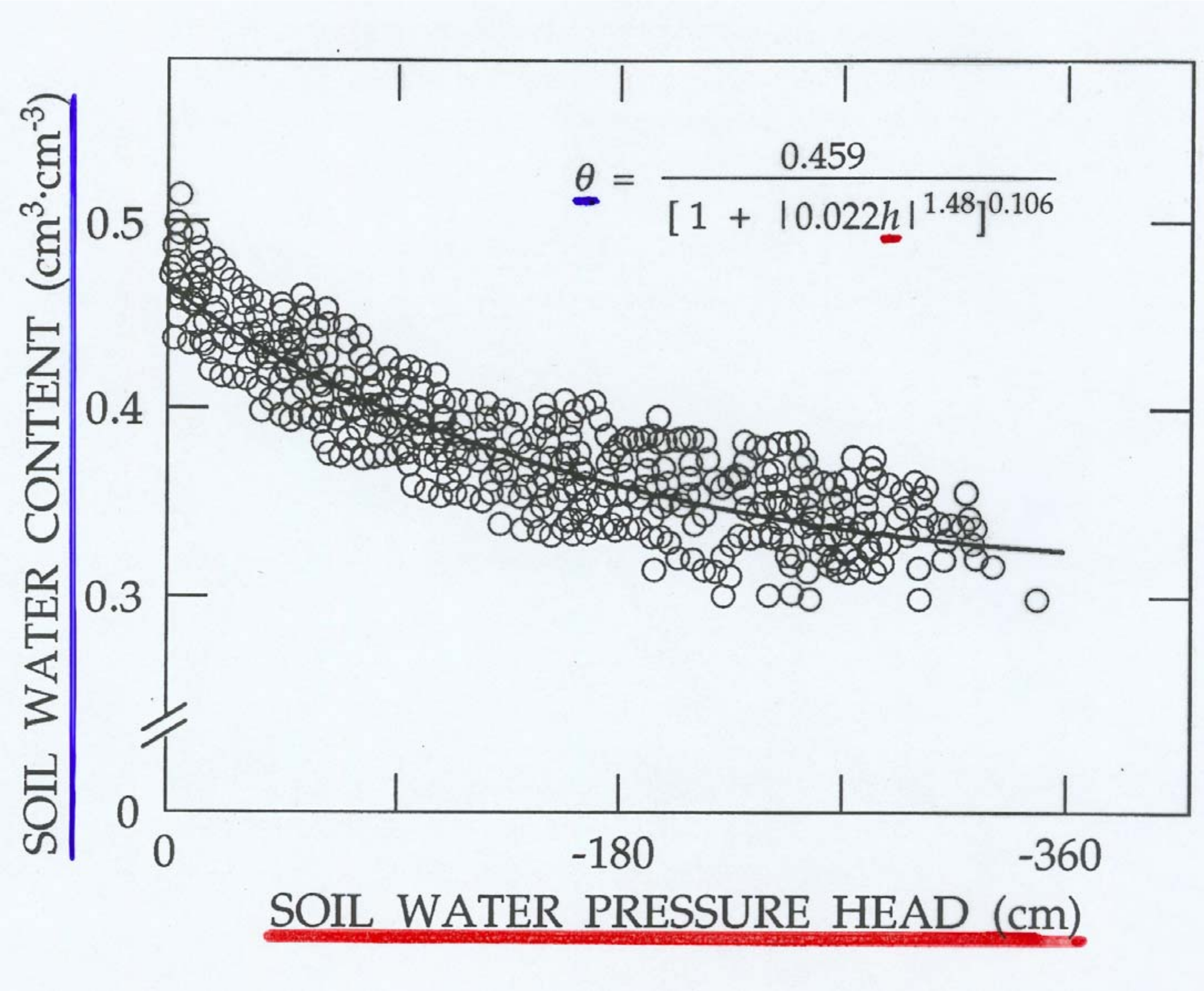
Theta vs h at10 days 0 lag



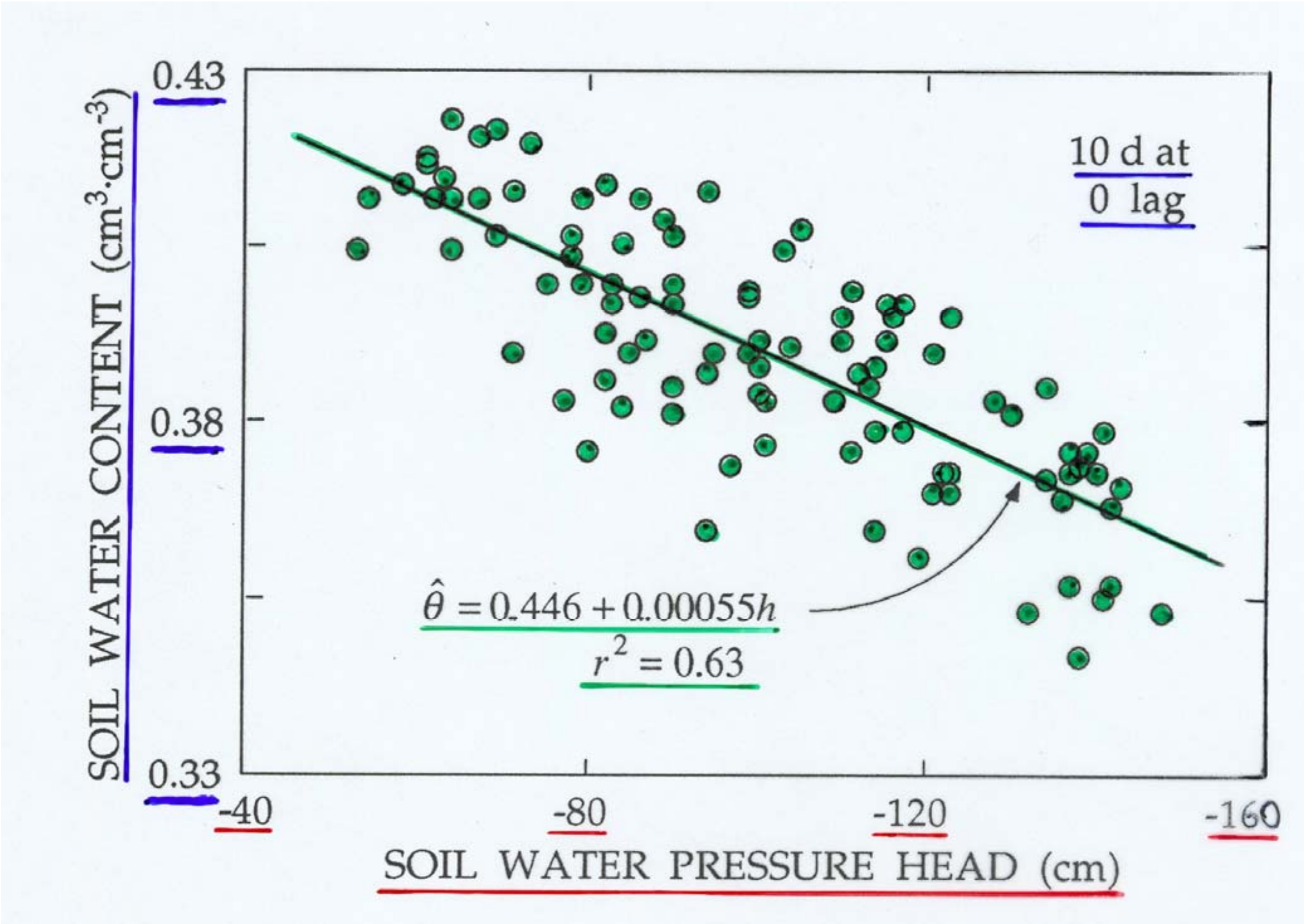
θ vs h 0-30 lags



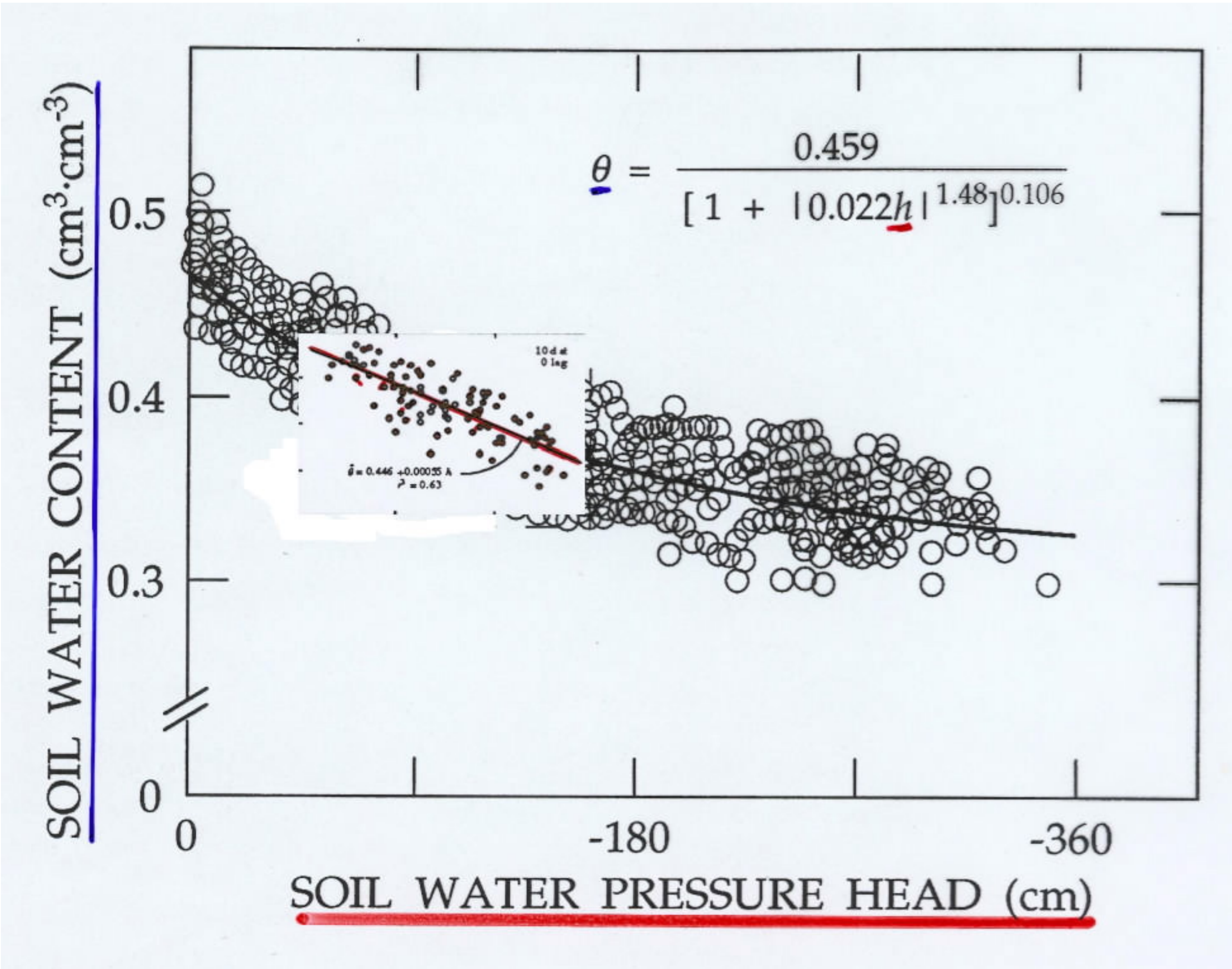
θ vs h all data



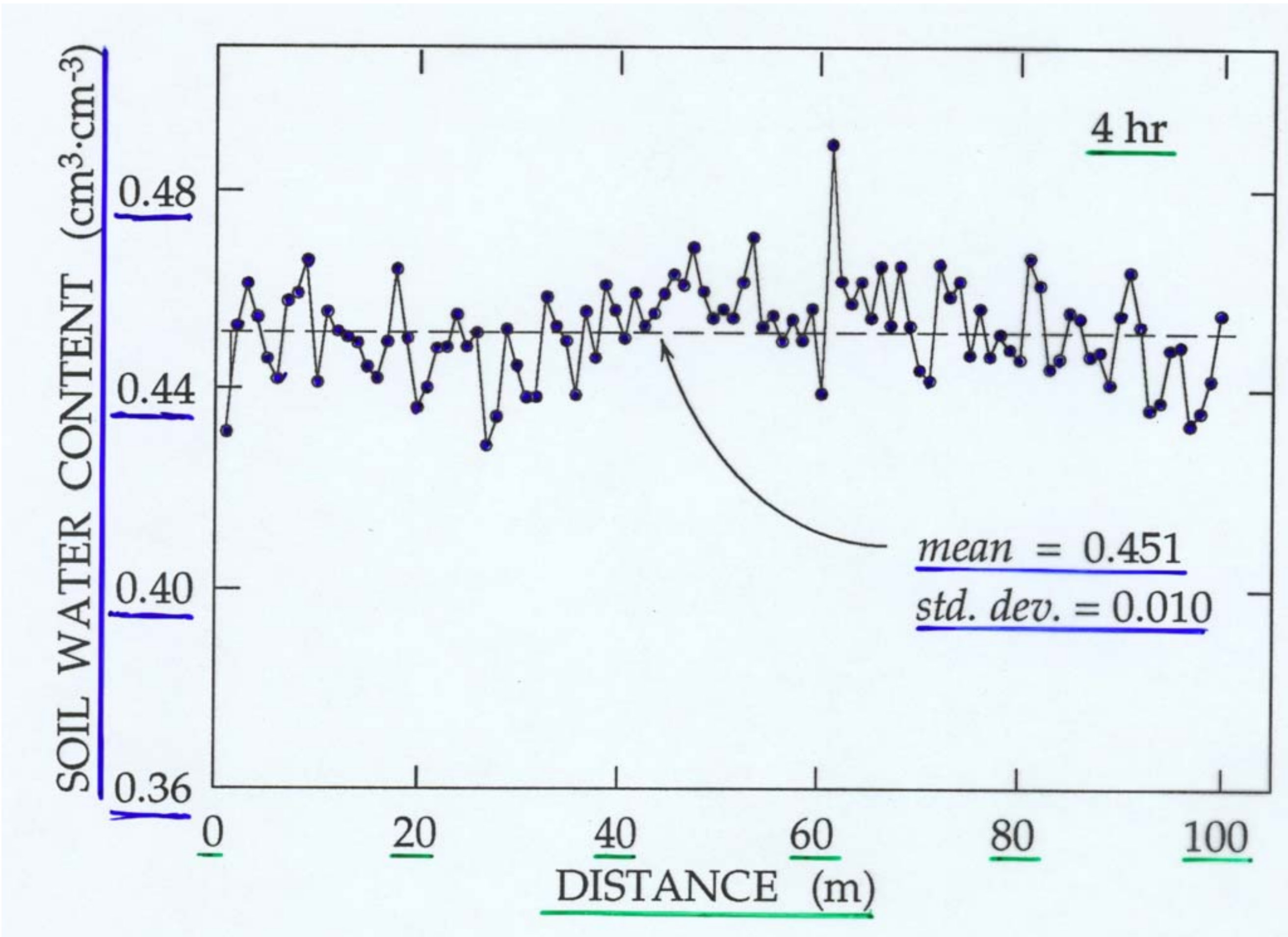
θ vs h 10 d 0 lag



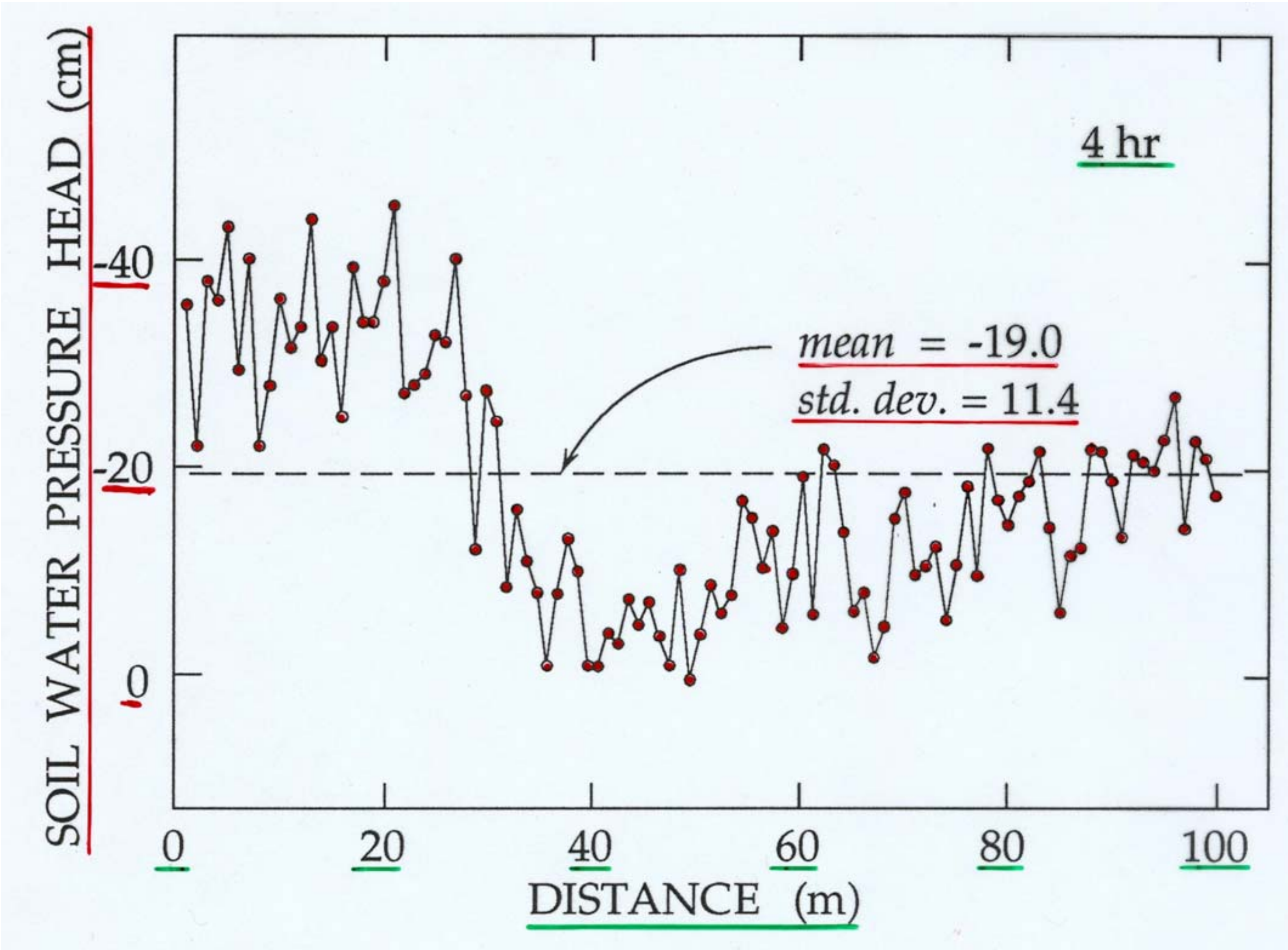
q vs h all data + 0 lag



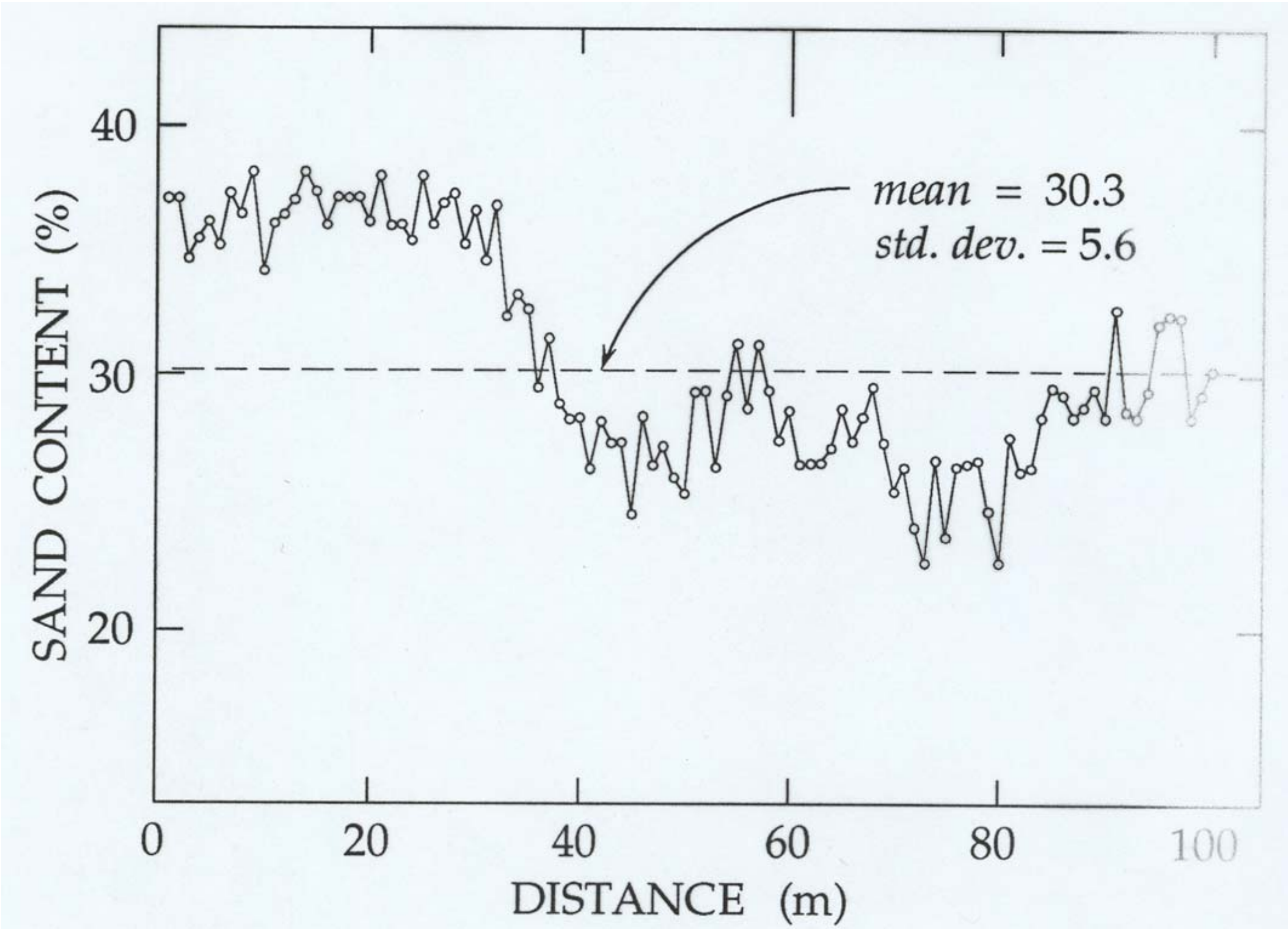
q vs distance 4 hr



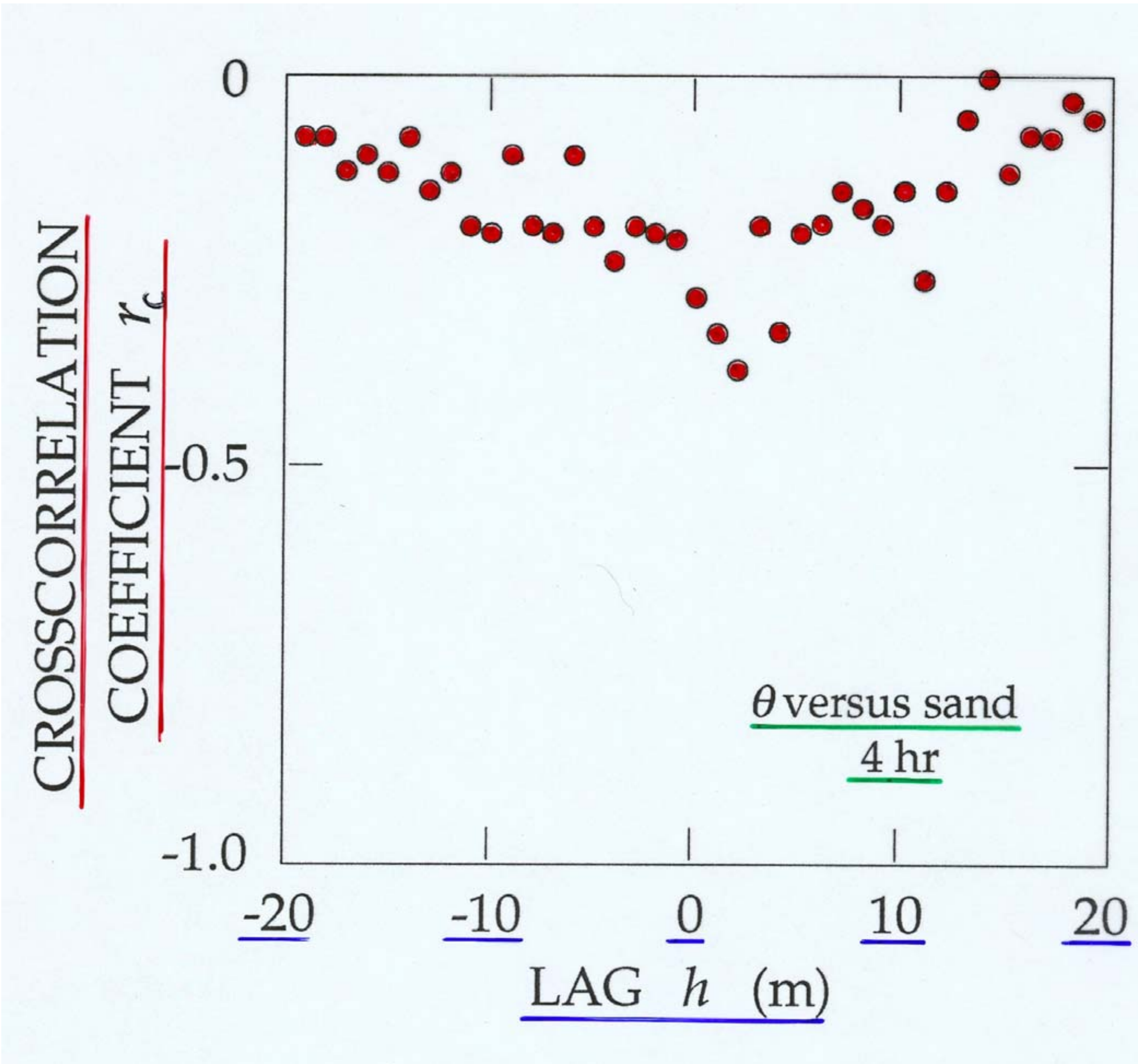
h vs distance 4 hr



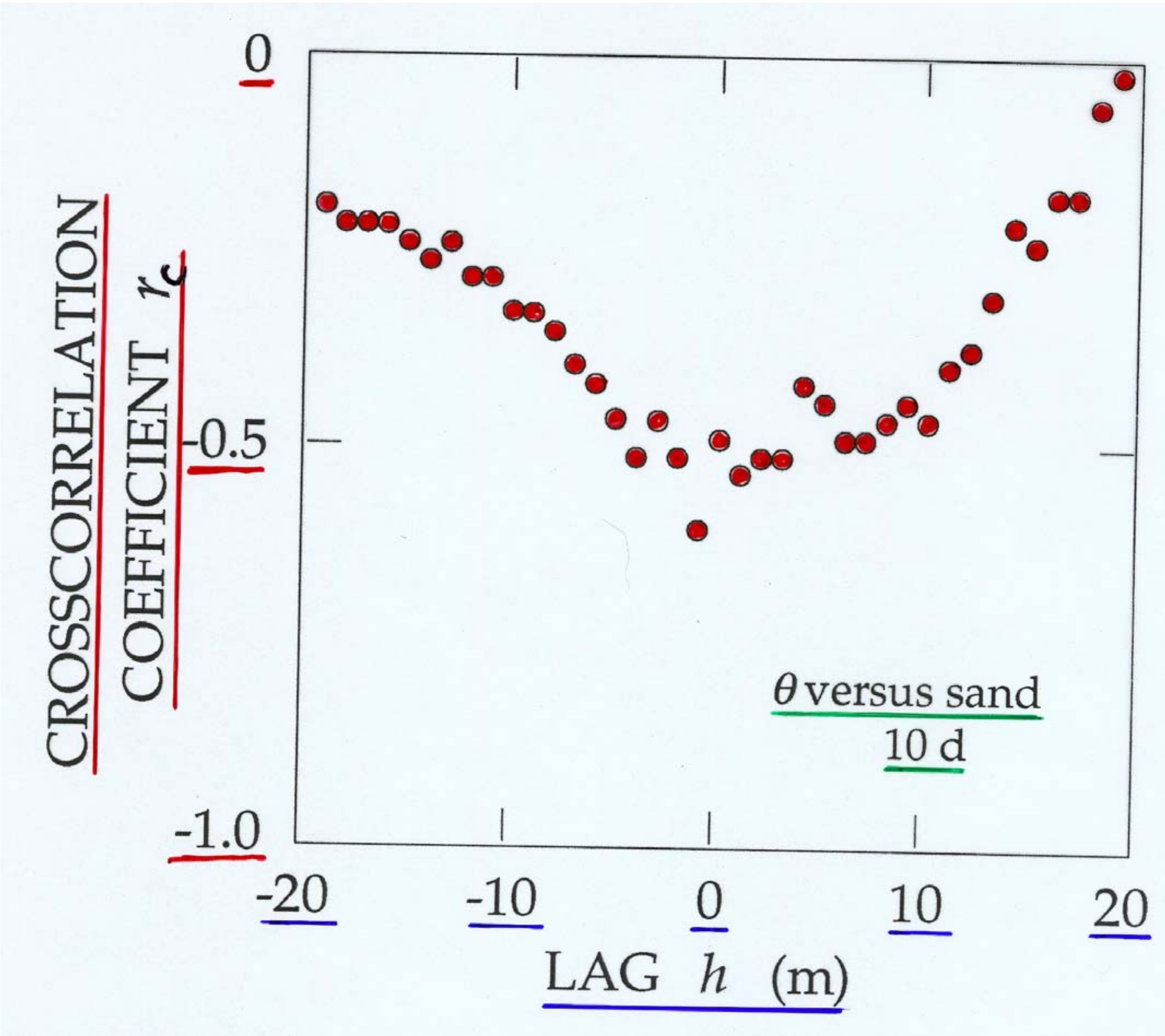
sand vs distance



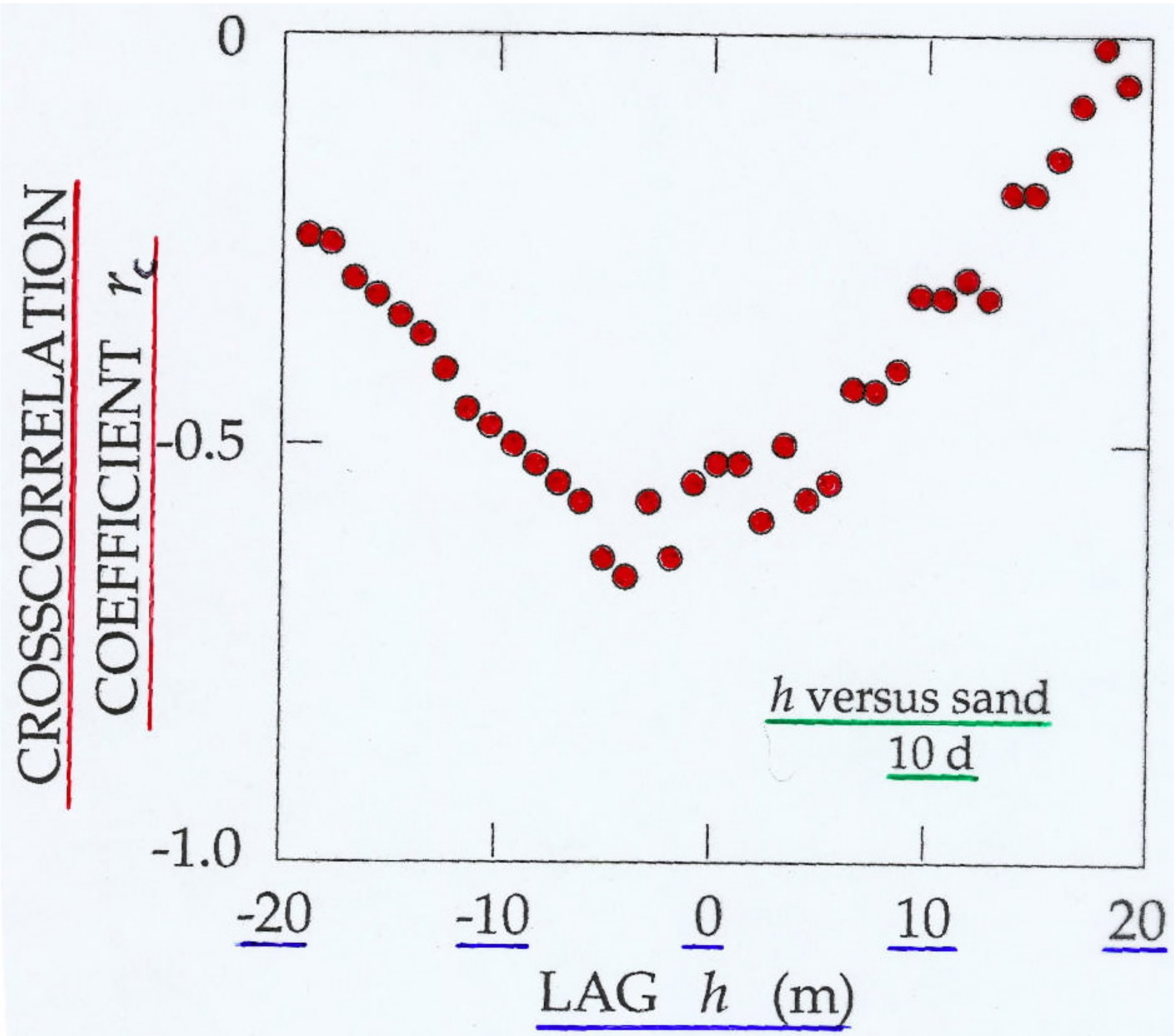
CCF theta vs sand 4 hr



CCF theta vs sand 10 days

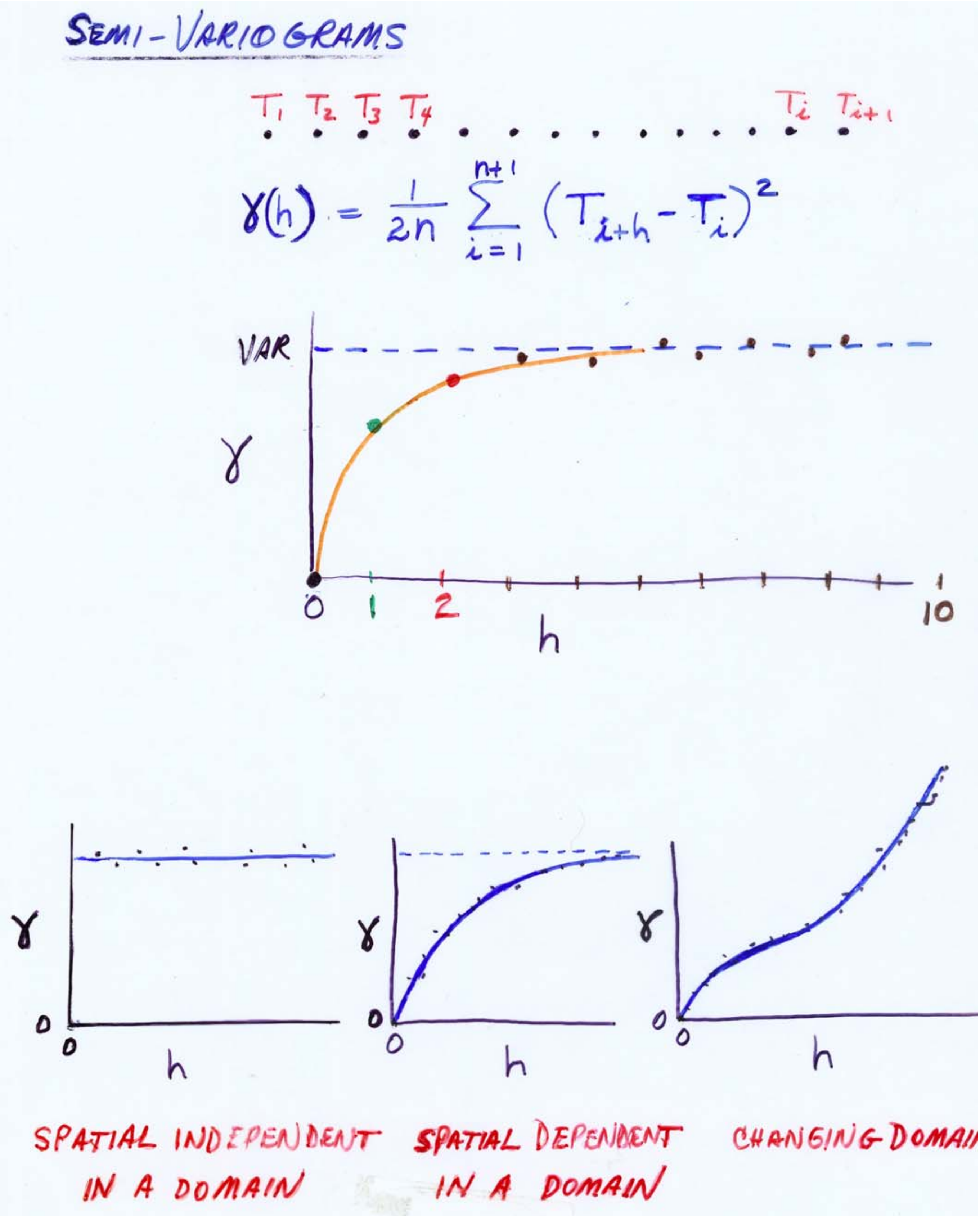


CCF h vs sand 10 days

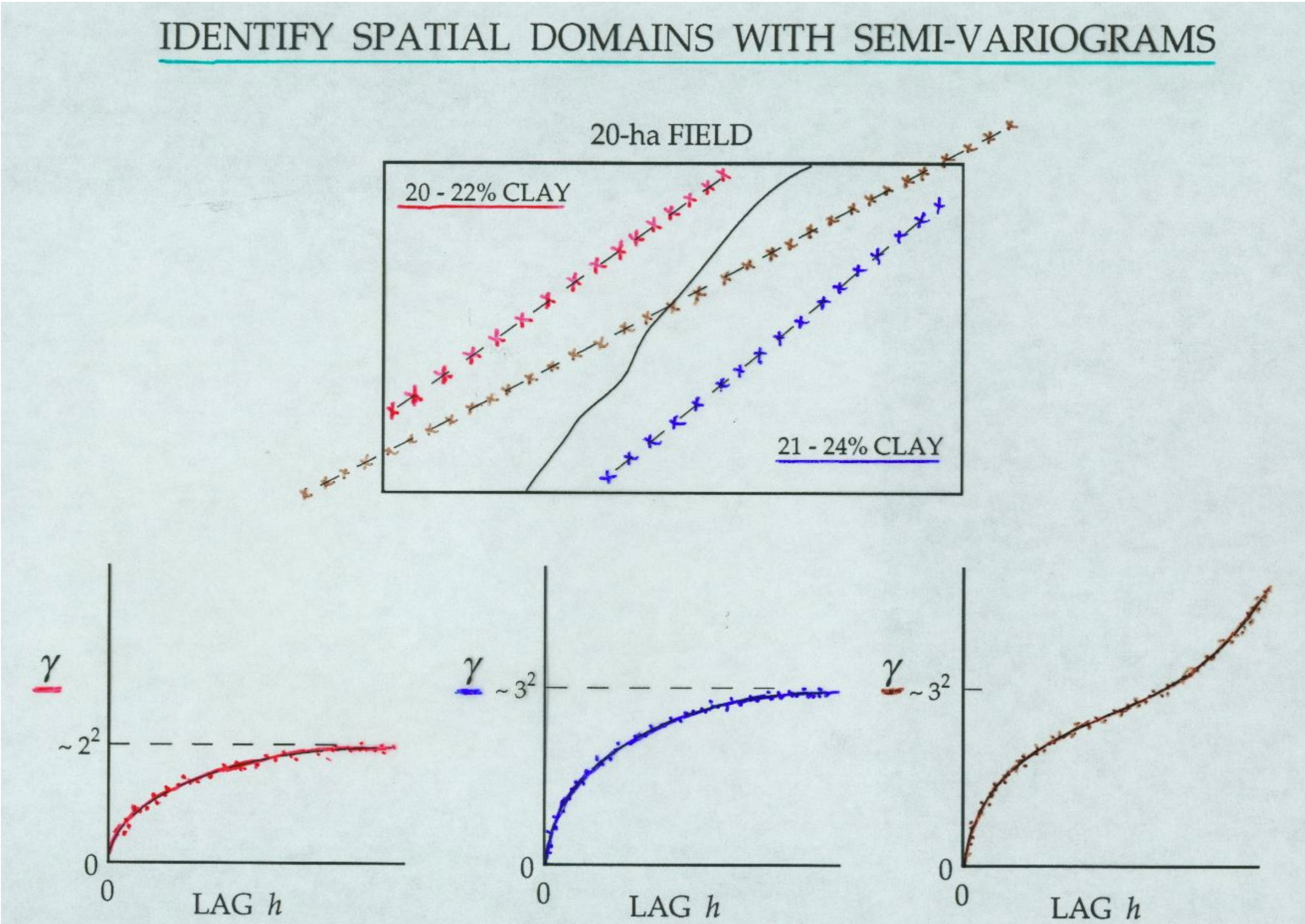


SEMI-VARIOGRAMS

Semivariogram calc



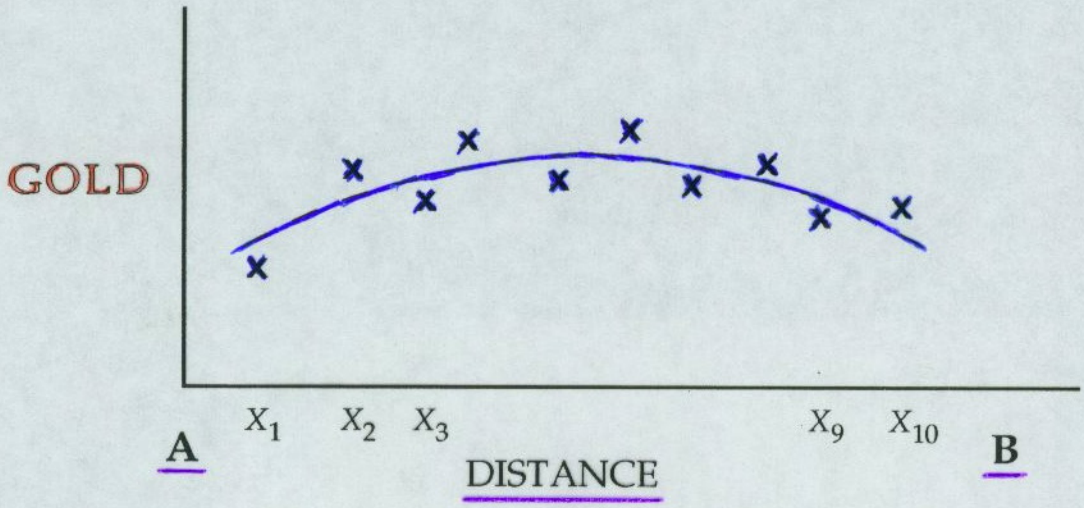
Identifying domains



KRIGING

Interpolating, Kriging

INTERPOLATE WITH SEMI-VARIOGRAMS - KRIGING



CLASSICAL REGRESSION

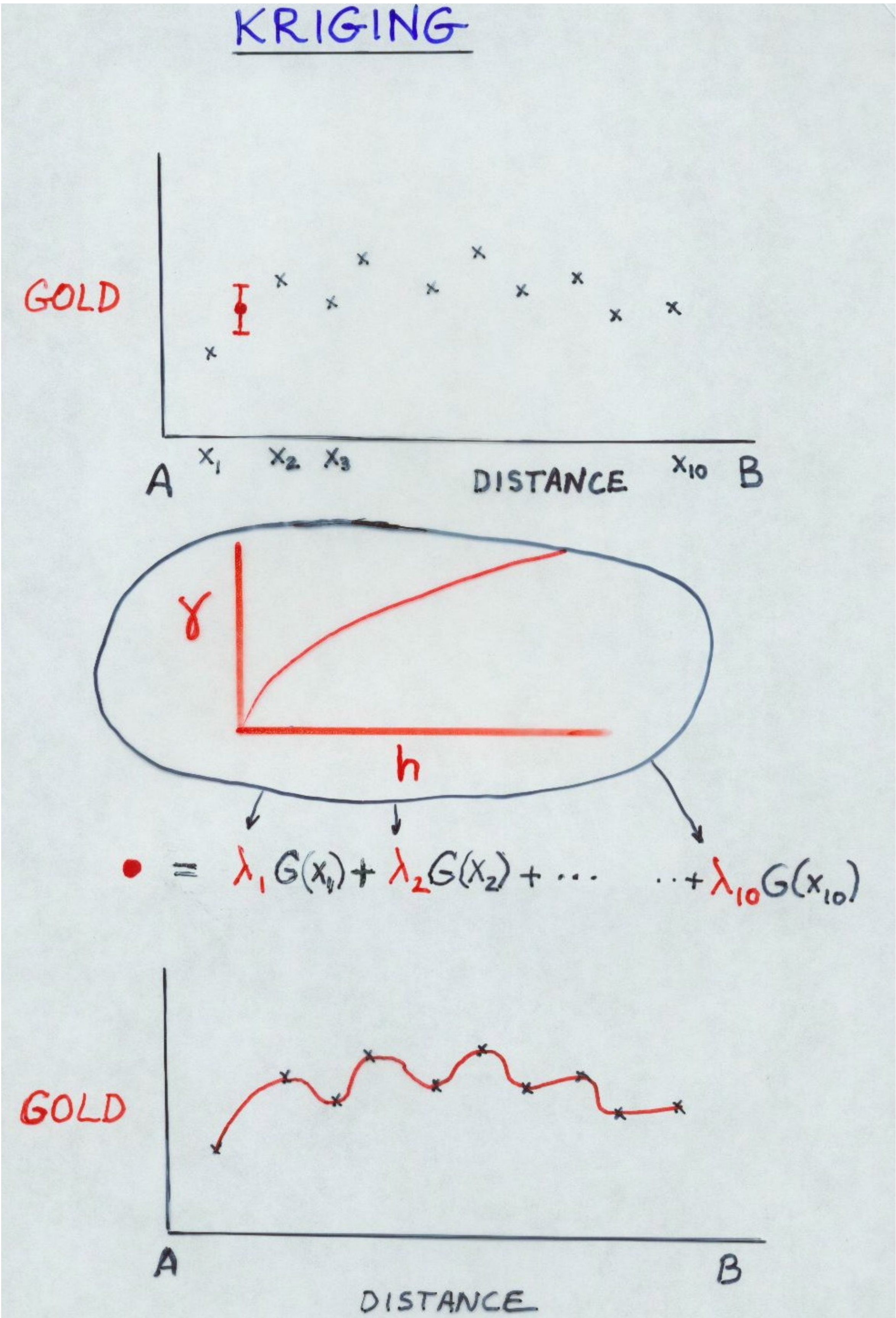
GOLD $= a_0$ $\qquad r = 0.5$

$= a_0 + a_1 x$ $\qquad r = 0.7$

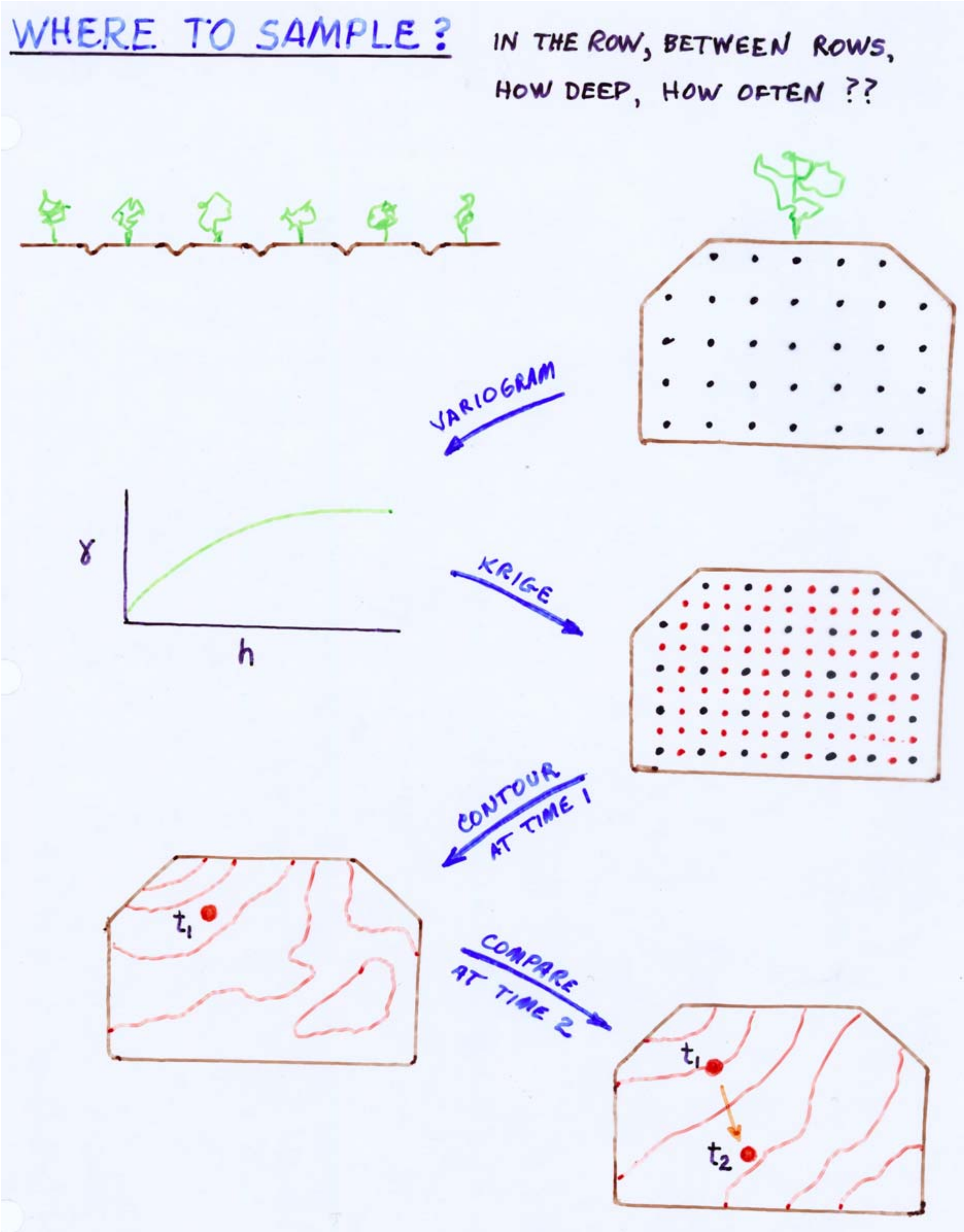
$= a_0 + a_1 x + a_2 x^2$ $\qquad r = 0.9$

$= a_0 + a_1 x + a_2 x^2 + \ldots \quad + a_9 x^9$ $\qquad r = 1$

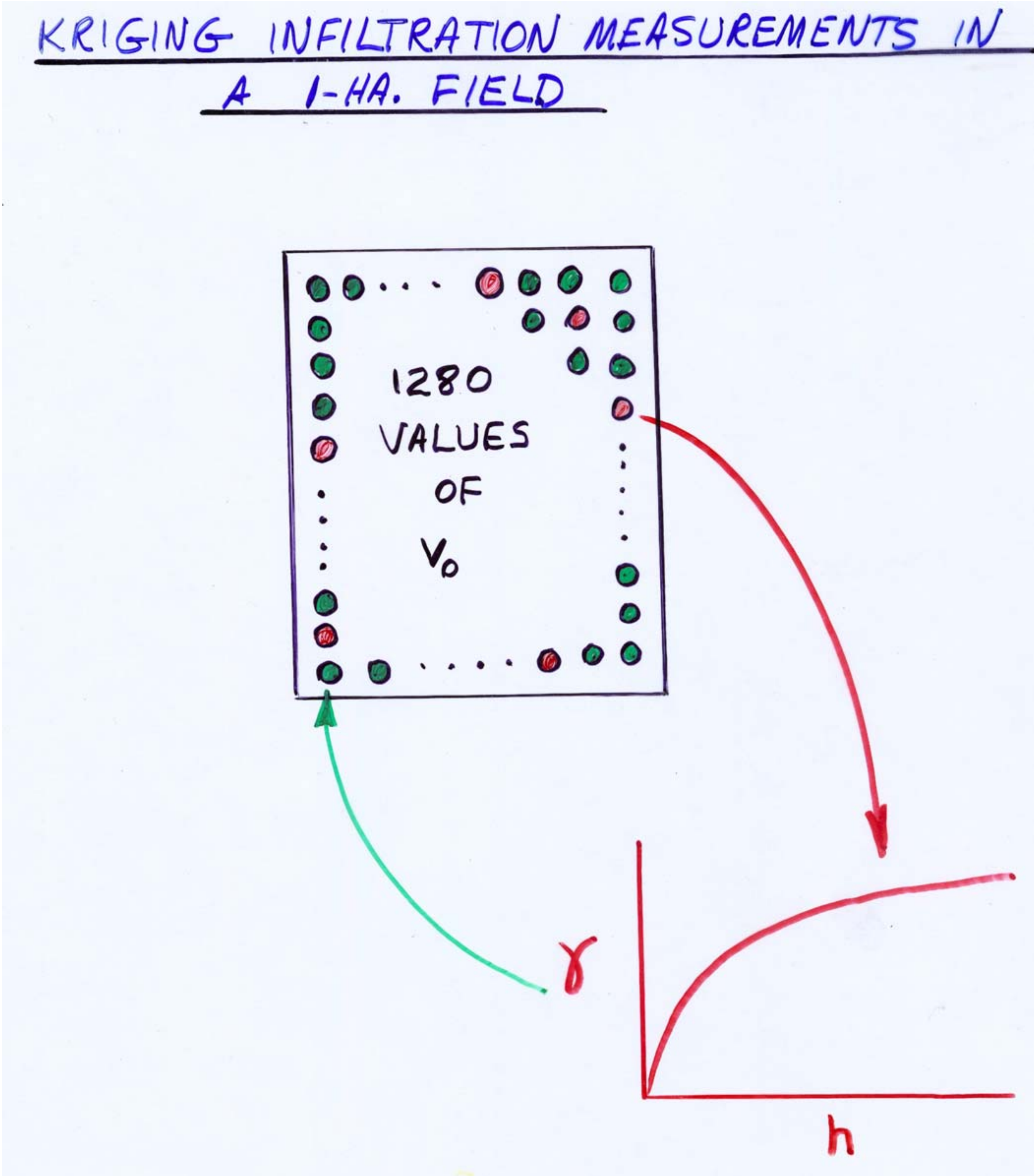
Kriging gold



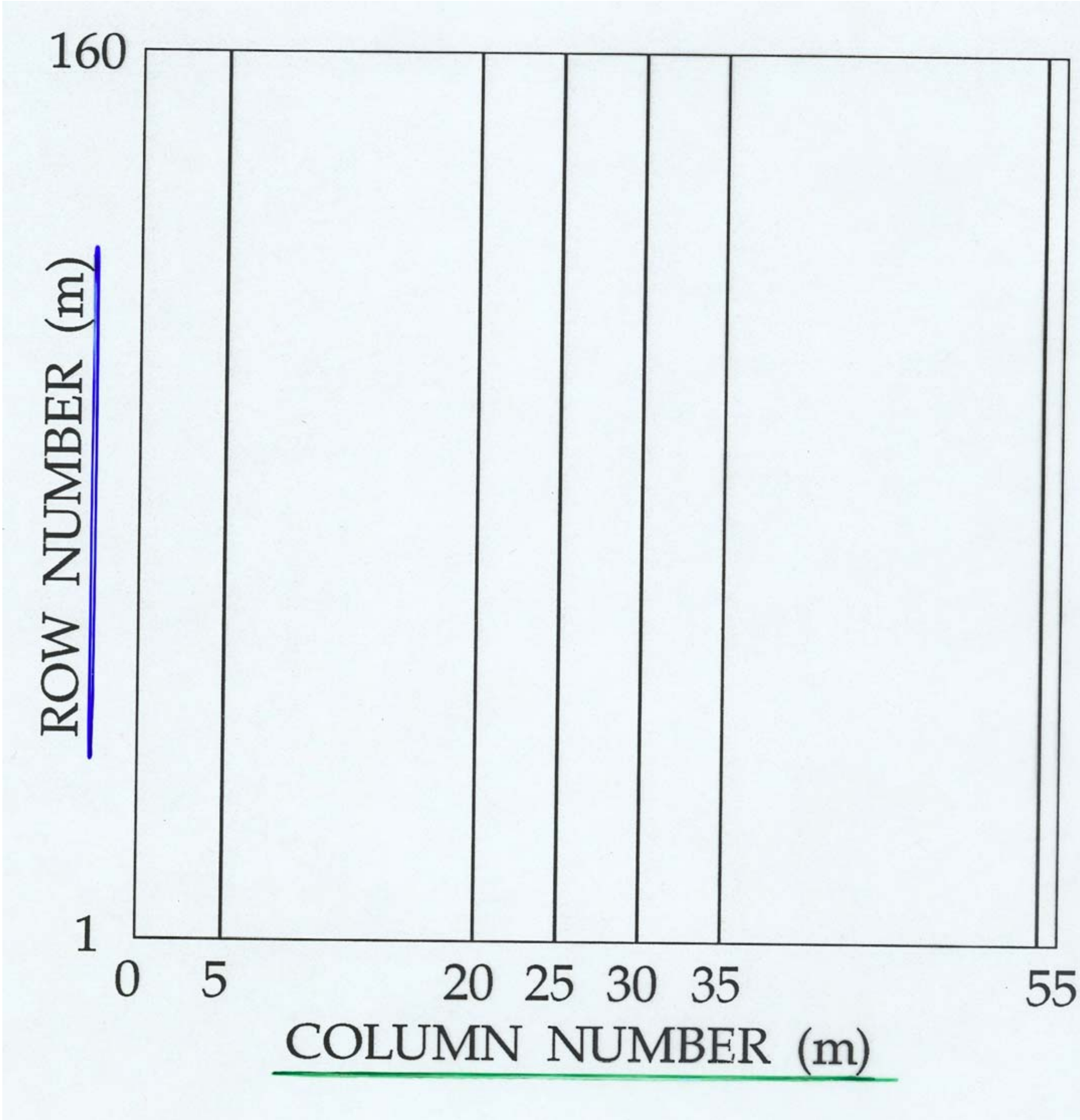
Where to sample in and between rows



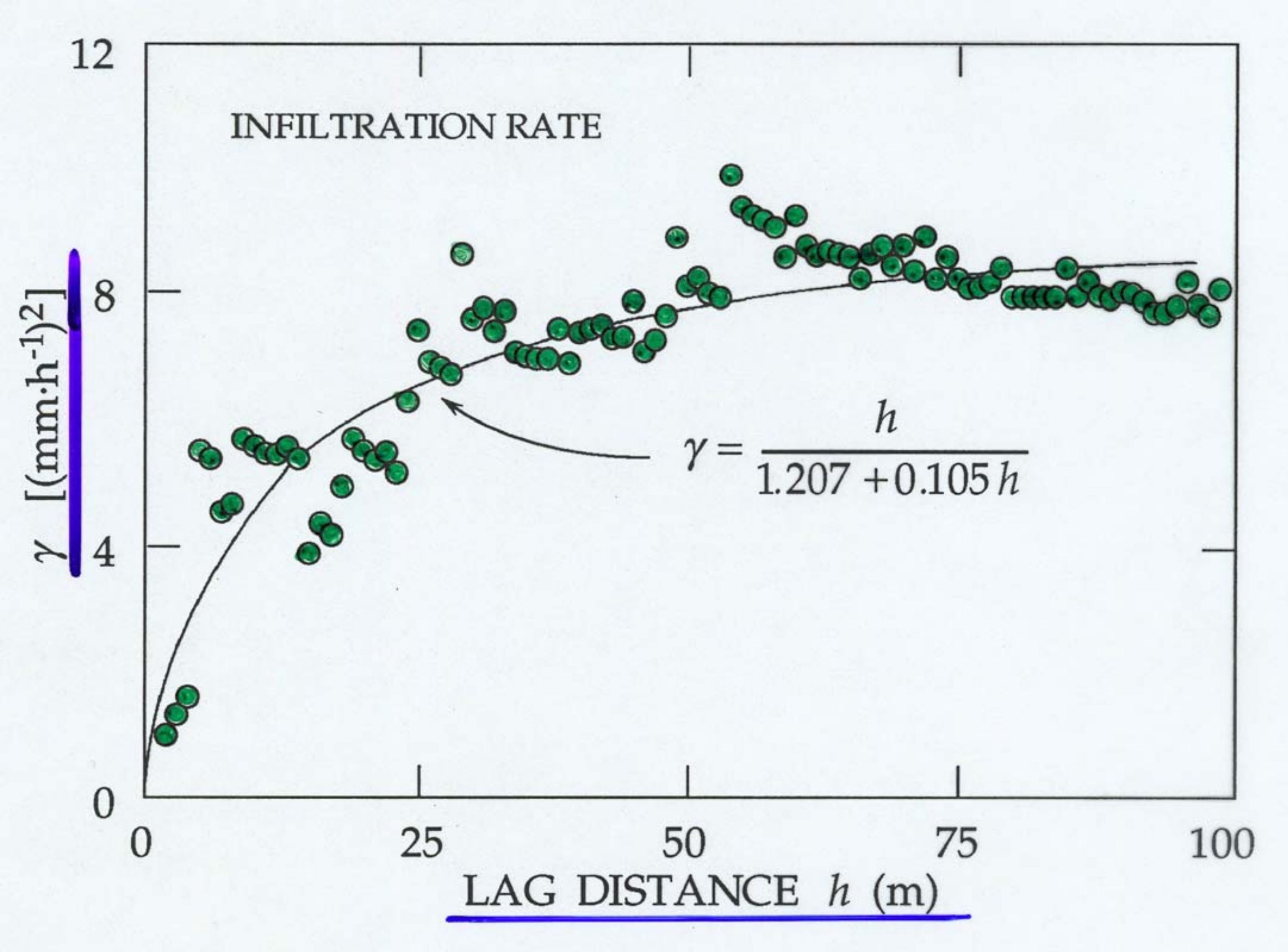
1280 infiltration measurements



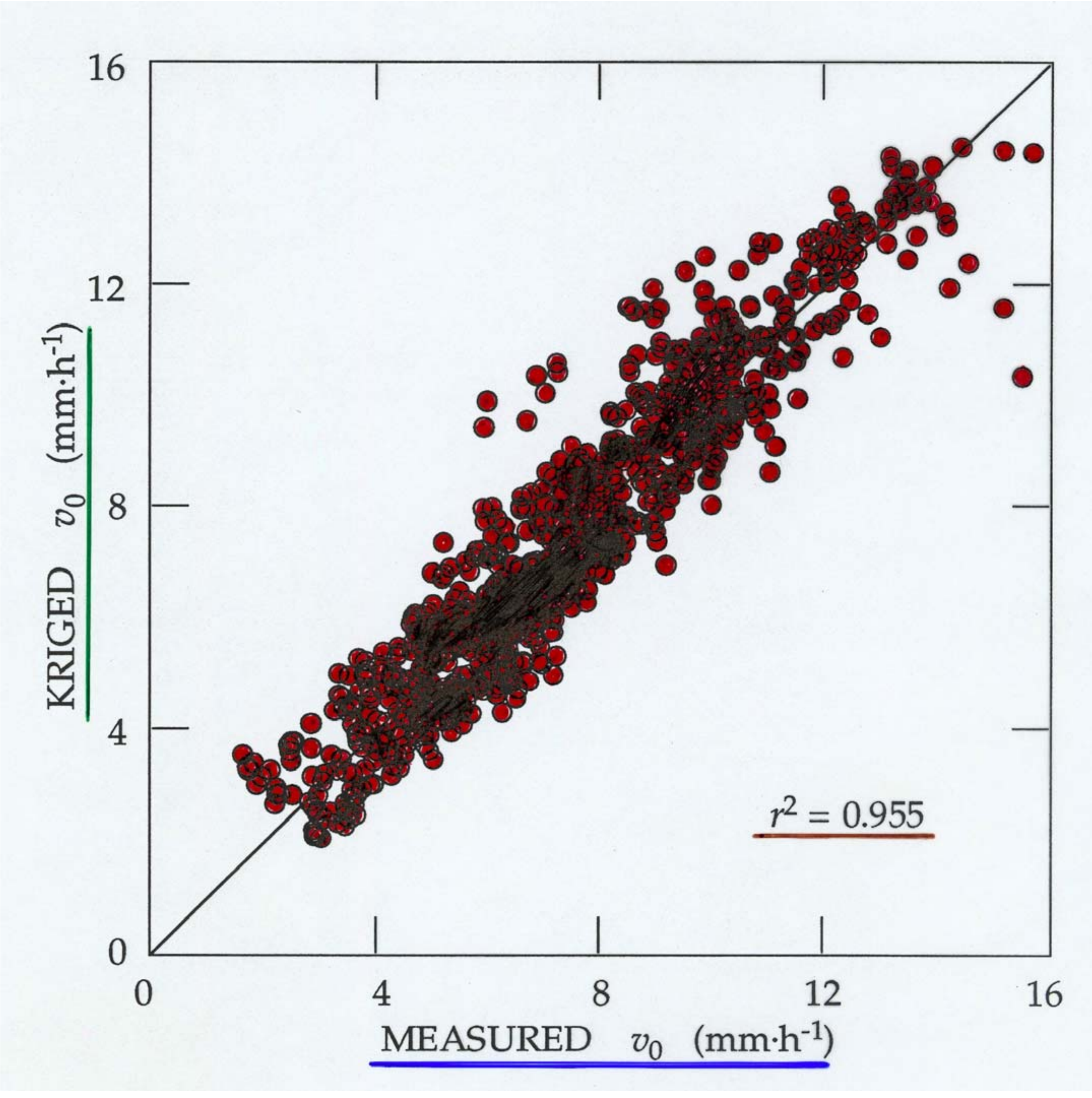
Row & column number



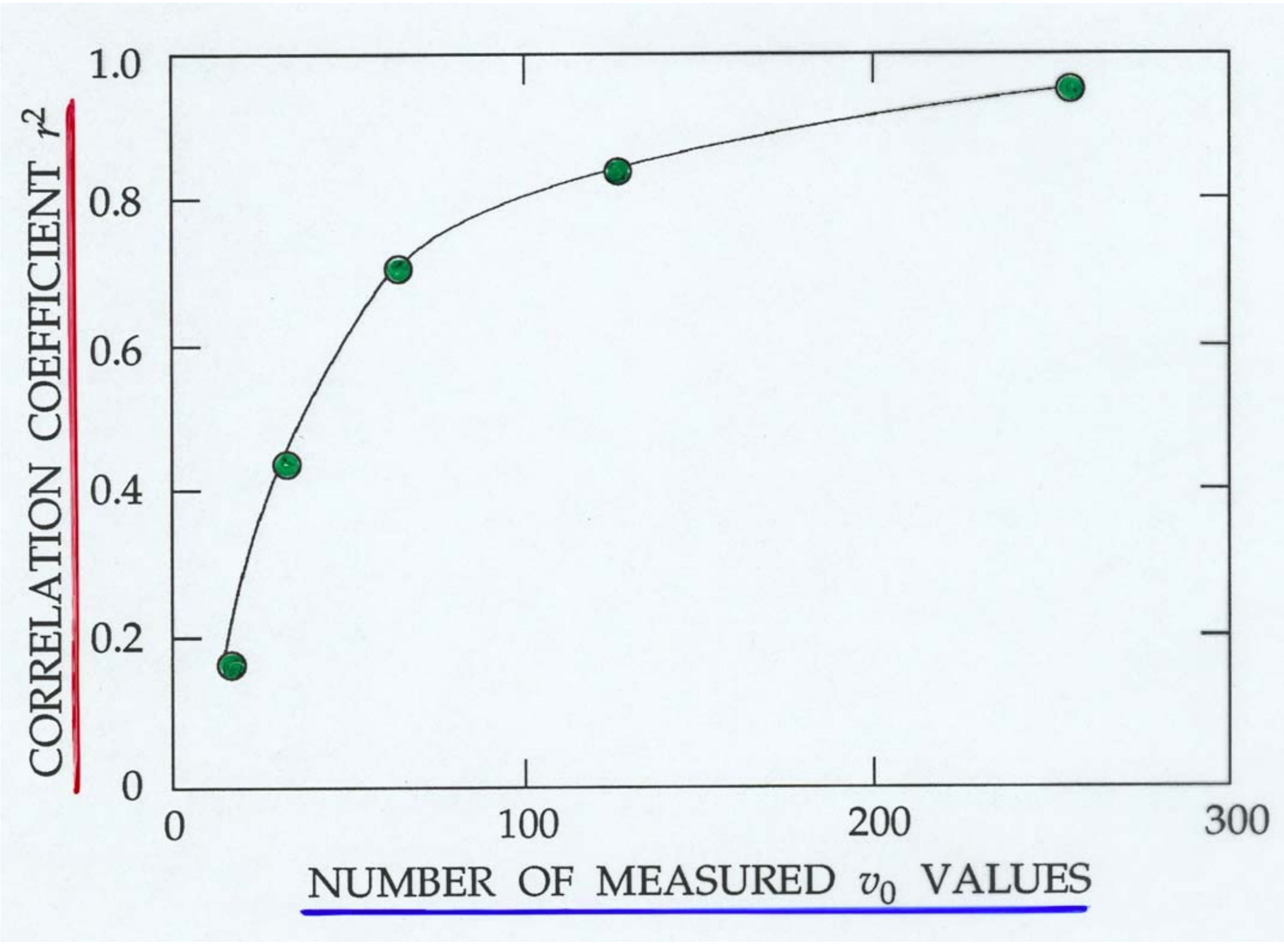
Infilt. rate semivariogram



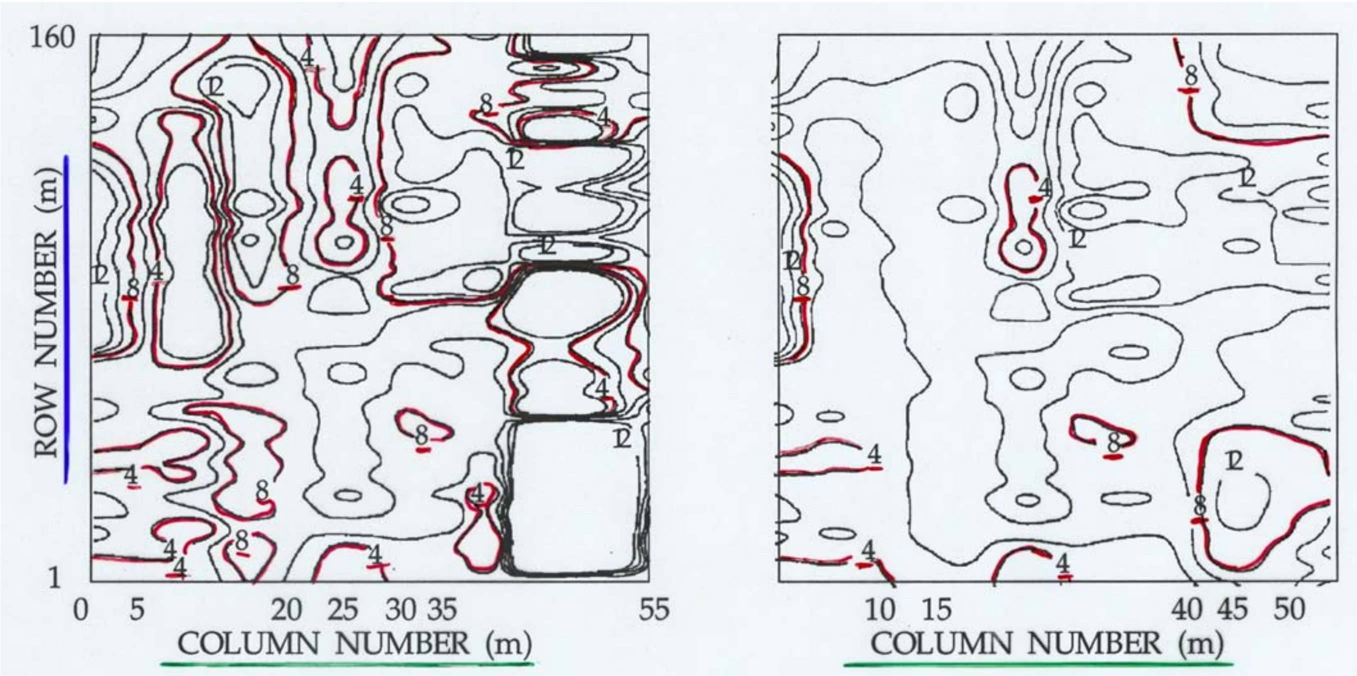
Kriging vs measured v0



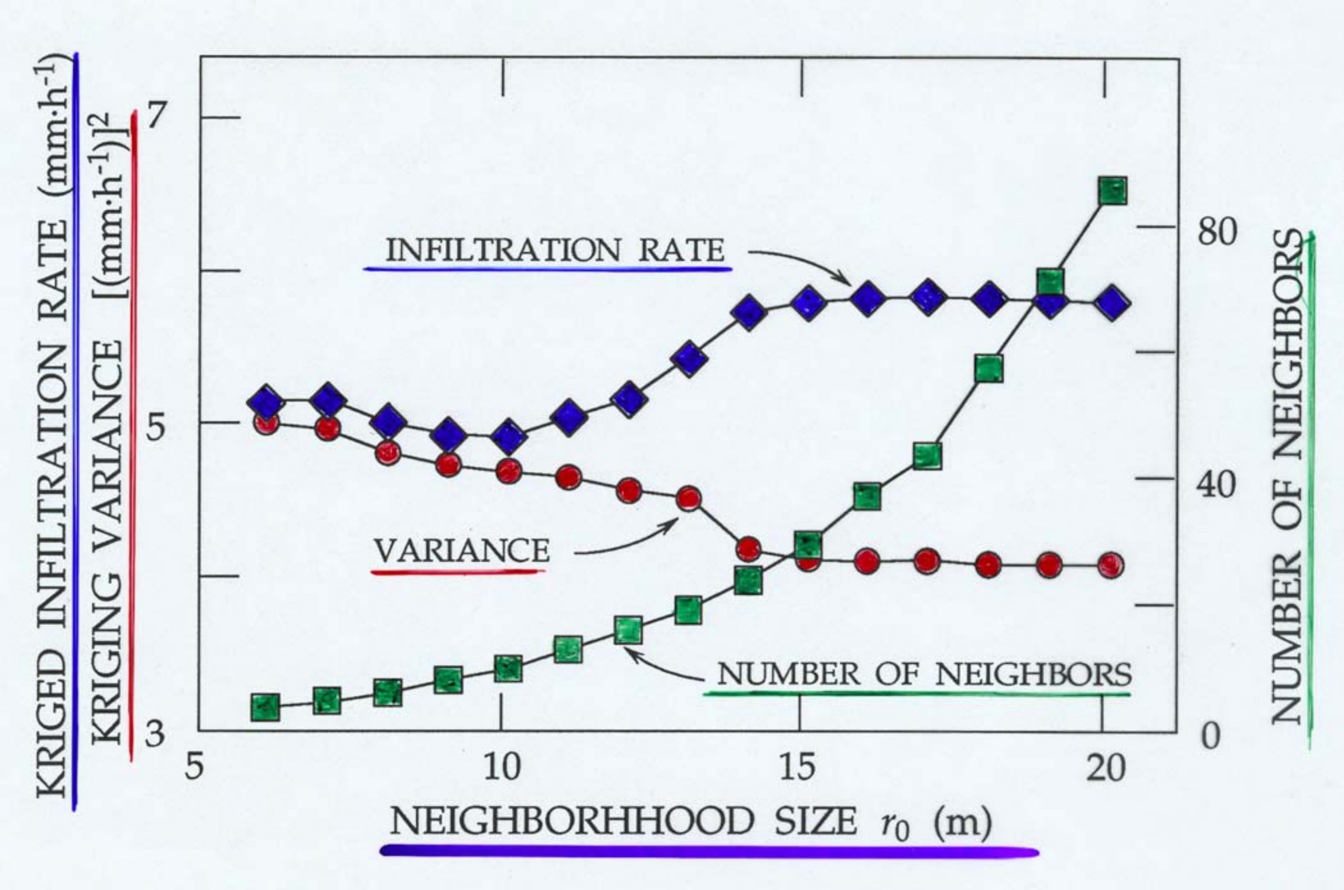
Correl coeff per no. of measurements



Without and with 800 kriged values using same degree polynomial

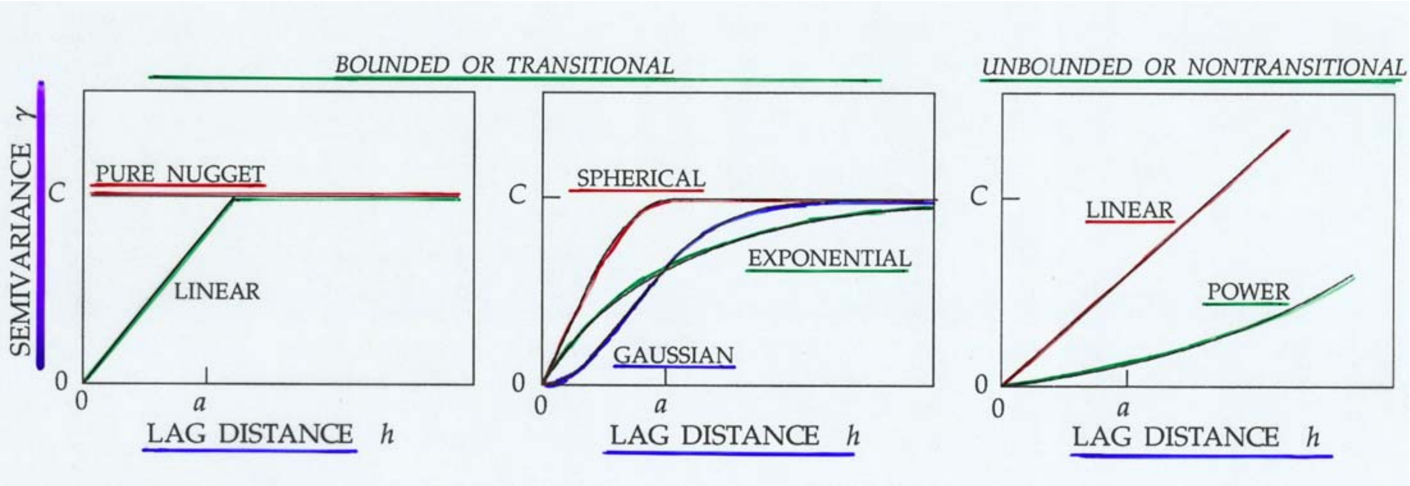


infilt rate-neighborhood size



SEMI-VARIOGRAMS

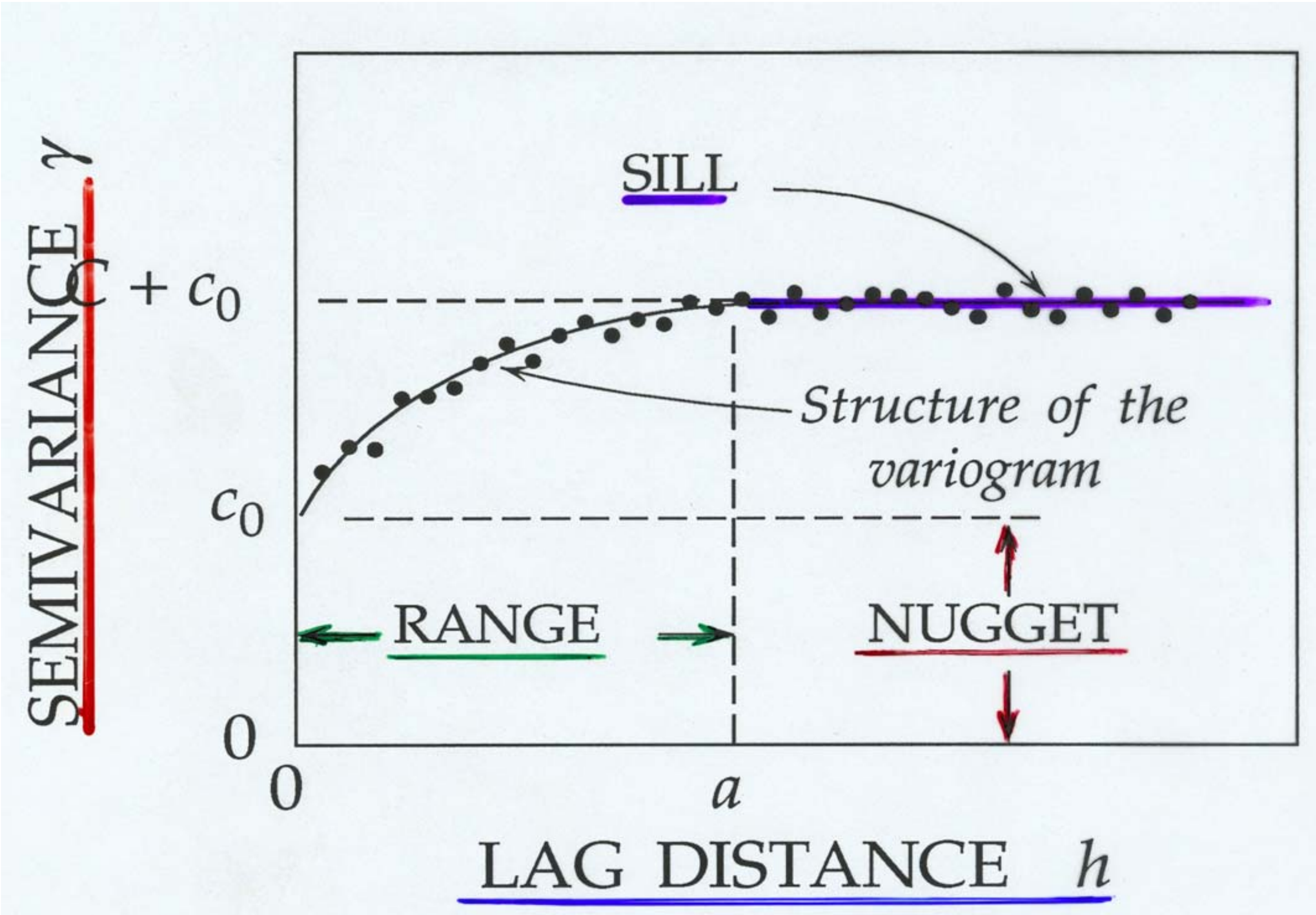
Bounded & unbounded semivariograms



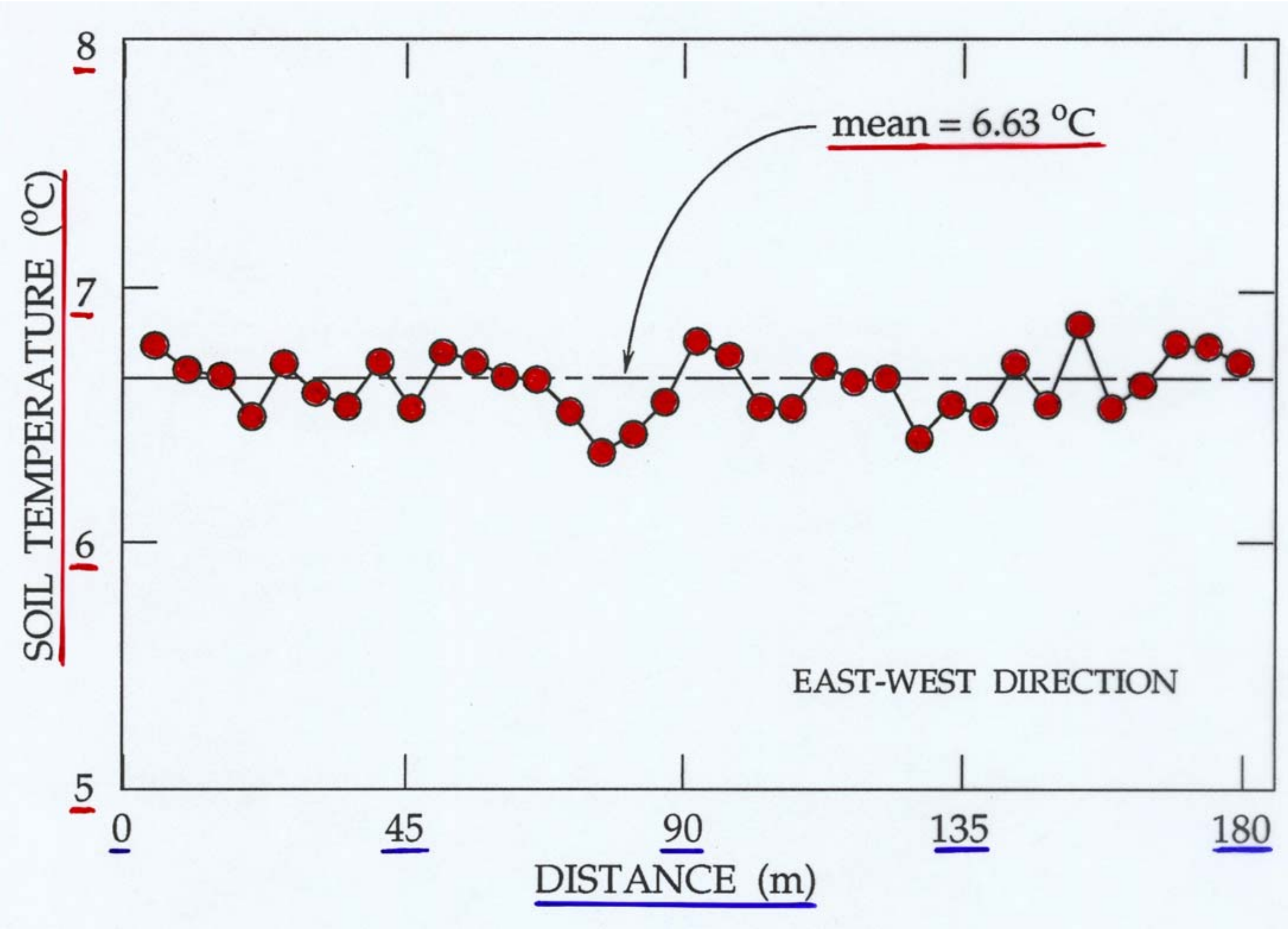
Variogram equations

Model	Equation	Consideration
	Bounded or Transitional	
Pure nugget	$\gamma(h)=\begin{cases}0\\C\end{cases}$	$h=0$ $h\geq 1$
Linear	$\gamma(h)=\begin{cases}Ch/a\\C\end{cases}$	$0\leq h\leq a$ $h>a$
Spherical	$\gamma(h)=\begin{cases}C\left[\frac{3h}{2a}-\frac{1}{2}\left(\frac{h}{a}\right)^3\right]\\C\end{cases}$	$0\leq h\leq a$ $h>a$
Exponential	$\gamma(h)=C[1-\exp(-h/a)]$	$h\geq 0$
Gaussian	$\gamma(h)=C\{1-\exp[-(h/a)^2]\}$	$h\geq 0$
	Unbounded or Nontransitional	
Linear	$\gamma(h)=mh$	$h\geq 0$
Power	$\gamma(h)=\mathrm{m}h^{\beta}$	$h\geq 0; 1<\beta<2$

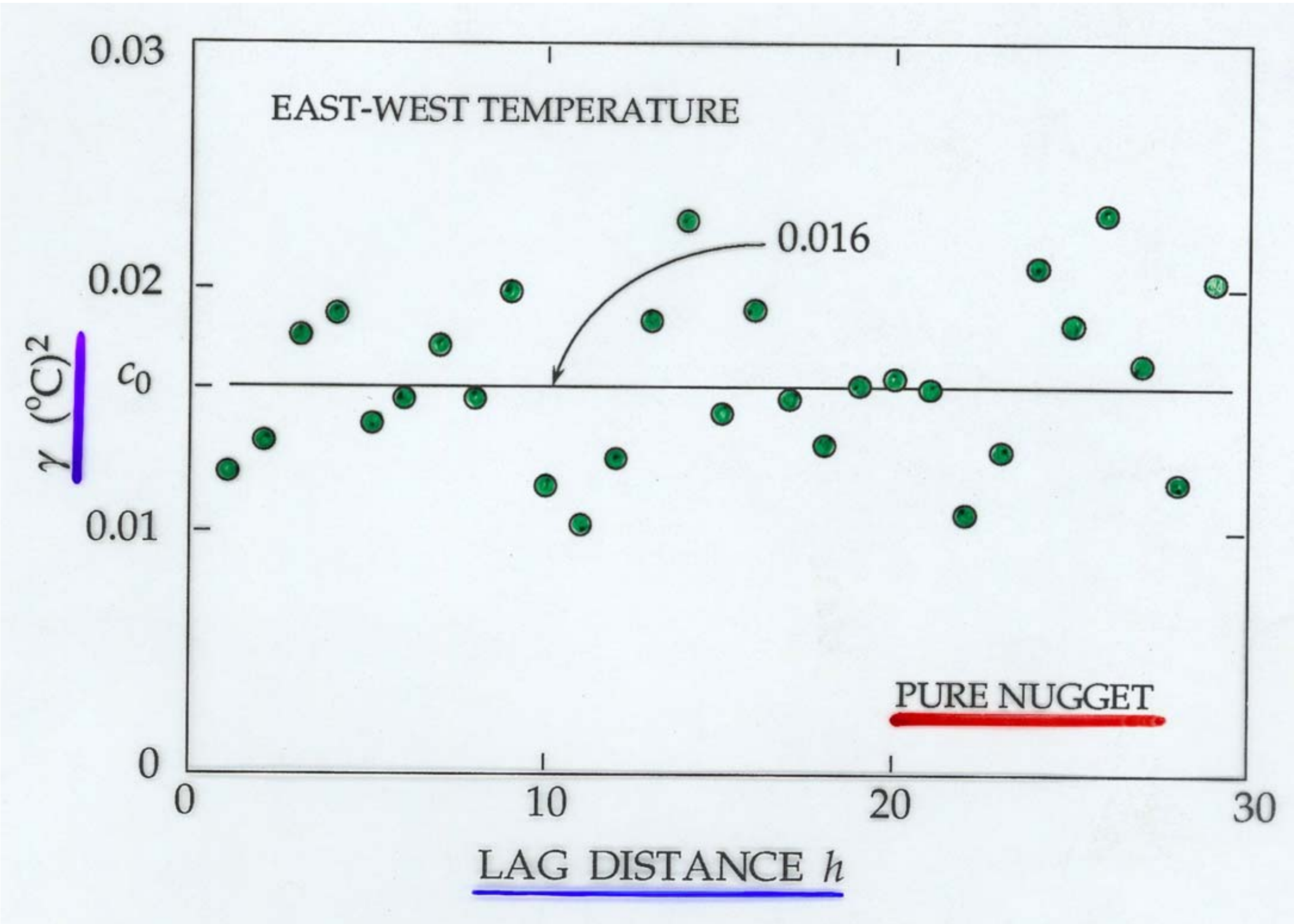
Variogram structure



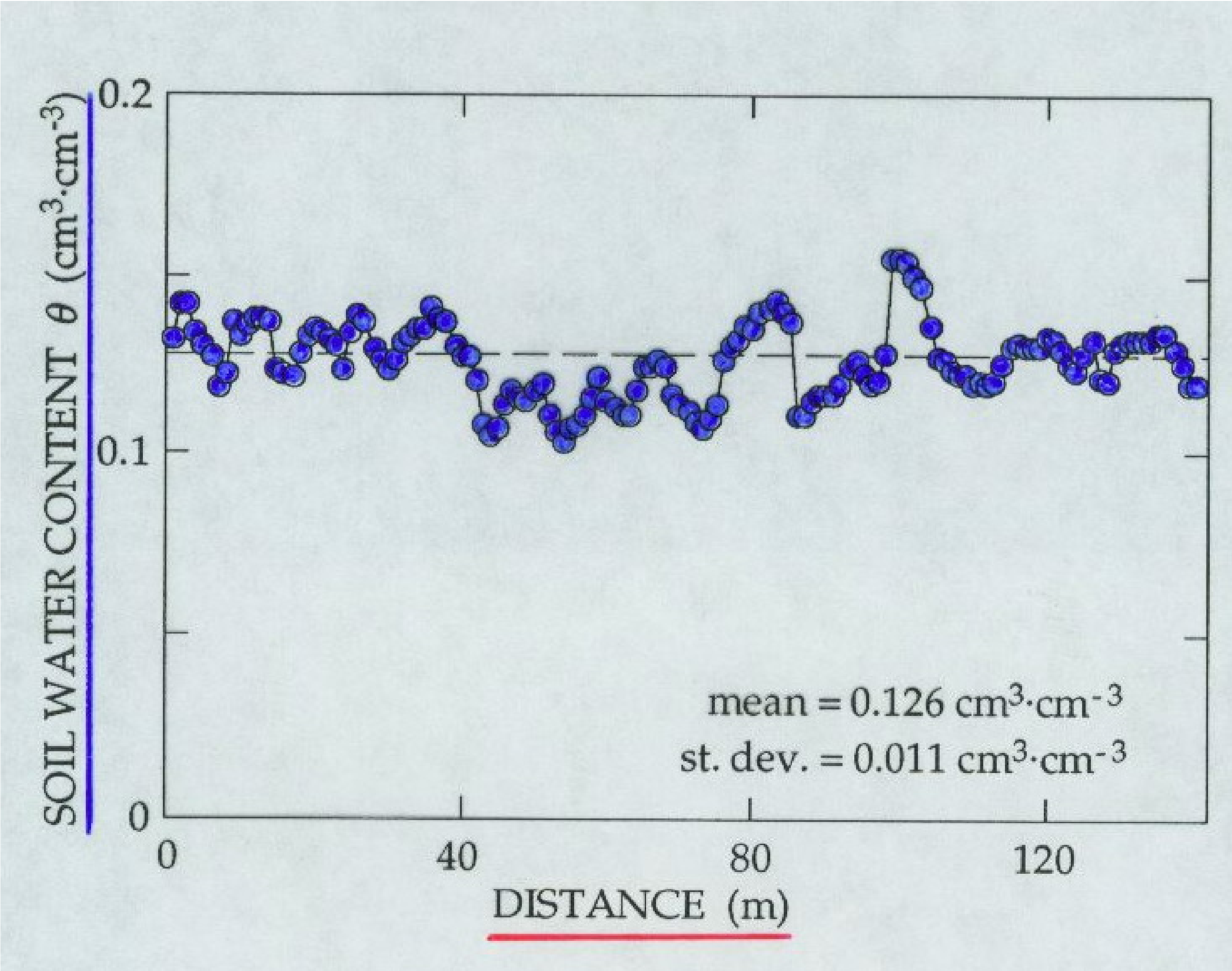
Soil temp vs E-W distance



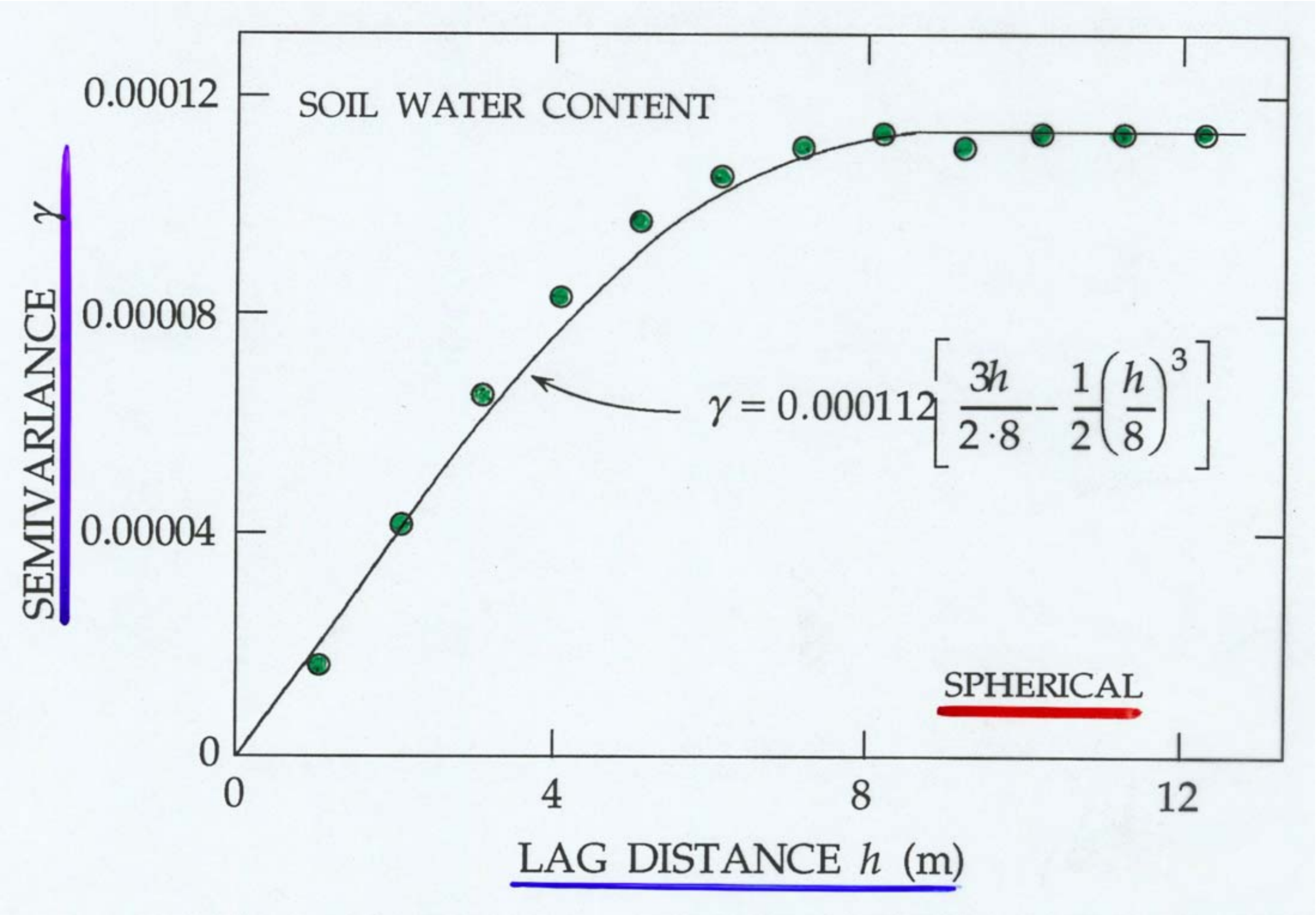
Nugget variogram of E-W temp



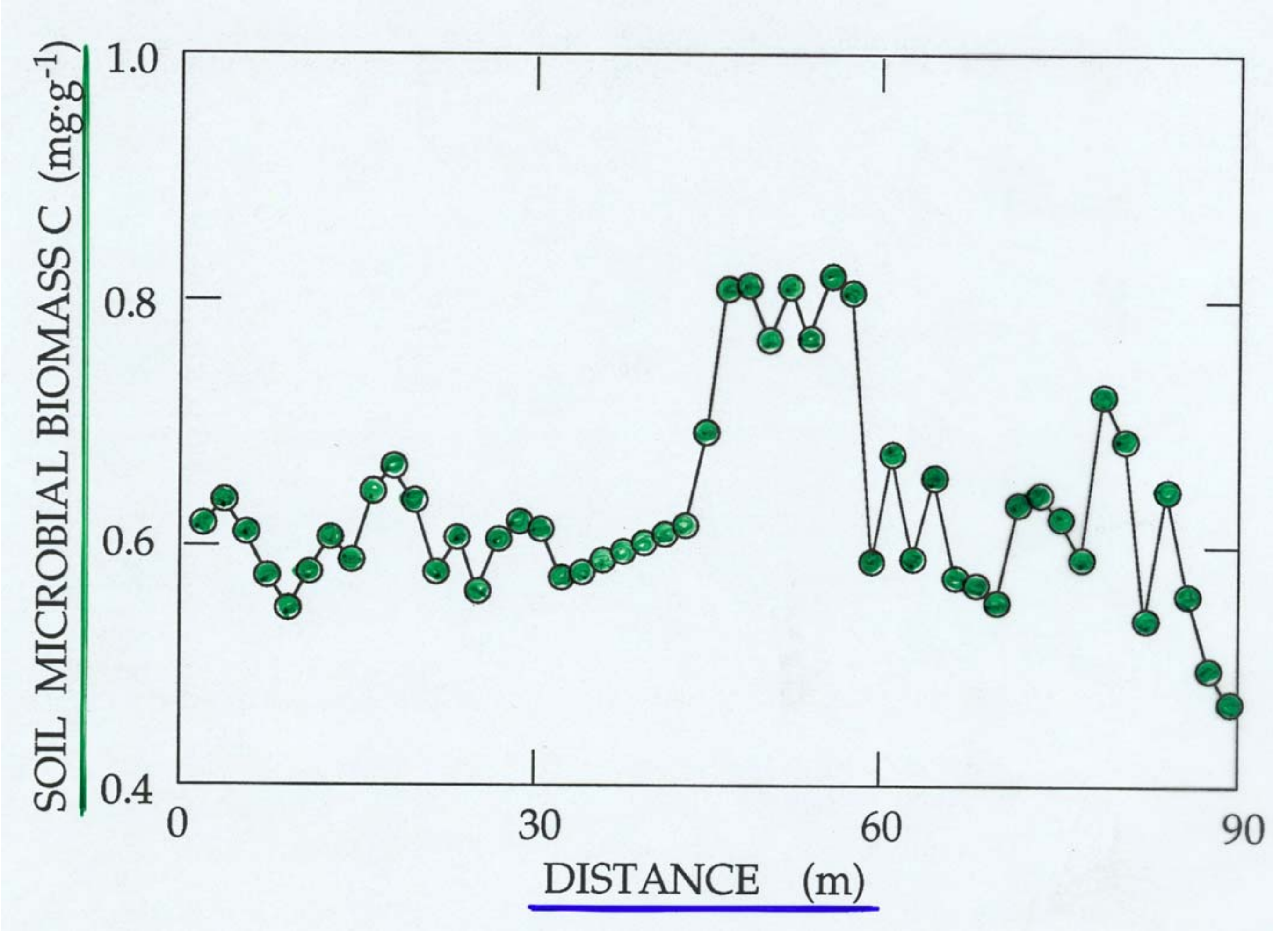
Soil water vs distance



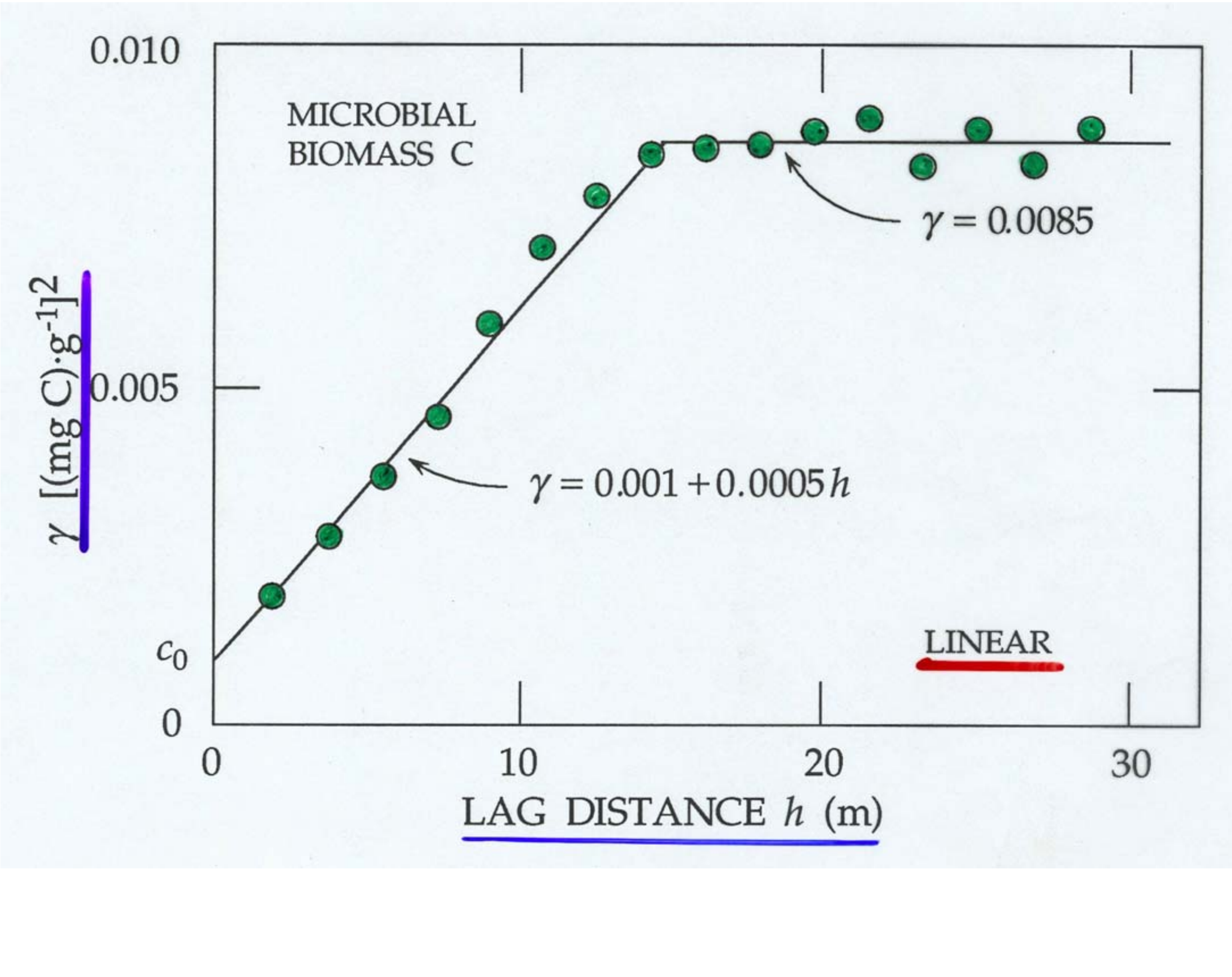
Spherical variogram soil water



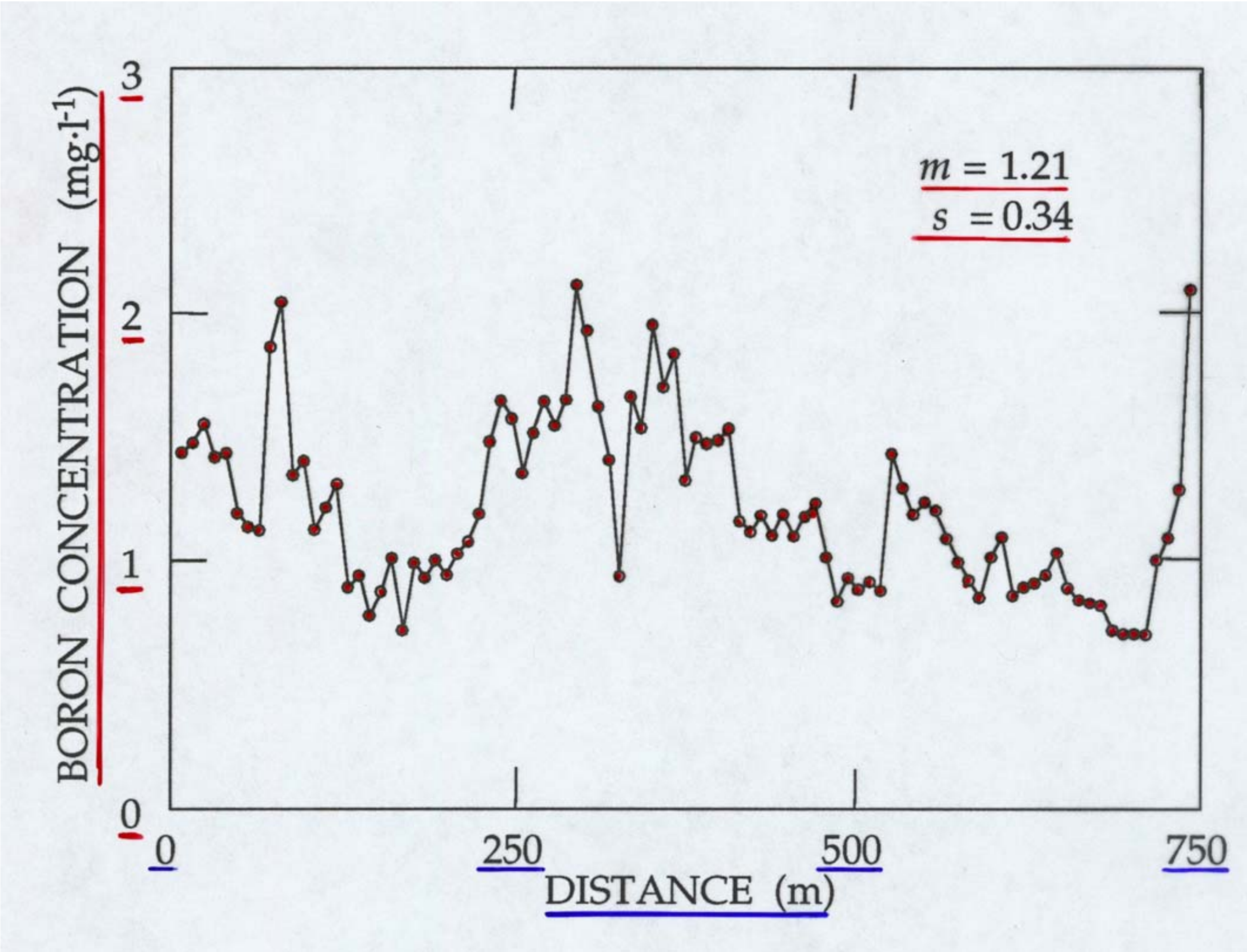
Microbial biomass C vs distance



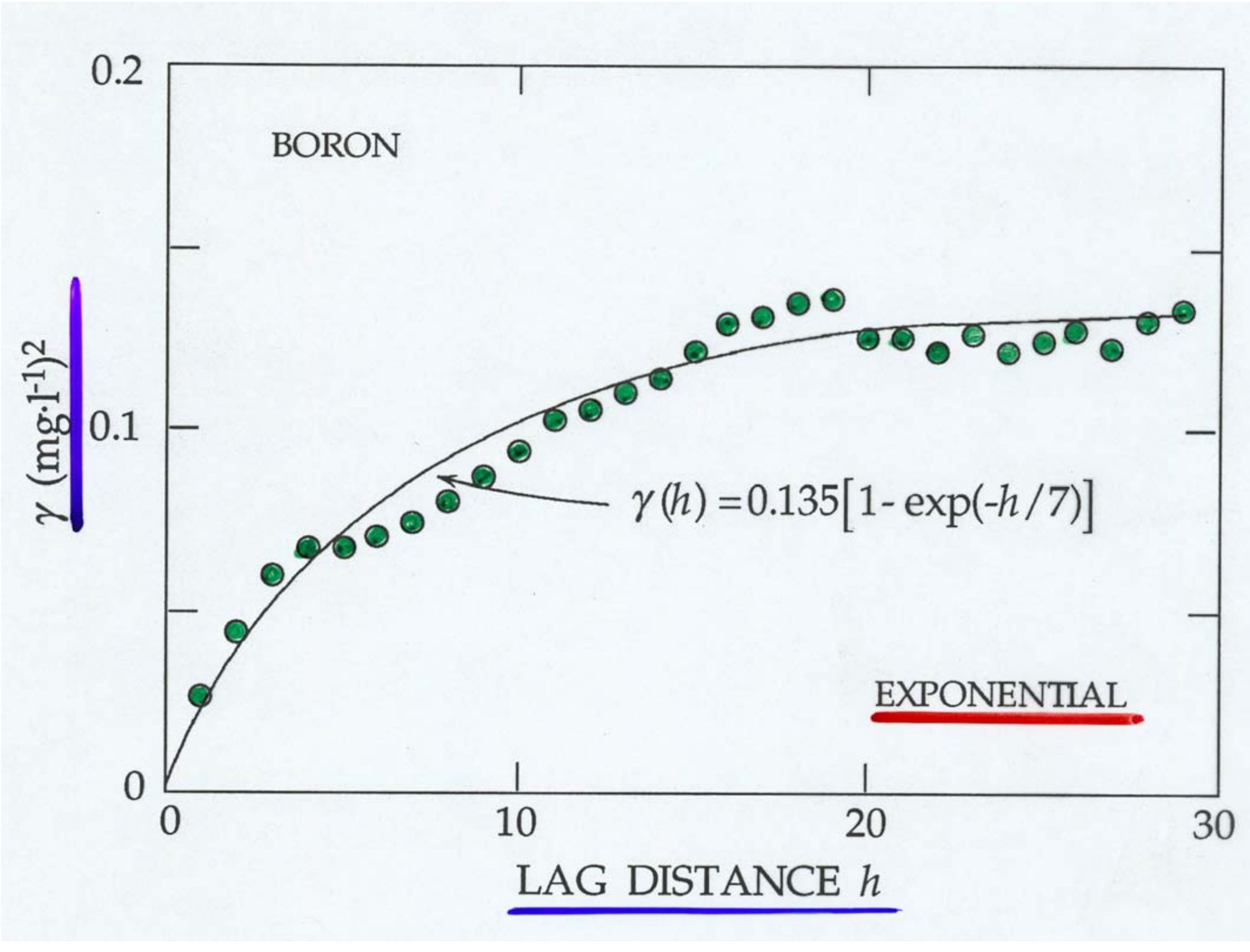
Microbial biomass C variogram



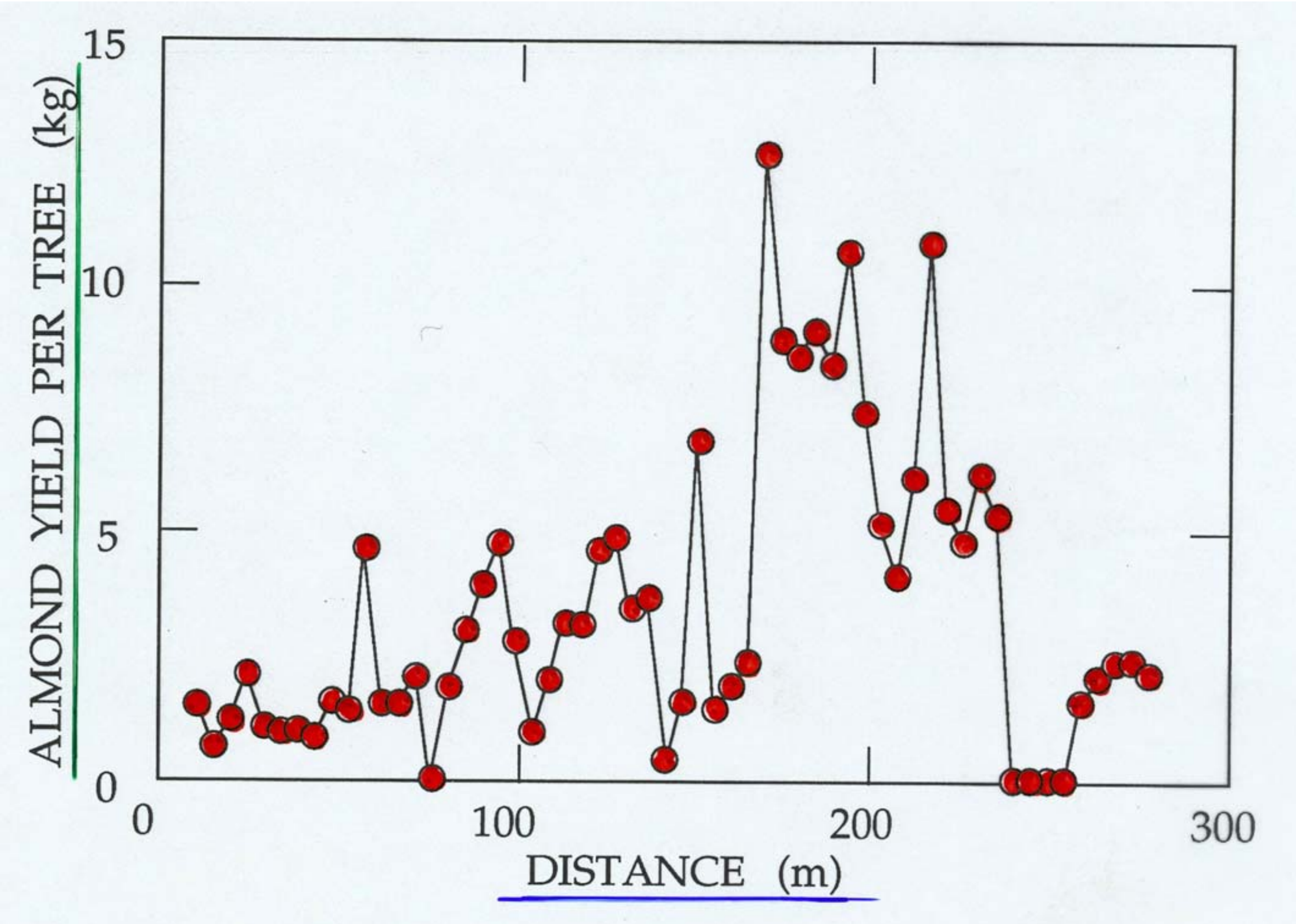
Boron vs distance



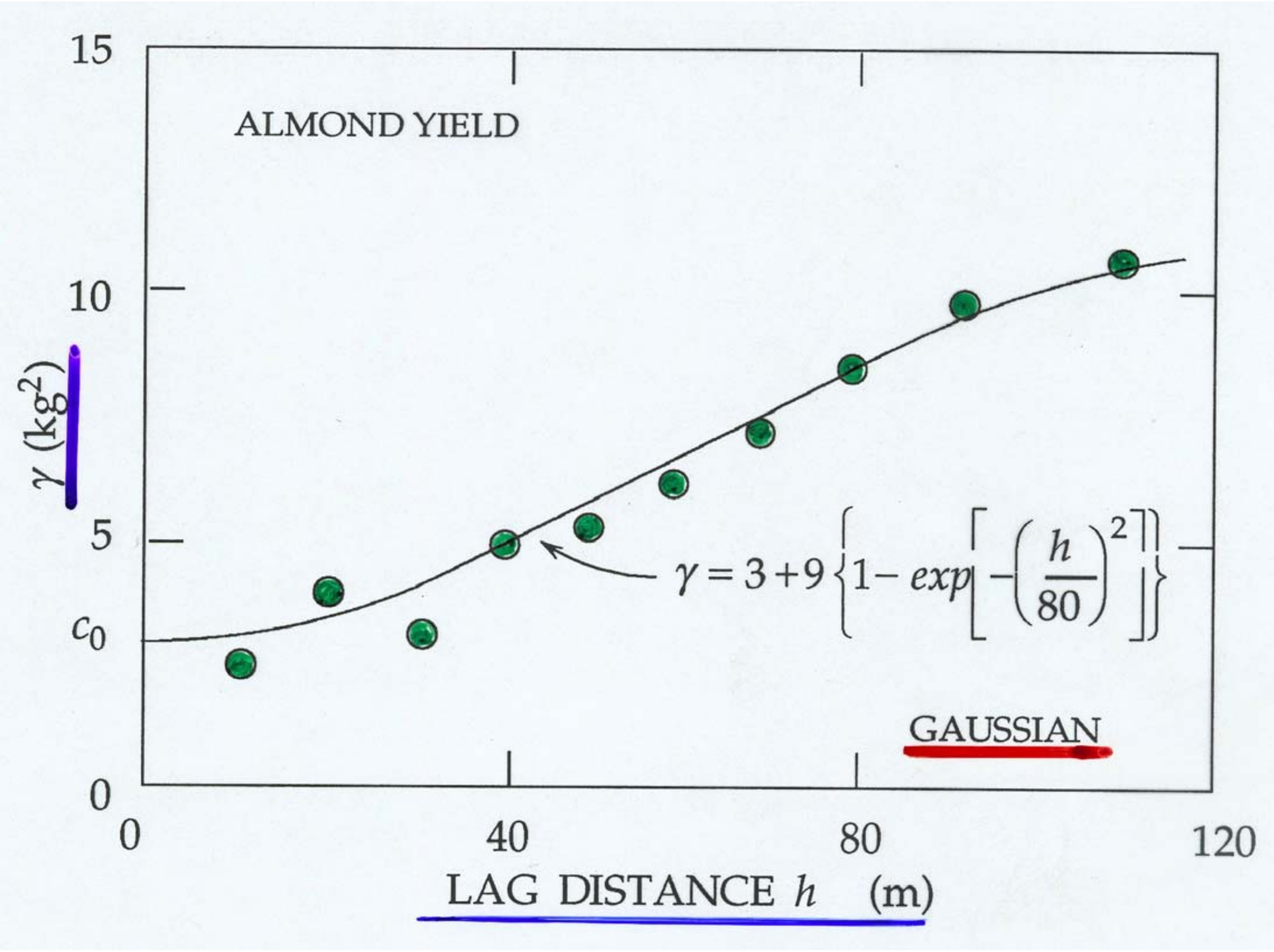
Boron exponential variogram



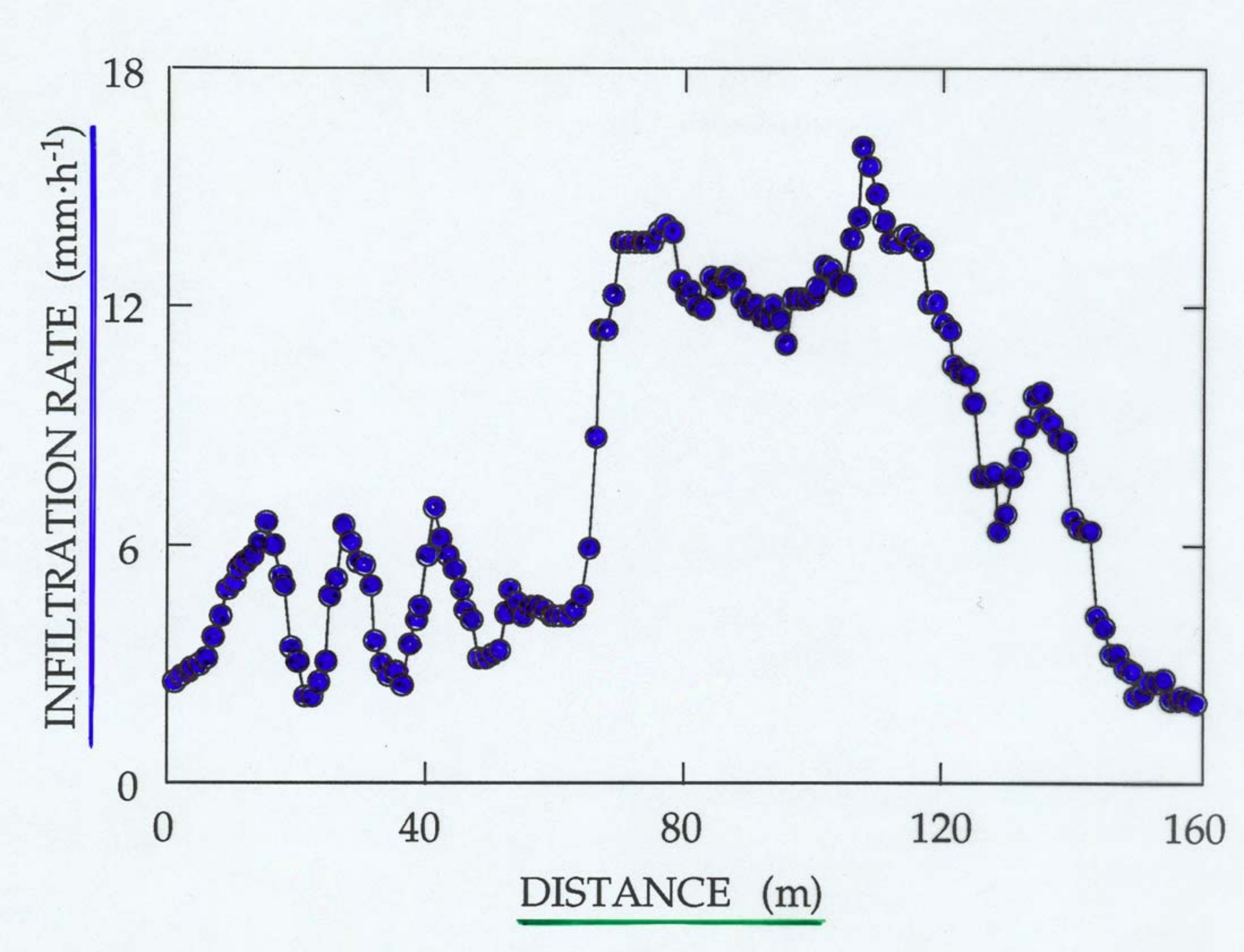
Almond yield per tree vs distance



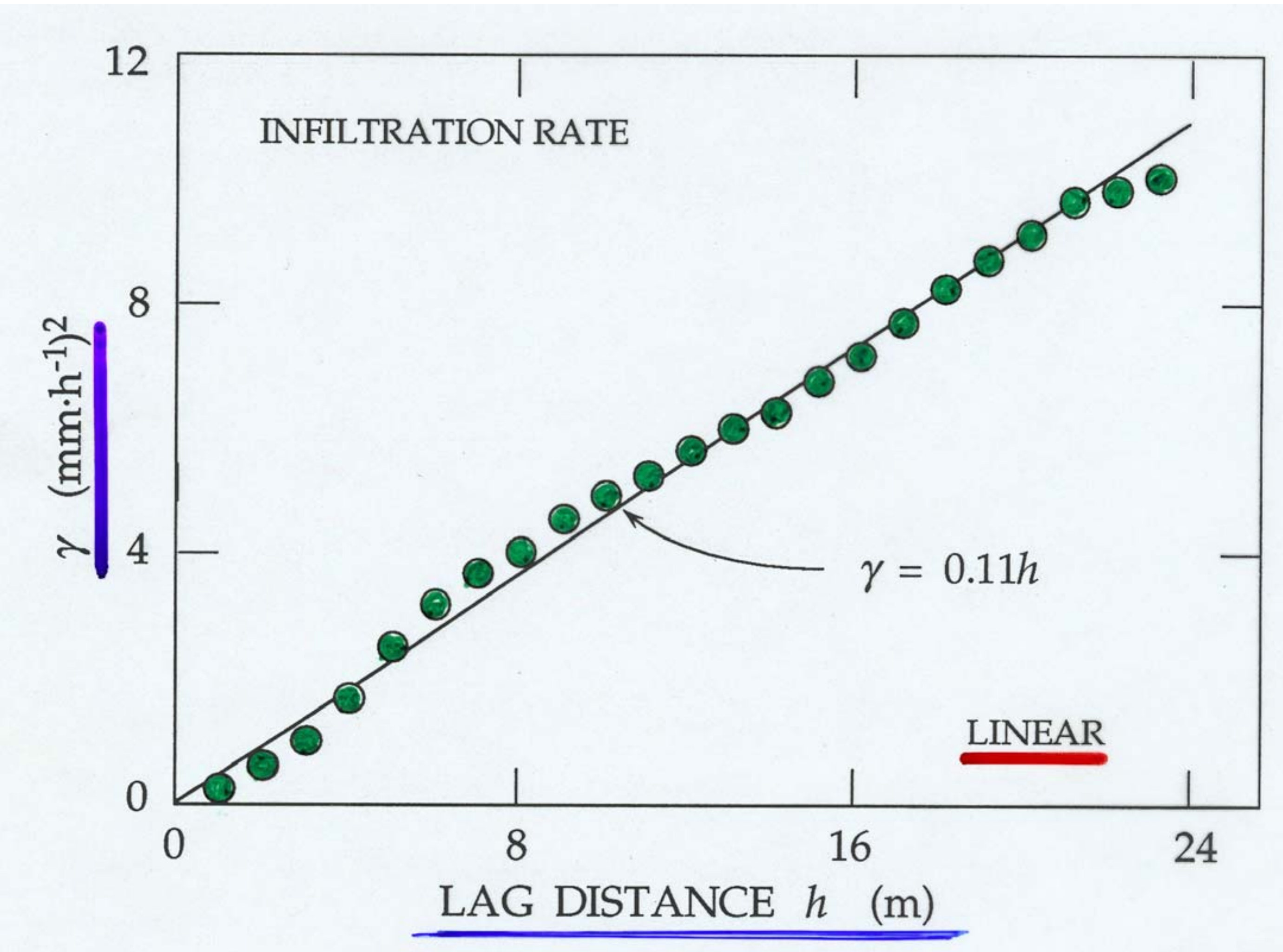
Almond yield Gaussian variogram



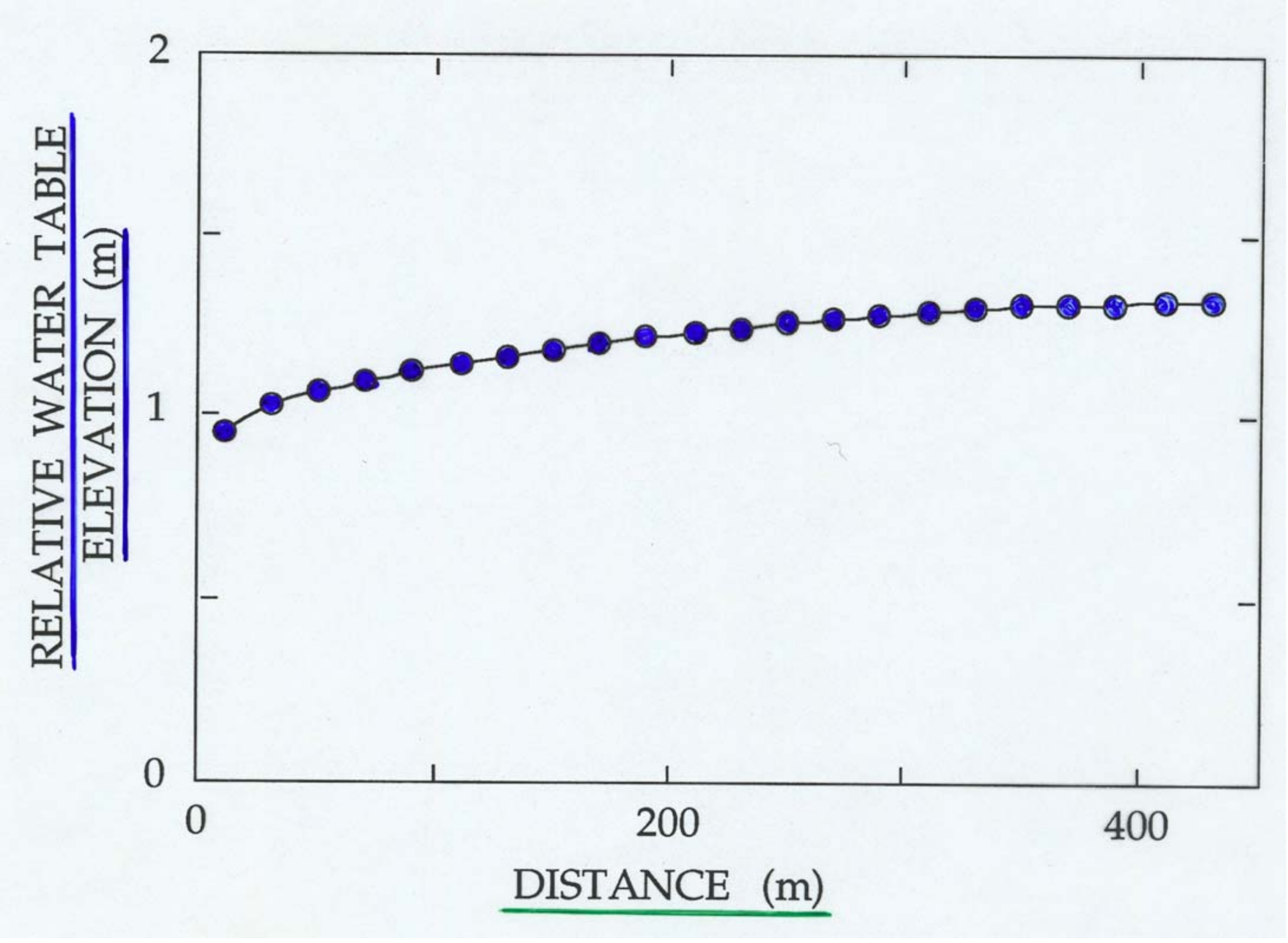
infiltration rate vs distance



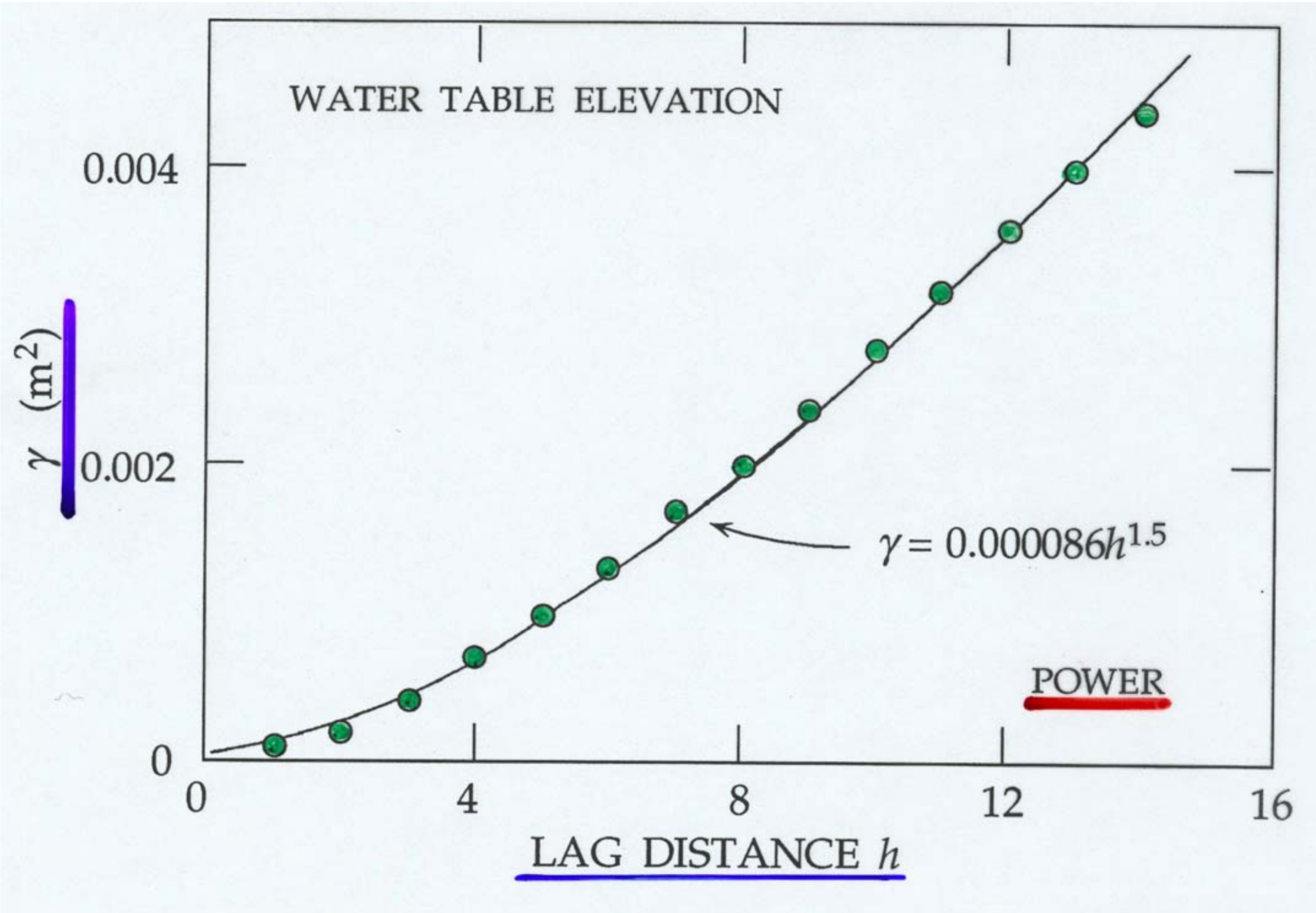
infiltration rate linear variogram



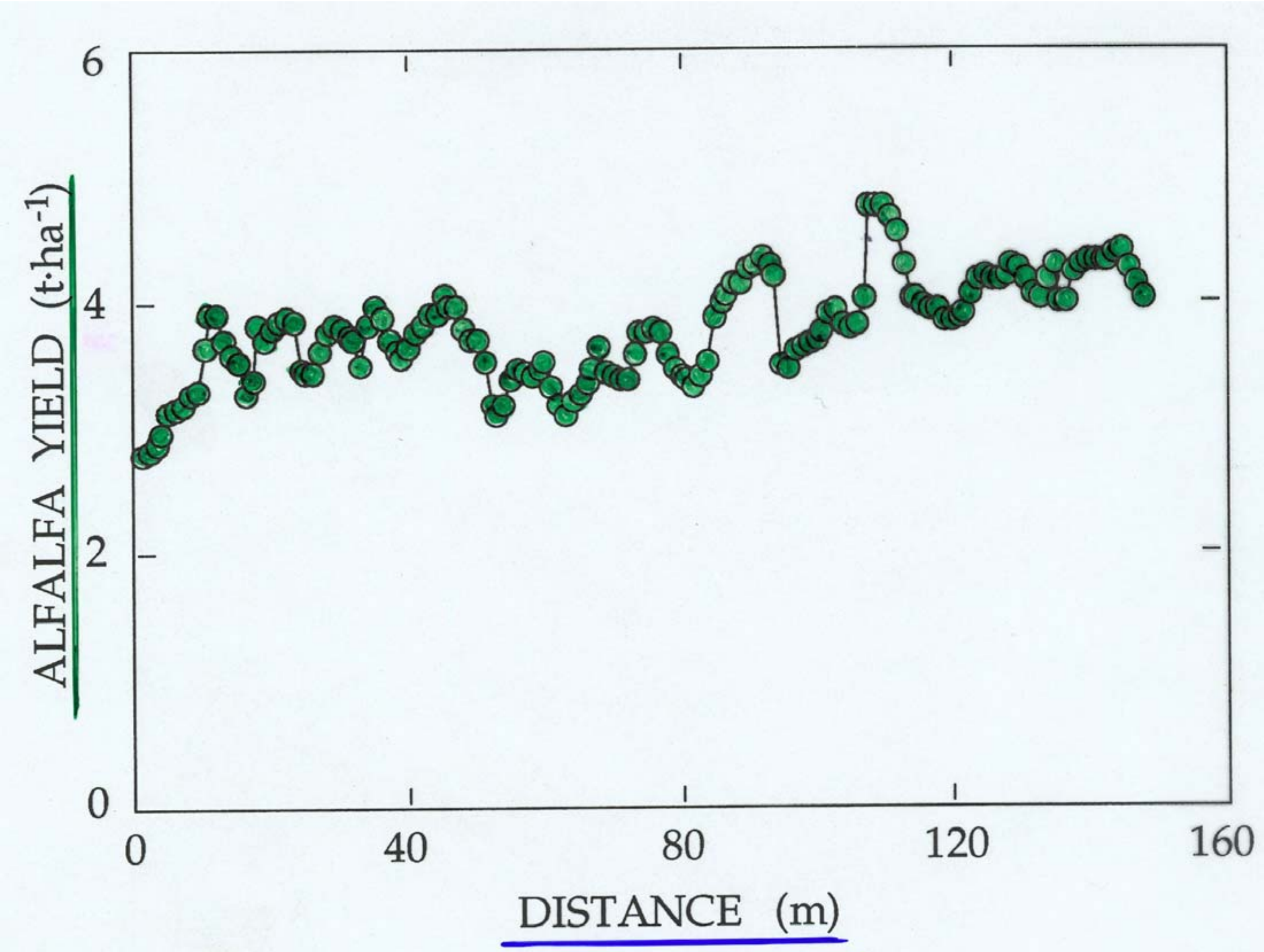
water table elevation vs distance



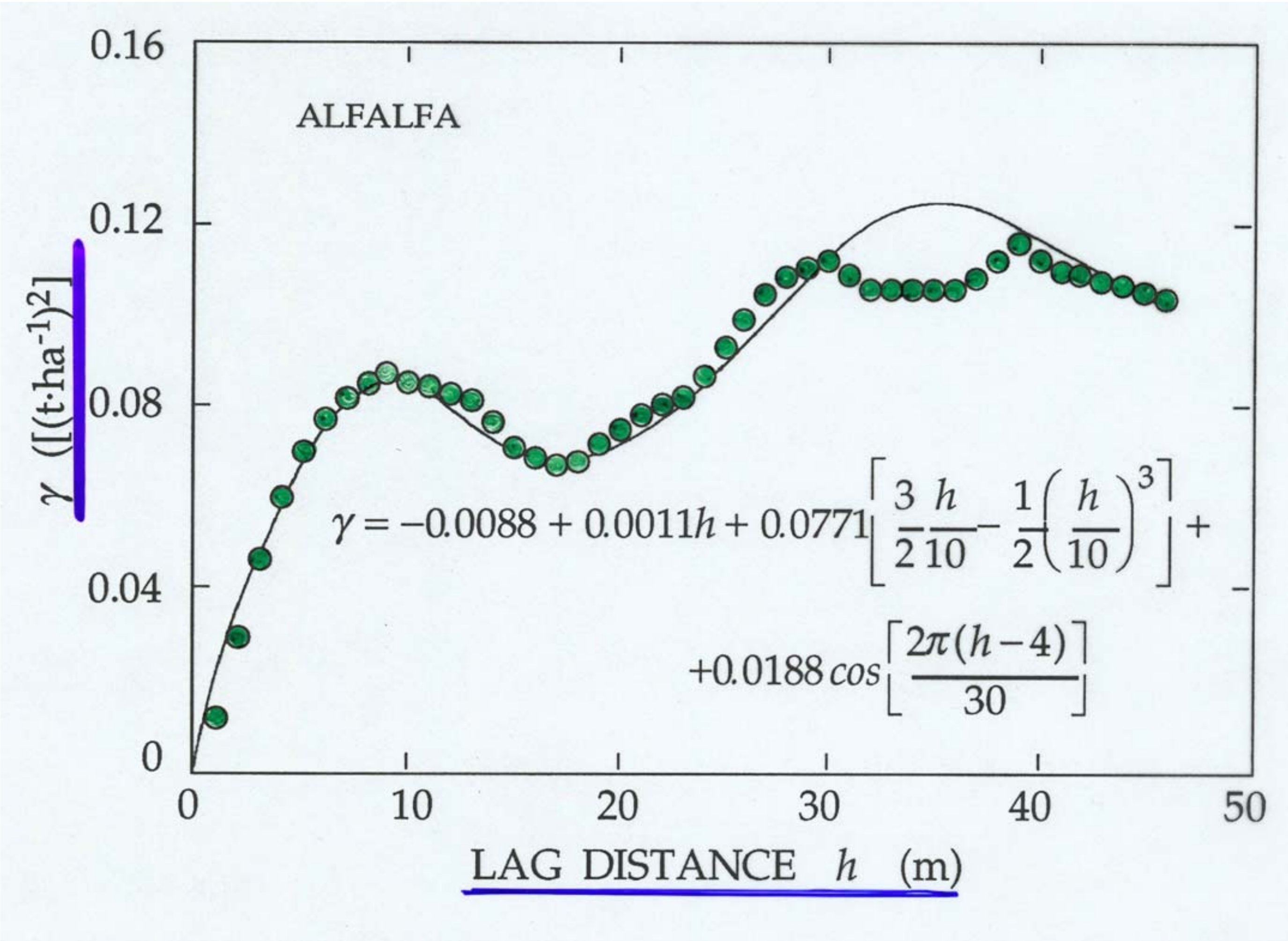
water table elevation
power variogram



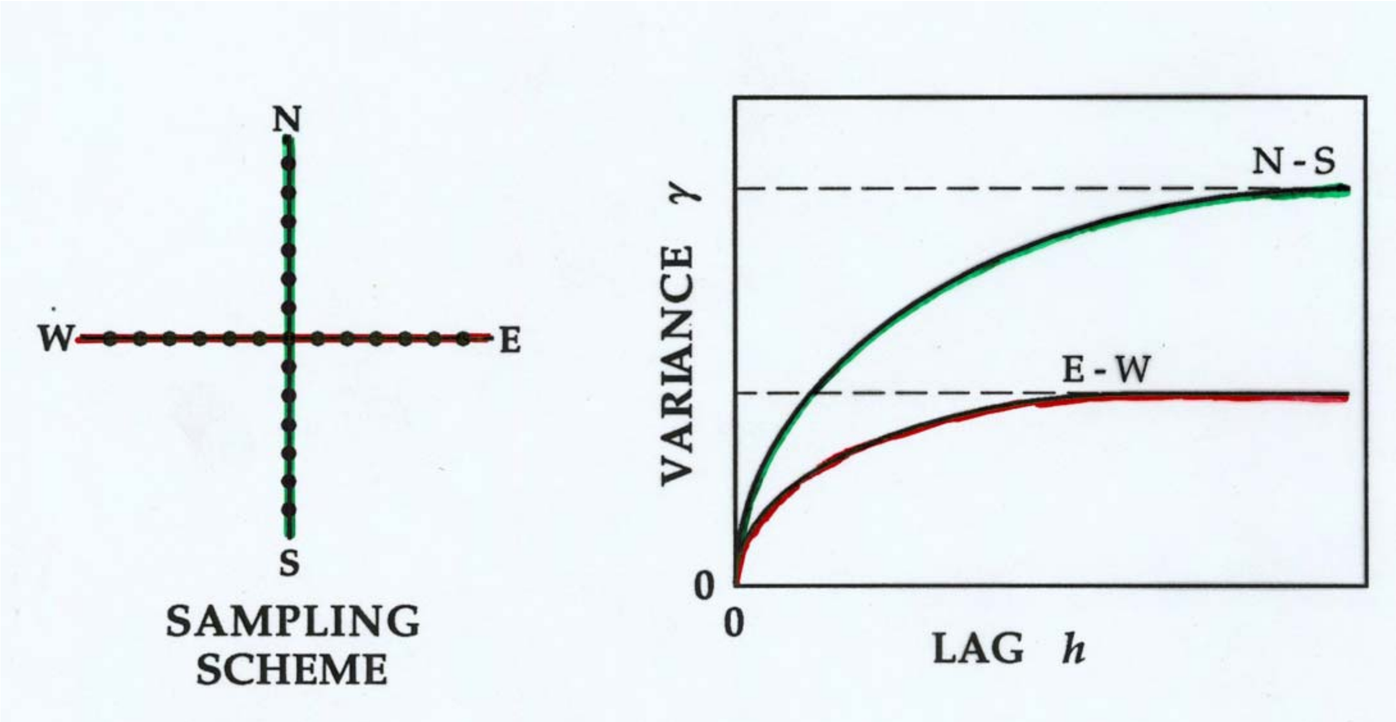
alfalfa yield vs distance



alfalfa comb. variogram

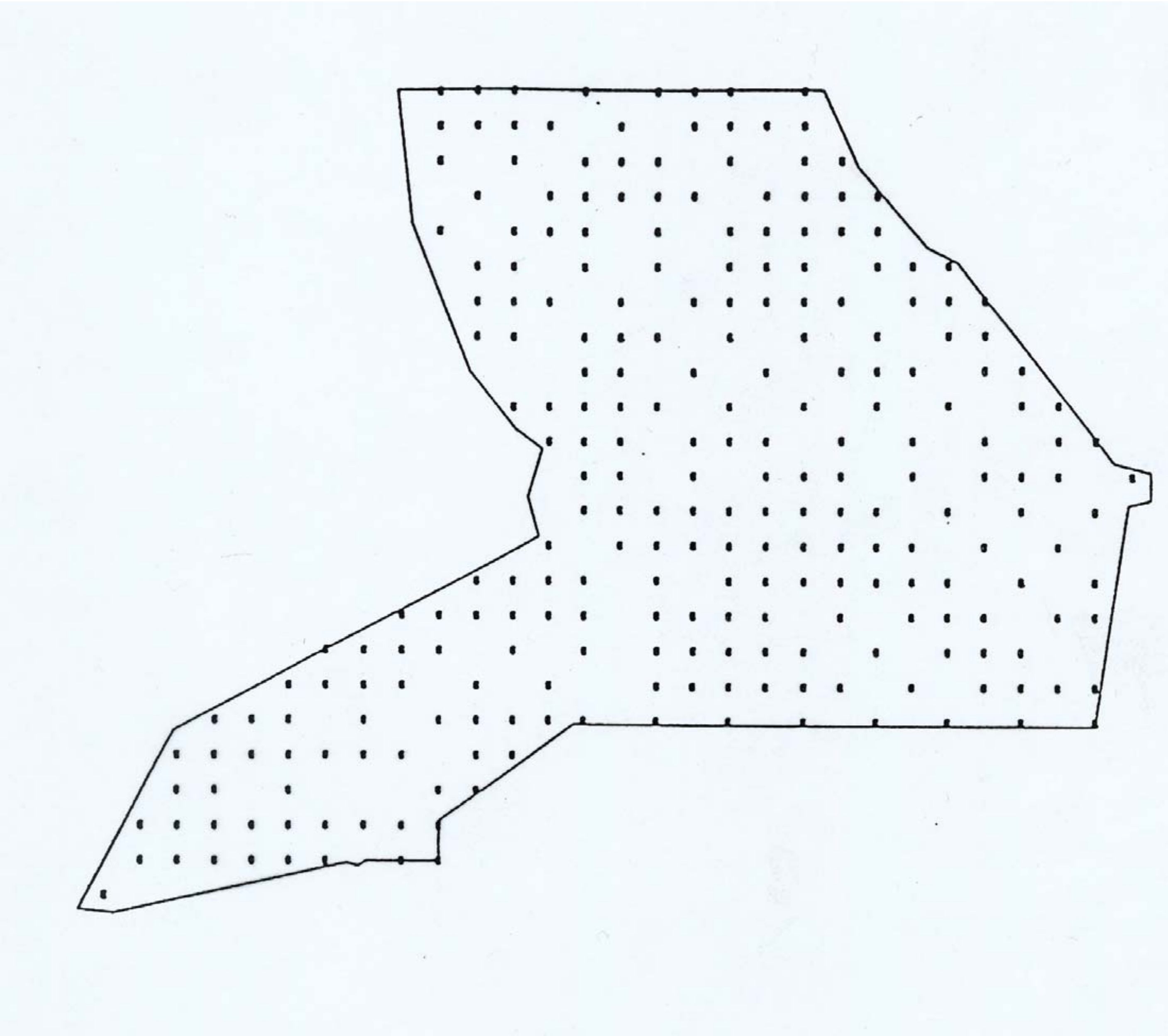


directional variograms

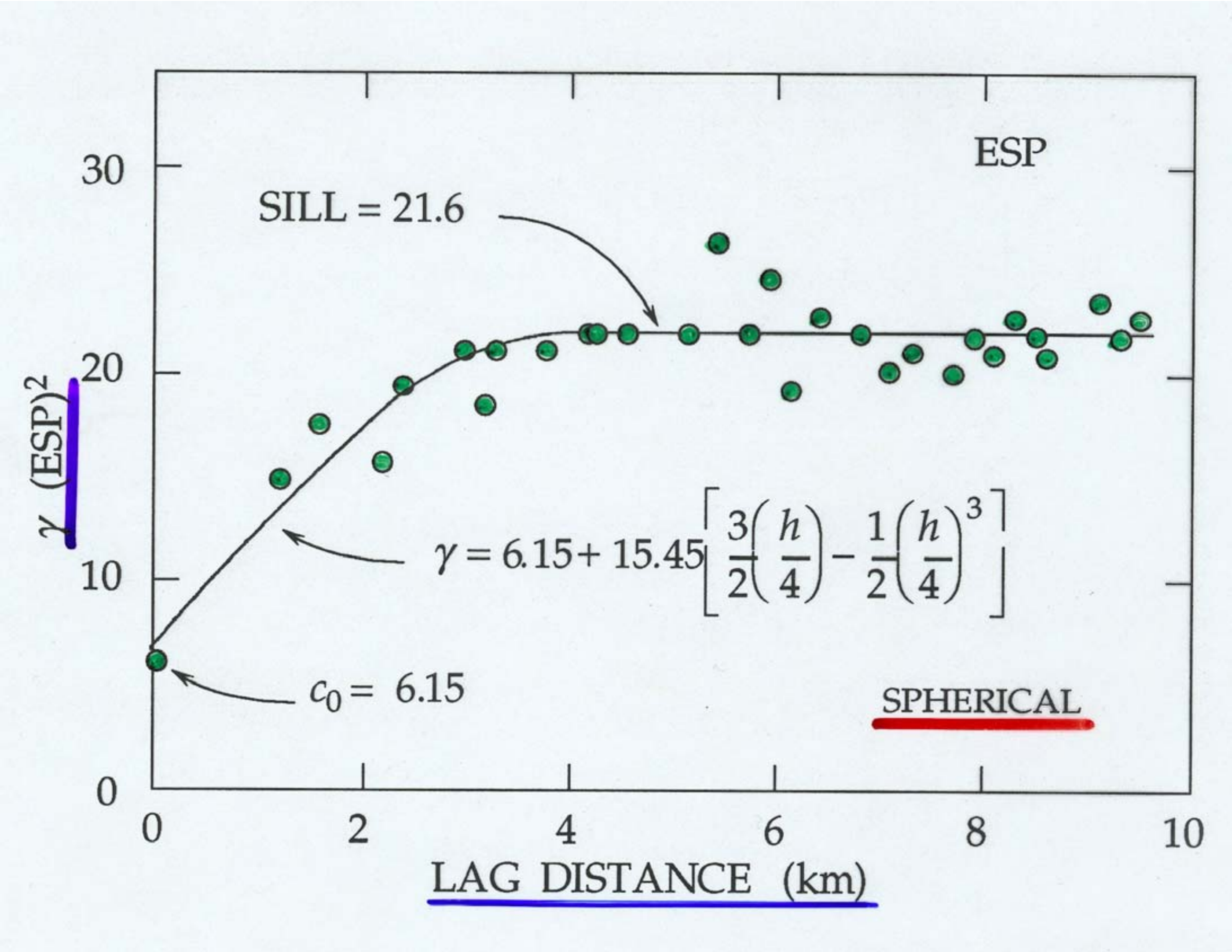


EVALUATING THE "NUGGET"

Sampling scheme in Sudan

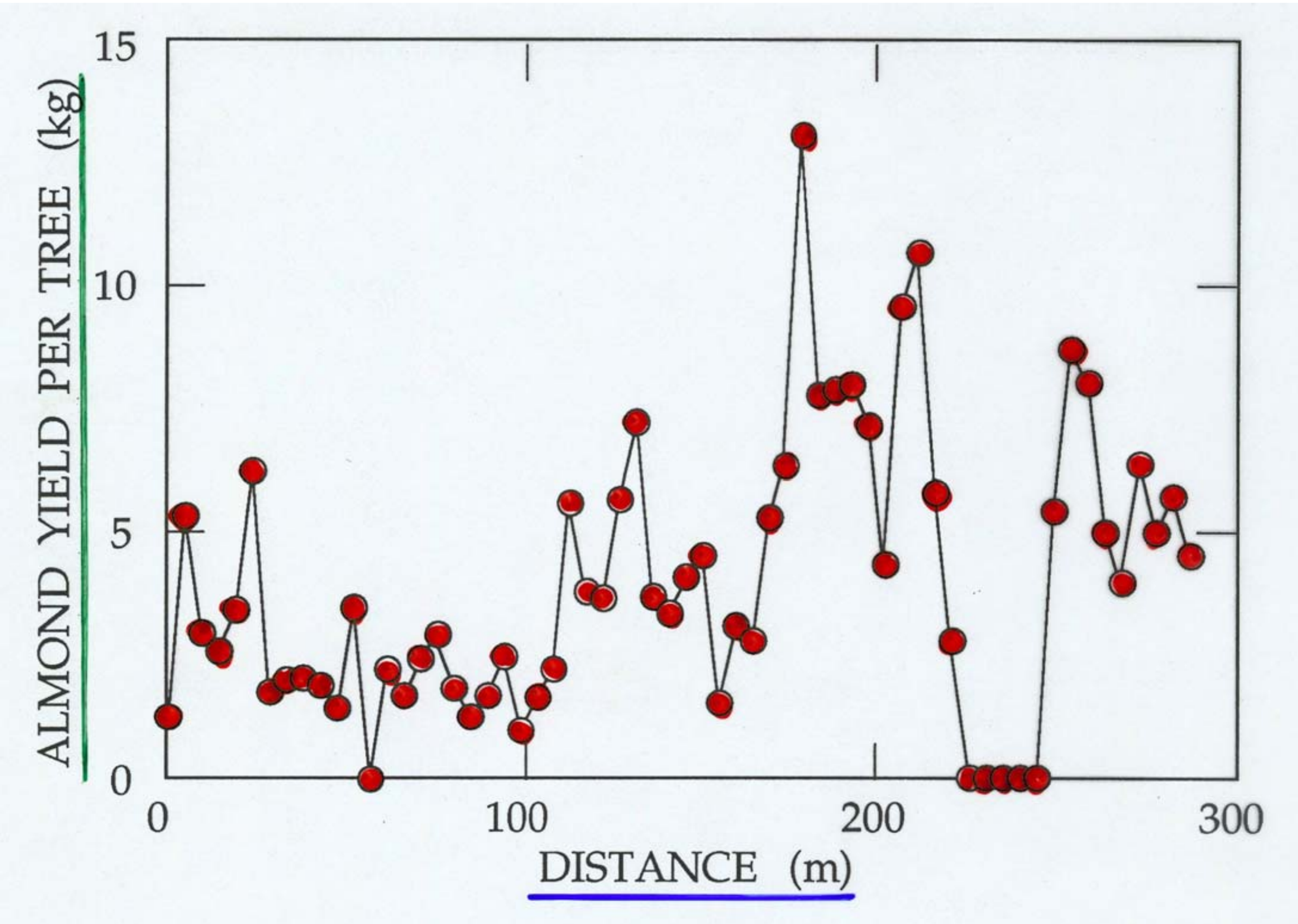


ESP variogram Sudan

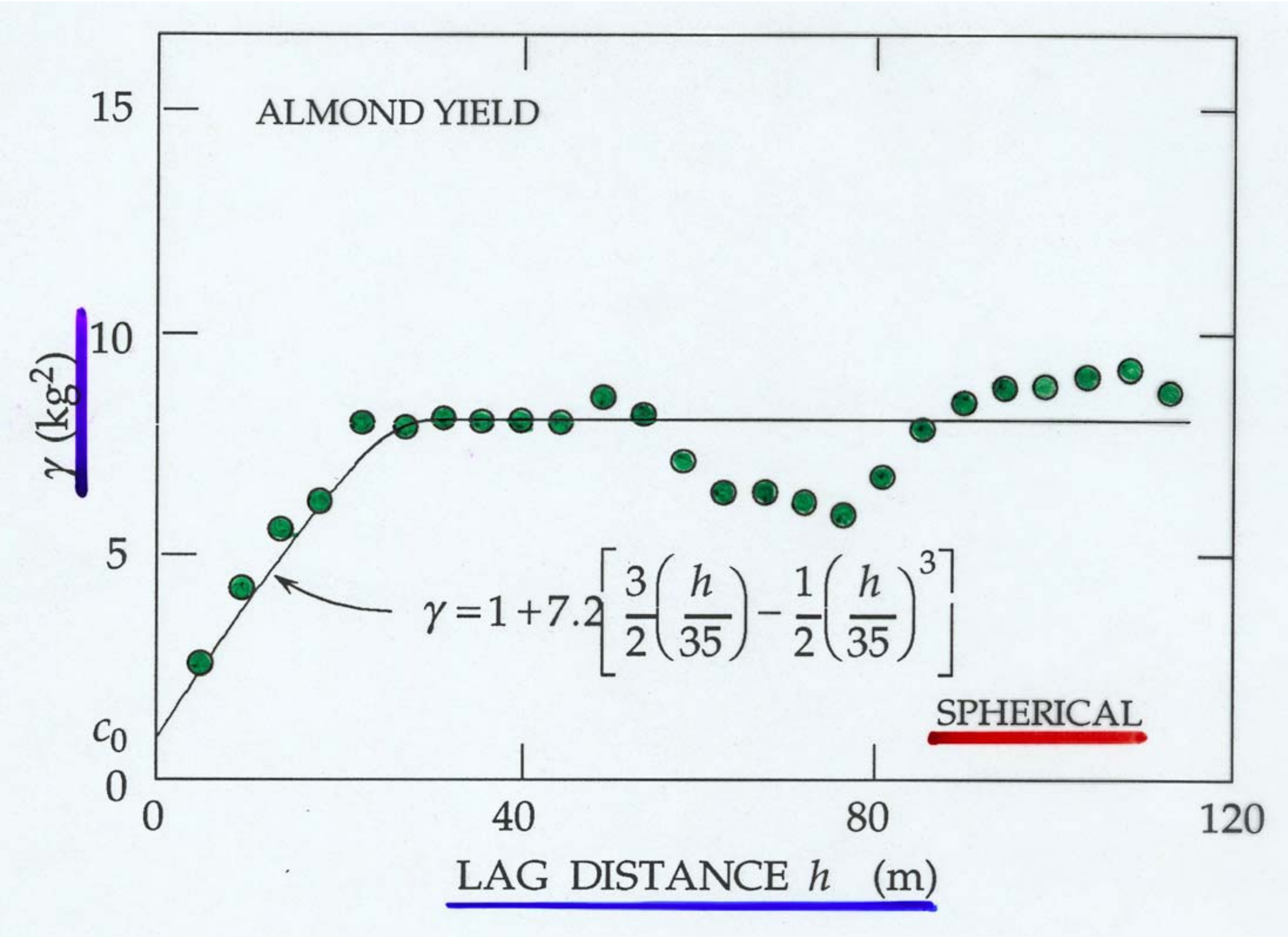


KRIGING ALMOND NUT YIELDS

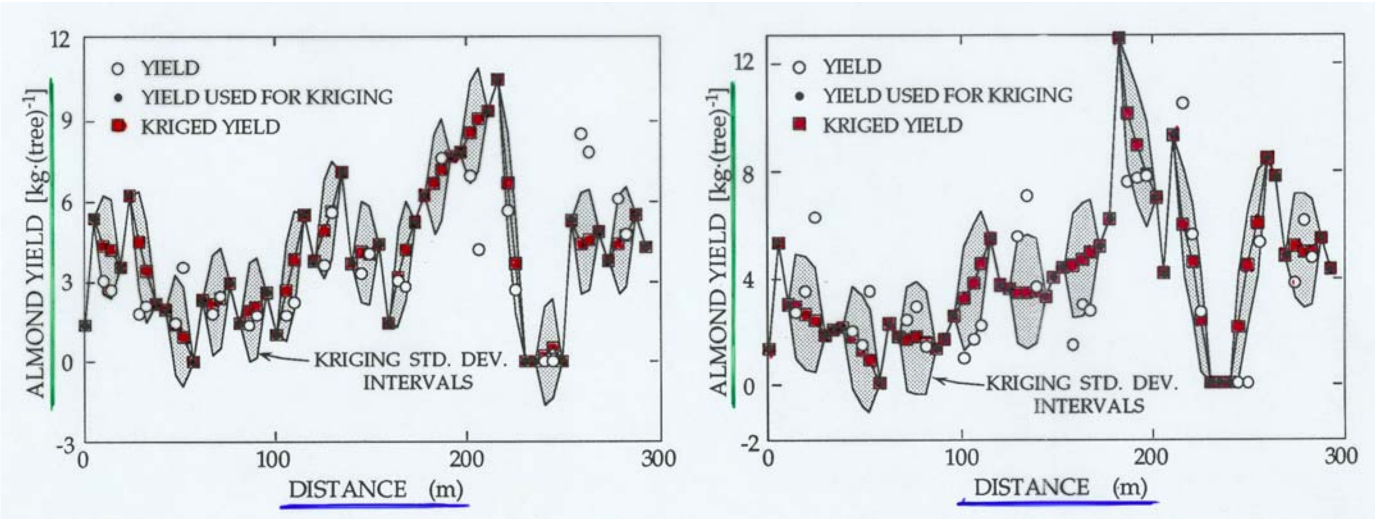
almond yield per tree vs distance



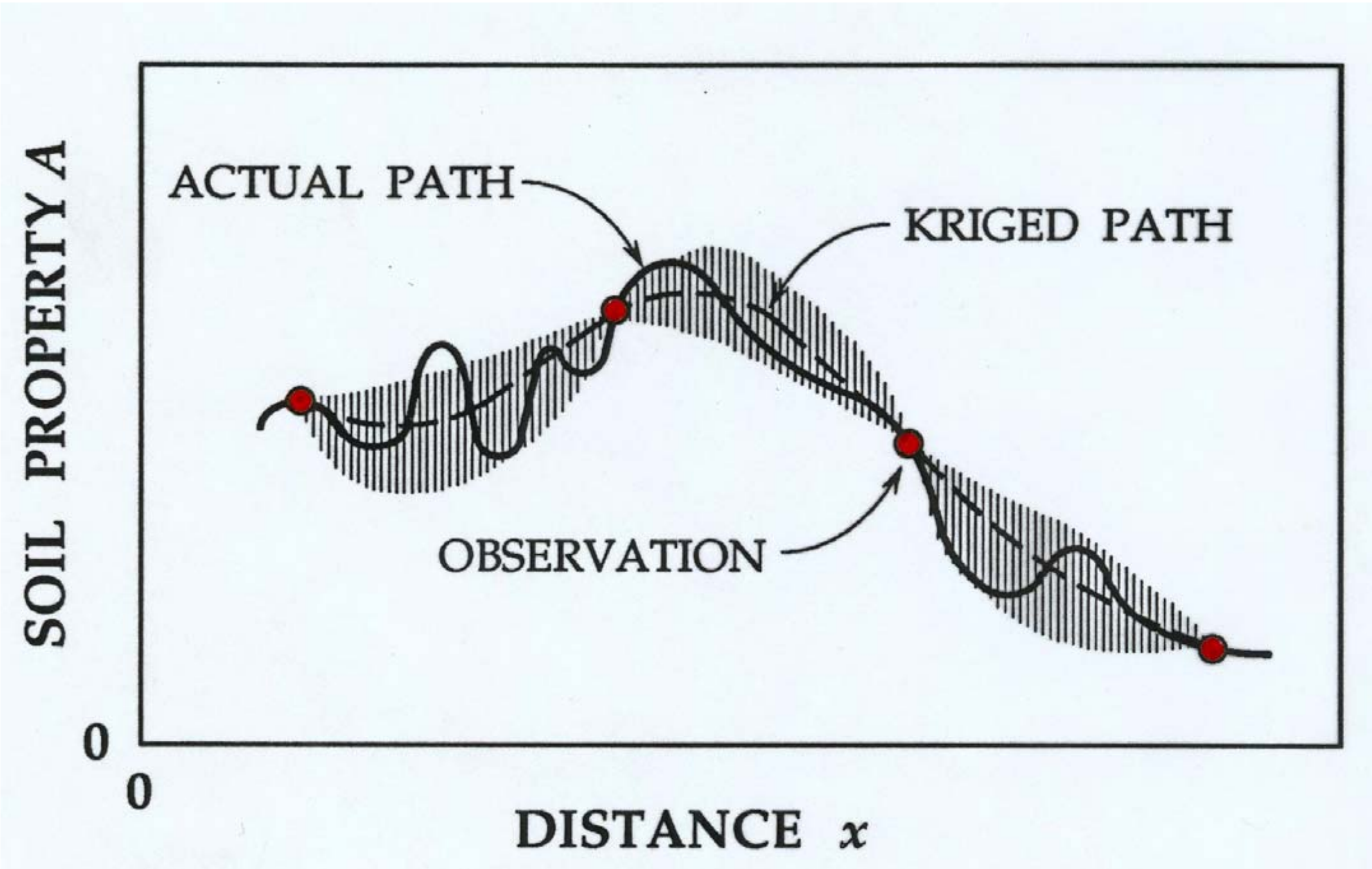
almond yield spherical variogram



kriging almond yield vs distance

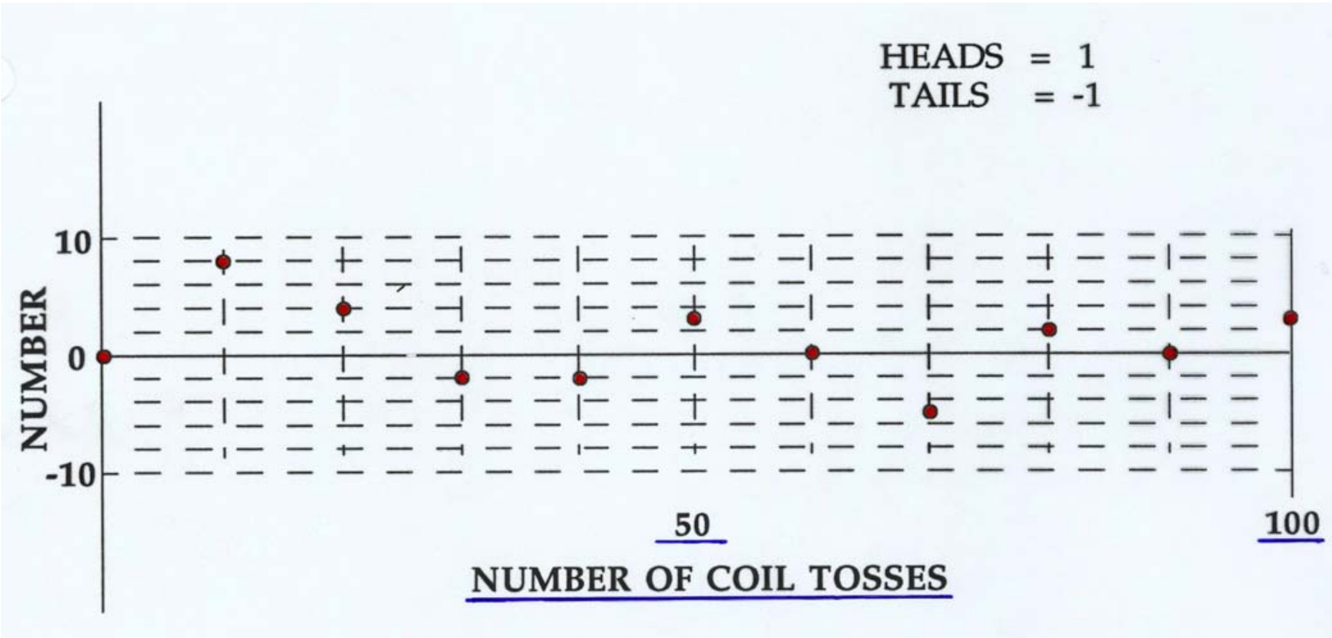


kriging & real path

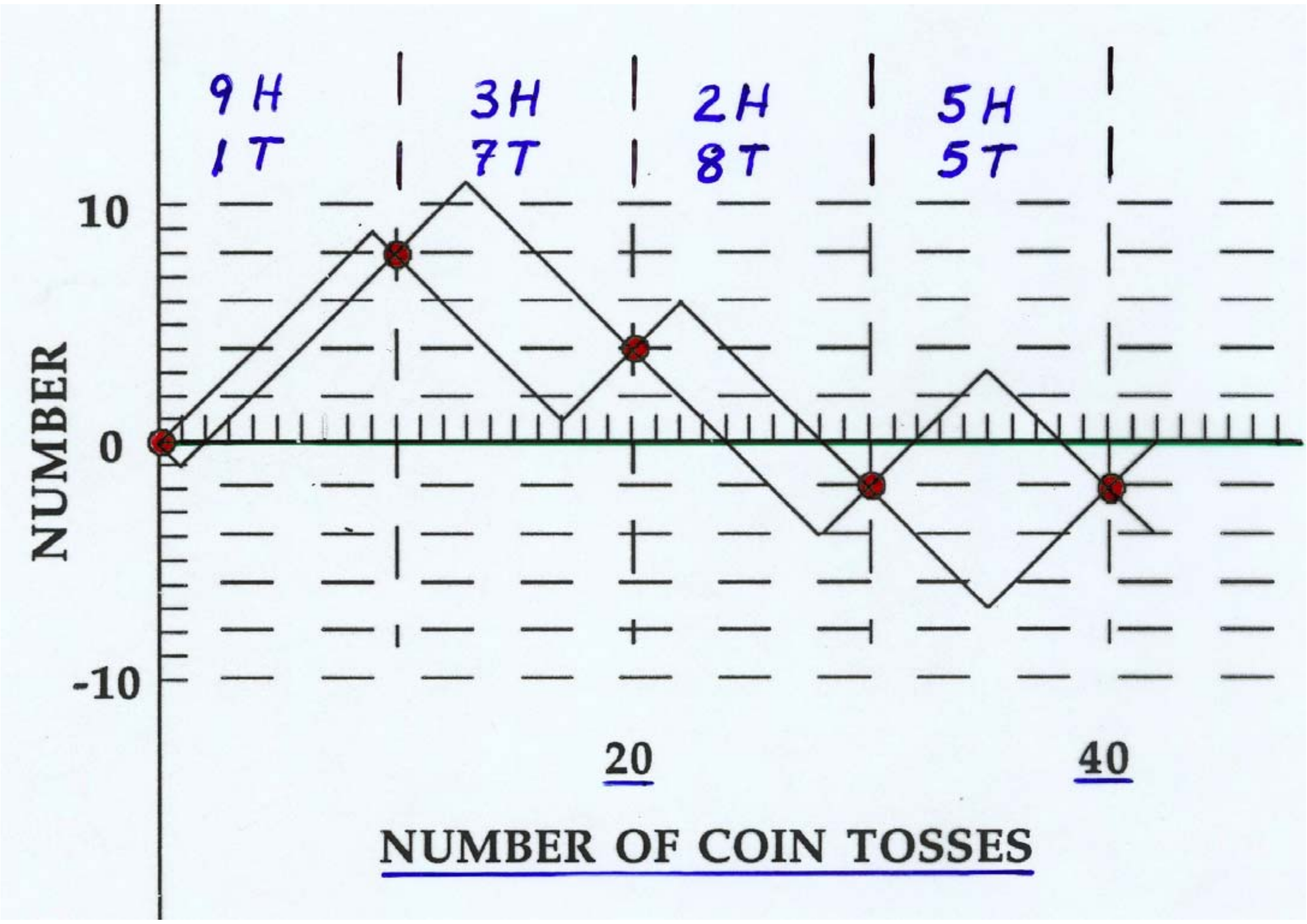


AN INSIGHT INTO THE KRIGING INTERPOLATION

number of coin tosses (100)



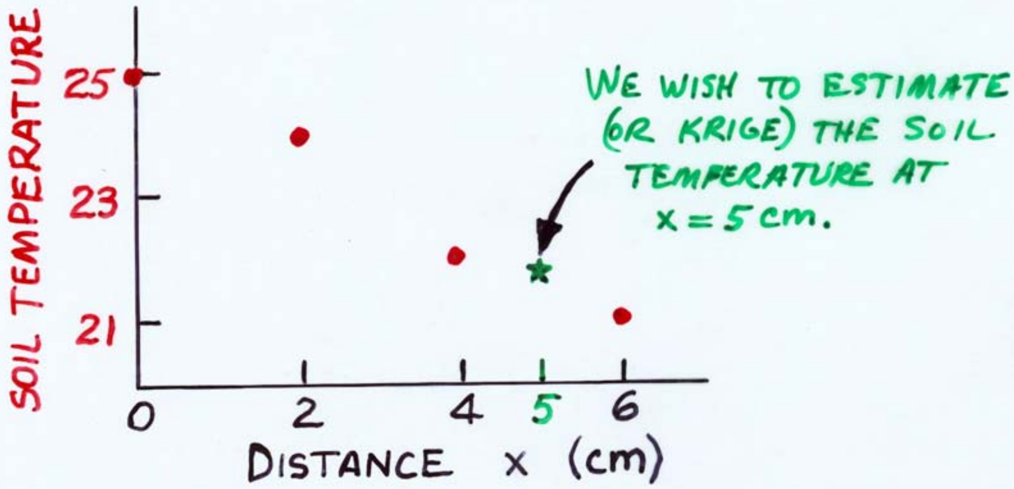
number of coin tosses (40)



simple example of kriging

SIMPLE EXAMPLE OF KRIGING

SOIL TEMPERATURE MEASURED AT 4 LOCATIONS



COORDINATE	0	2	4	6
LOCATION NUMBER	1	2	3	4
MEASURED VALUE	25	24	22	21

COMPUTATION OF THE VARIOGRAM

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} \left[T(x_i + h) - T(x_i) \right]^2 \qquad [1]$$

WHERE $N(h)$ IS NUMBER OF COUPLES OF LOCATIONS SEPARATED BY A DISTANCE h.

kriging example continued

FOR $h = 2$, $N(2) = 3$

$$\gamma(2) = \frac{1}{2(3)}\left[(24-25)^2 + (22-24)^2 + (21-22)^2\right] = 1$$

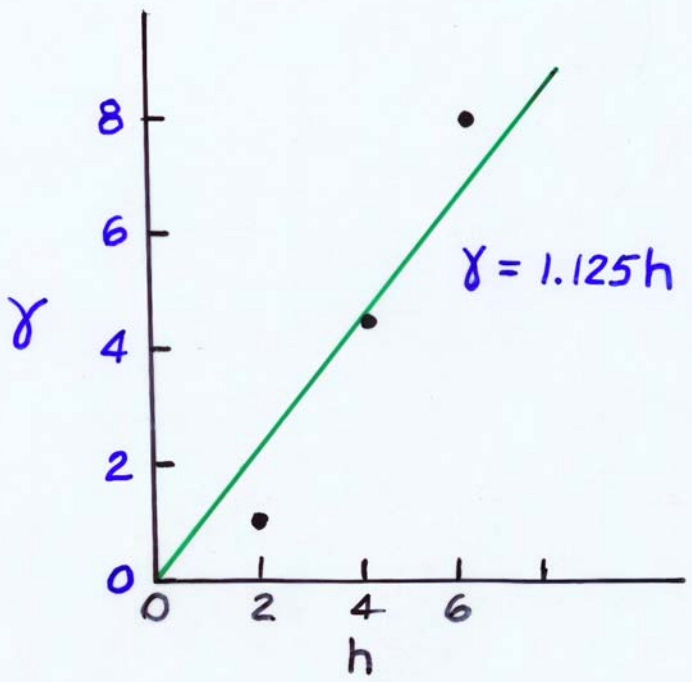
FOR $h = 4$, $N(4) = 2$

$$\gamma(4) = \frac{1}{2(2)}\left[(22-25)^2 + (21-24)^2\right] = 4.5$$

FOR $h = 6$, $N(6) = 1$

$$\gamma(6) = \frac{1}{2(1)}\left[(21-25)^2\right] = 8$$

CALCULATE SMOOTH FUNCTION TO DESCRIBE THE RAW VARIOGRAM



kriging the value of T

USING THE SMOOTH VARIOGRAM $(\gamma = 1.125h)$, WE CALCULATE VALUES OF γ AT EACH SEPARATION h:

$\gamma(0) = 0$ $\gamma(4) = 4.5$

$\gamma(2) = 2.25$ $\gamma(6) = 6.75$

KRIGING THE VALUE OF T AT x = 5 cm

$$T^*(x_0) = \lambda_1 T(x_1) + \lambda_2 T(x_2) + \lambda_3 T(x_3) + \lambda_4 T(x_4)$$

$$T^*(5) = \lambda_1 \cdot 25 + \lambda_2 \cdot 24 + \lambda_3 \cdot 22 + \lambda_4 \cdot 21$$

THE WEIGHTS λ_i ARE CALCULATED ON THE BASIS THAT:

$$E[T^*(x_0) - T(x_0)] = 0$$

AND

$$VAR[T^*(x_0) - T(x_0)] \text{ IS A MINIMUM}$$

WHERE $T^*(x_0)$ IS THE ESTIMATED VALUE AT x_0

$T(x_0)$ IS THE TRUE VALUE AT x_0

THESE ASSUMPTIONS LEAD TO 5 EQUATIONS AND 5 UNKNOWNS.

five equations to be solved

FIVE EQUATIONS TO BE SOLVED:

$$\lambda_1 \gamma_{11} + \lambda_2 \gamma_{12} + \lambda_3 \gamma_{13} + \lambda_4 \gamma_{14} + \mu = \gamma_{10}$$

$$\lambda_1 \gamma_{21} + \lambda_2 \gamma_{22} + \lambda_3 \gamma_{23} + \lambda_4 \gamma_{24} + \mu = \gamma_{20}$$

$$\lambda_1 \gamma_{31} + \lambda_2 \gamma_{32} + \lambda_3 \gamma_{33} + \lambda_4 \gamma_{34} + \mu = \gamma_{30}$$

$$\lambda_1 \gamma_{41} + \lambda_2 \gamma_{42} + \lambda_3 \gamma_{43} + \lambda_4 \gamma_{44} + \mu = \gamma_{40}$$

$$\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 = 1$$

FROM THE SMOOTH VARIOGRAM, WE CALCULATE γ_{ij}

$h = 2$ $\gamma_{12} = \gamma_{21} = 2.25$

$h = 4$ $\gamma_{13} = \gamma_{31} = 4.50$

$h = 6$ $\gamma_{14} = \gamma_{41} = 6.75$

$h = 2$ $\gamma_{23} = \gamma_{32} = 2.25$

$h = 4$ $\gamma_{24} = \gamma_{42} = 4.50$

$h = 2$ $\gamma_{34} = \gamma_{43} = 2.25$

$h = 0$ $\gamma_{11} = \gamma_{22} = \gamma_{33} = \gamma_{44} = 0$

$h = 5$ $\gamma_{10} = 5.625$

$h = 3$ $\gamma_{20} = 3.375$

$h = 1$ $\gamma_{30} = 1.125$

$h = 1$ $\gamma_{40} = 1.125$

SOLUTION OF FIVE EQUATIONS YIELD:

$\lambda_1 = 0$ $\lambda_3 = 0.5$ $\mu = 0$

$\lambda_2 = 0$ $\lambda_4 = 0.5$

kriged value of temp and its variance

KRIGED VALUE OF TEMPERATURE & ITS VARIANCE $(x=5)$:

$$T^*(x_0) = \lambda_1 T(x_1) + \lambda_2 T(x_2) + \lambda_3 T(x_3) + \lambda_4 T(x_4)$$

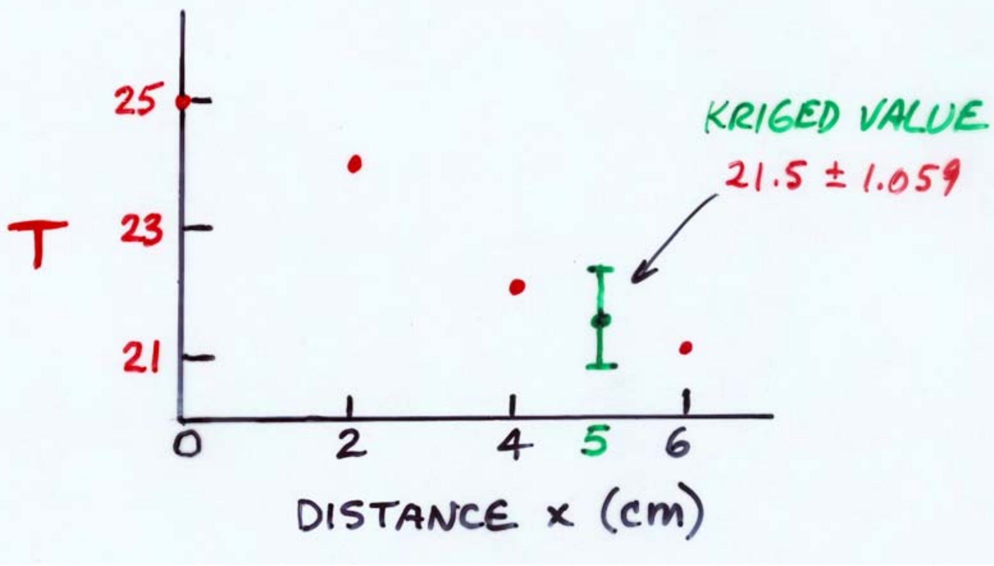
$$T^*(5) = \lambda_1 \cdot 25 + \lambda_2 \cdot 24 + \lambda_3 \cdot 22 + \lambda_4 \cdot 21$$

$$= 0 \cdot 25 + 0 \cdot 24 + 0.5 \cdot 22 + 0.5 \cdot 21 = 21.5$$

$$\sigma^2(x_0) = \lambda_1 \gamma_{10} + \lambda_2 \gamma_{20} + \lambda_3 \gamma_{30} + \lambda_4 \gamma_{40} + \mu$$

$$\sigma^2(5) = 0 \cdot 5.625 + 0 \cdot 3.375 + 0.5 \cdot 1.125 + 0.5 \cdot 1.125 + 0$$

$$= 1.125$$



CROSS VARIOGRAMS

cross variogram calc. A & B

CROSS VARIOGRAM

OBSERVATION A

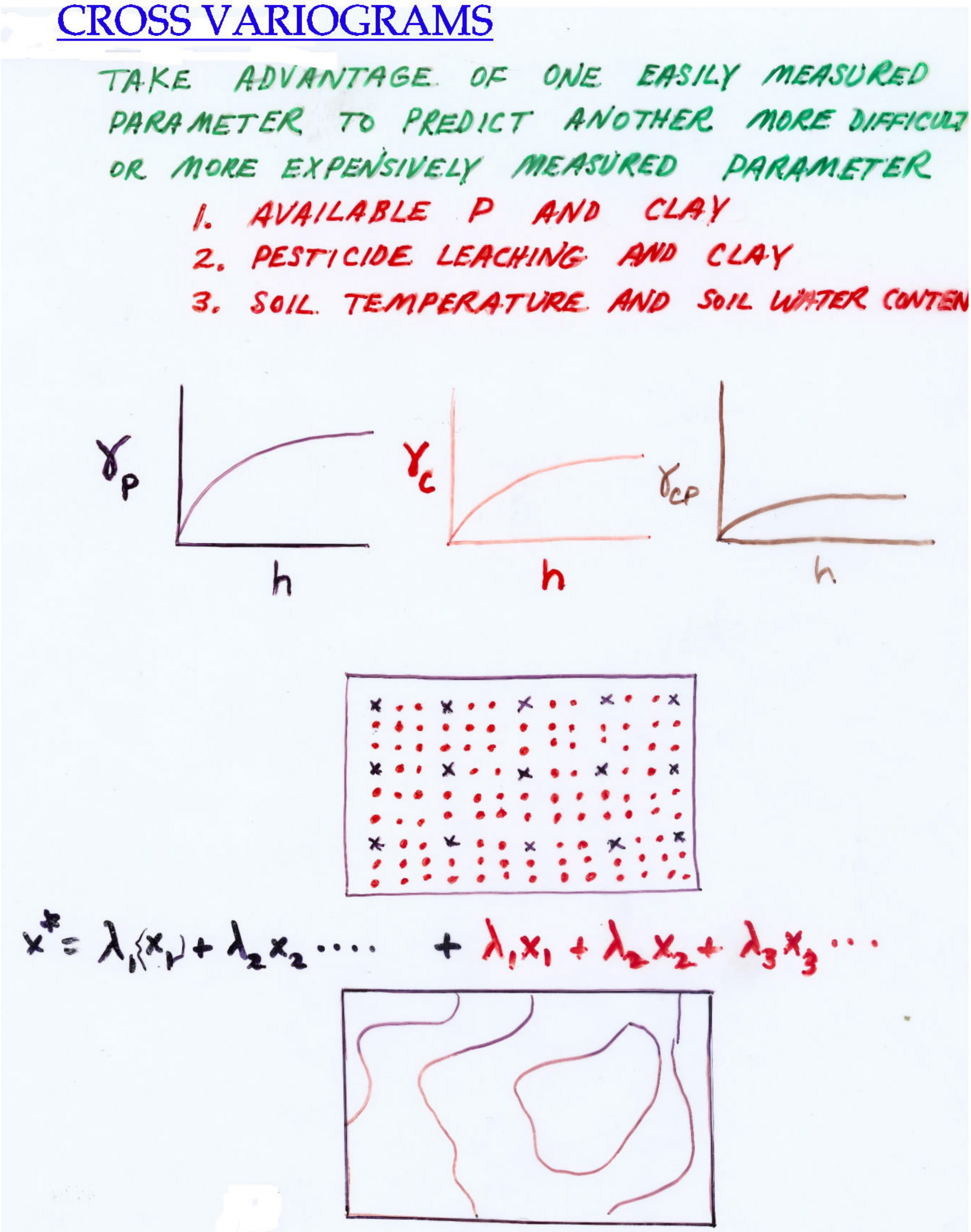
A_1	A_2	A_3	A_4	A_5	A_6	$A_7 \cdots$	$A_i \cdots$	A_n
o	o	o	o	o	o	o	o	o
x_1	x_2	x_3	x_4	x_5	x_6	$x_7 \cdots$	$x_i \cdots$	x_n

OBSERVATION B

B_1	B_2	B_3	B_4	B_5	B_6	$B_7 \cdots$	$B_i \cdots$	B_n
o	o	o	o	o	o	o	o	o
x_1	x_2	x_3	x_4	x_5	x_6	$x_7 \cdots$	$x_i \cdots$	x_n

$$\Gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} \left[A(x_i) - A(x_i + h)\right]\left[B(x_i) - B(x_i + h)\right]$$

cross variogram calculation scheme



CROP YIELD AND SOIL EROSION

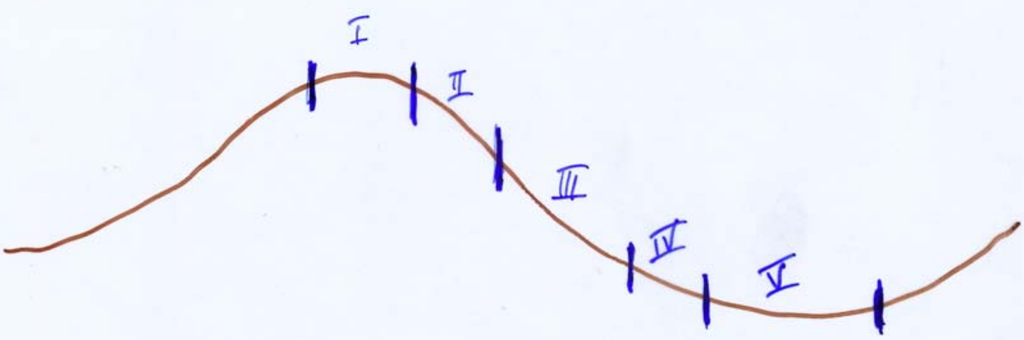
erosion study

ERosion STUDY

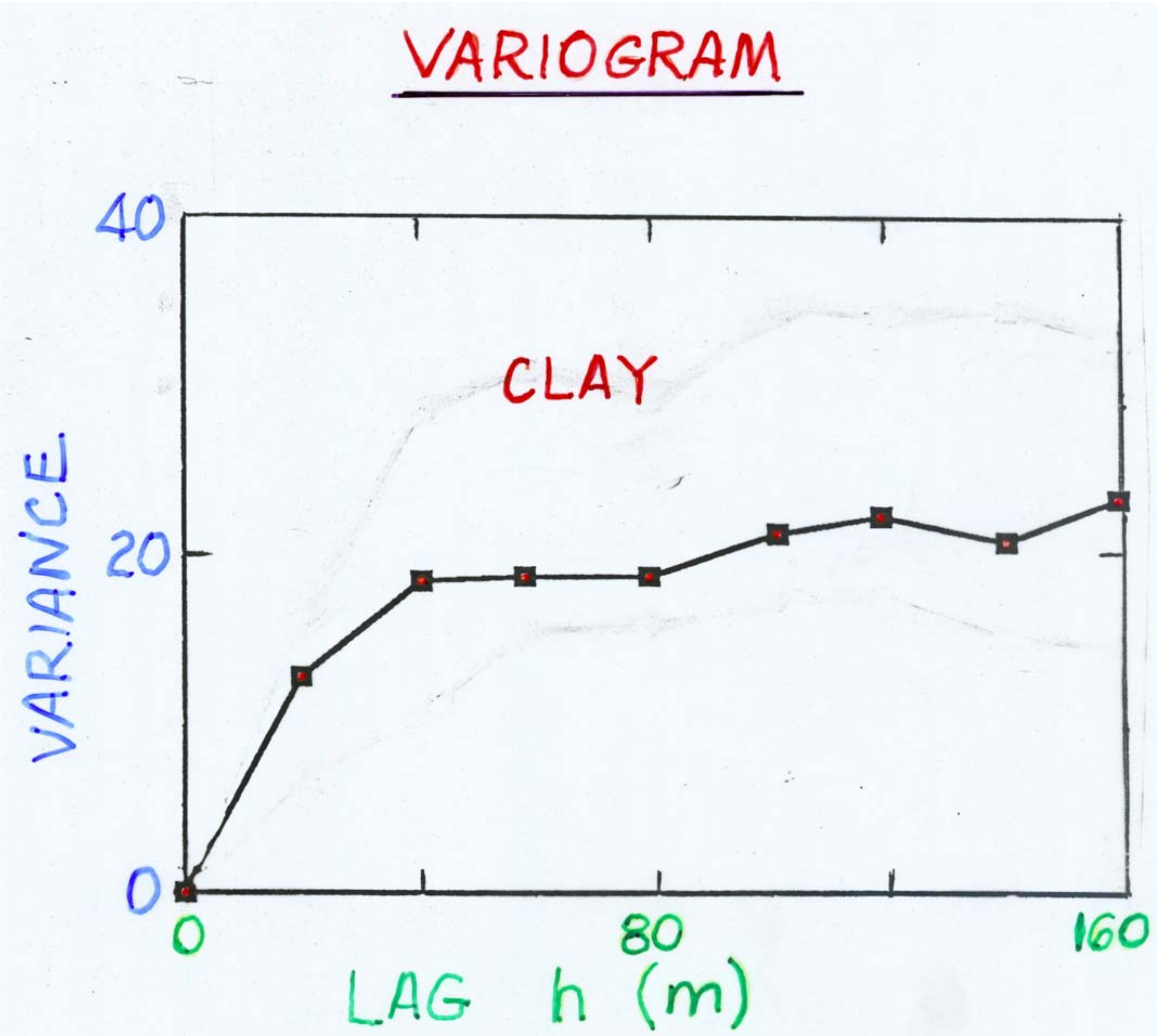
SEVERAL GEOLOGIC CYCLES OF GENTLE UPLIFTING & EROSION

→ HILLY & ROLLING RELIEF SEEN TODAY
→ WHEAT BIOMASS INCREASES FROM KNOLLS TO SWALES
→ CLAY & OTHER PROPERTIES VARY BY LANDSCAPE POSITION

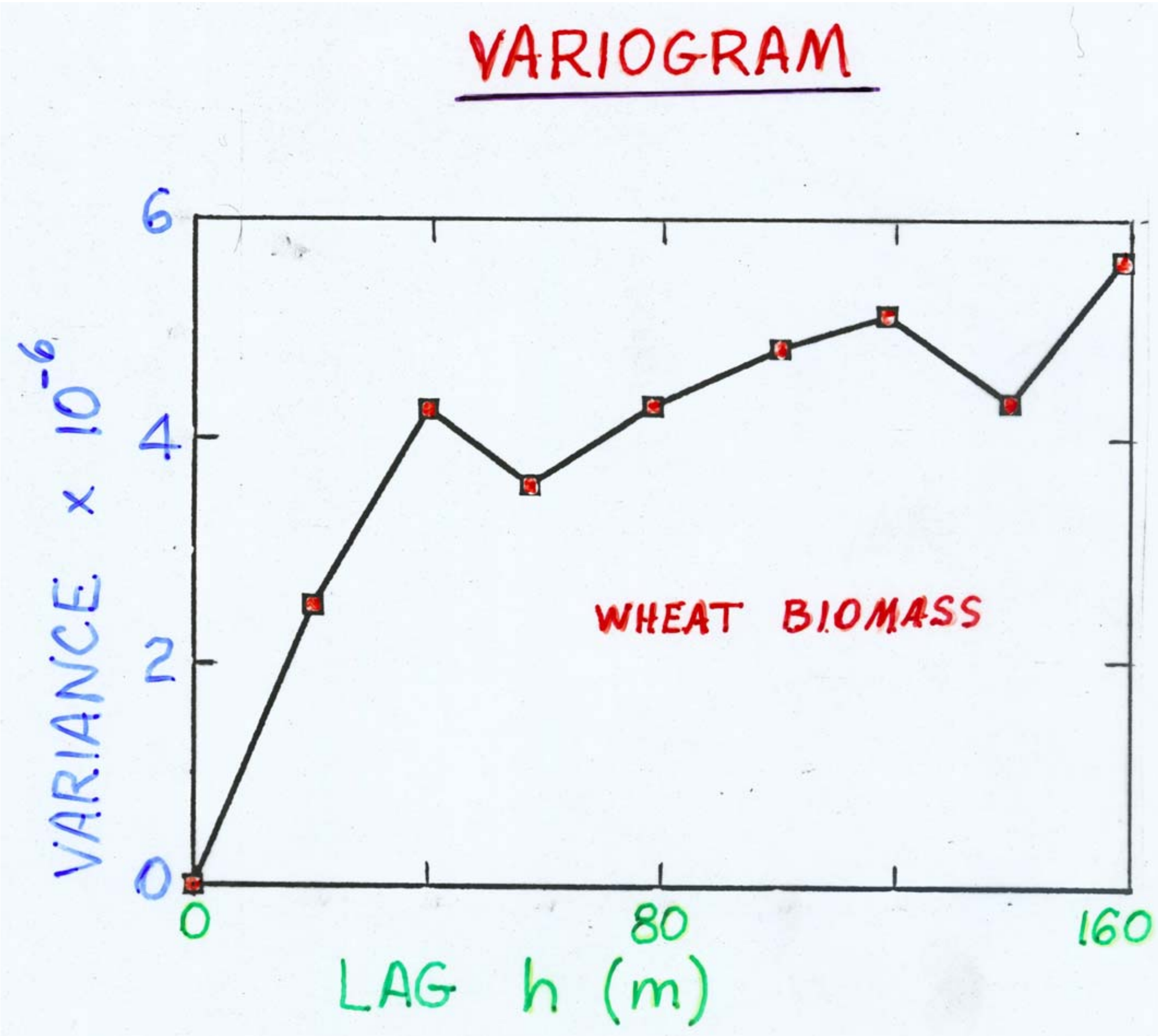
SAMPLED WHEAT & CLAY CONTENT ON A 20-M GRID



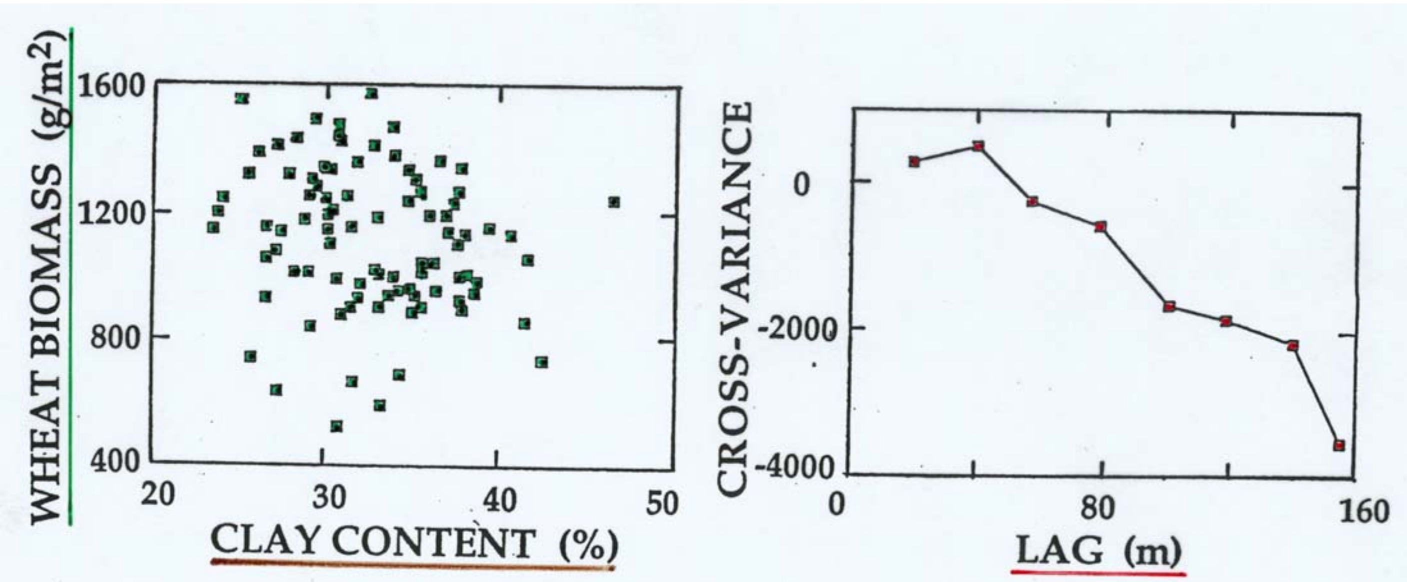
clay variogram



wheat biomass variogram

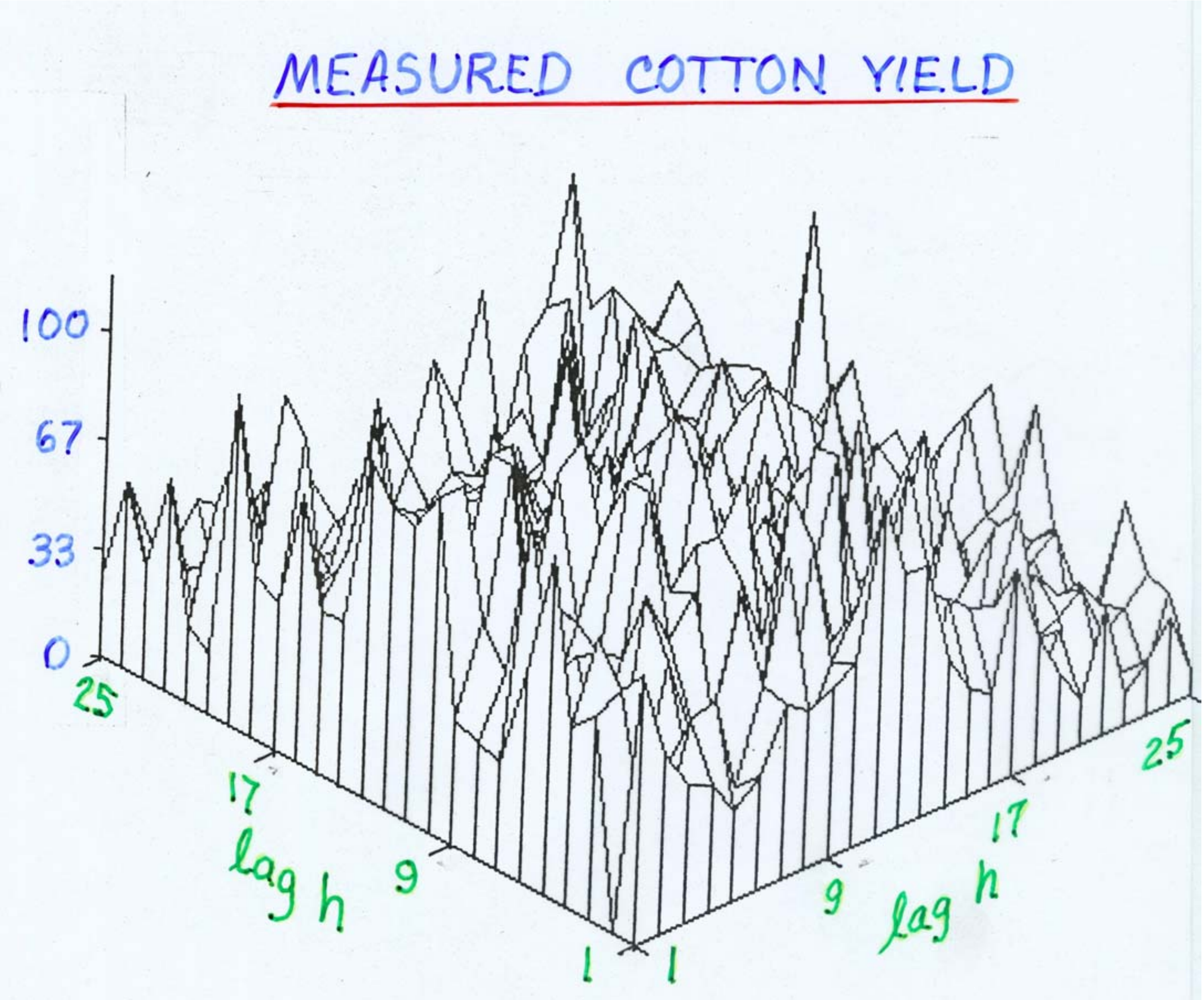


cross variogram wheat biomass vs clay

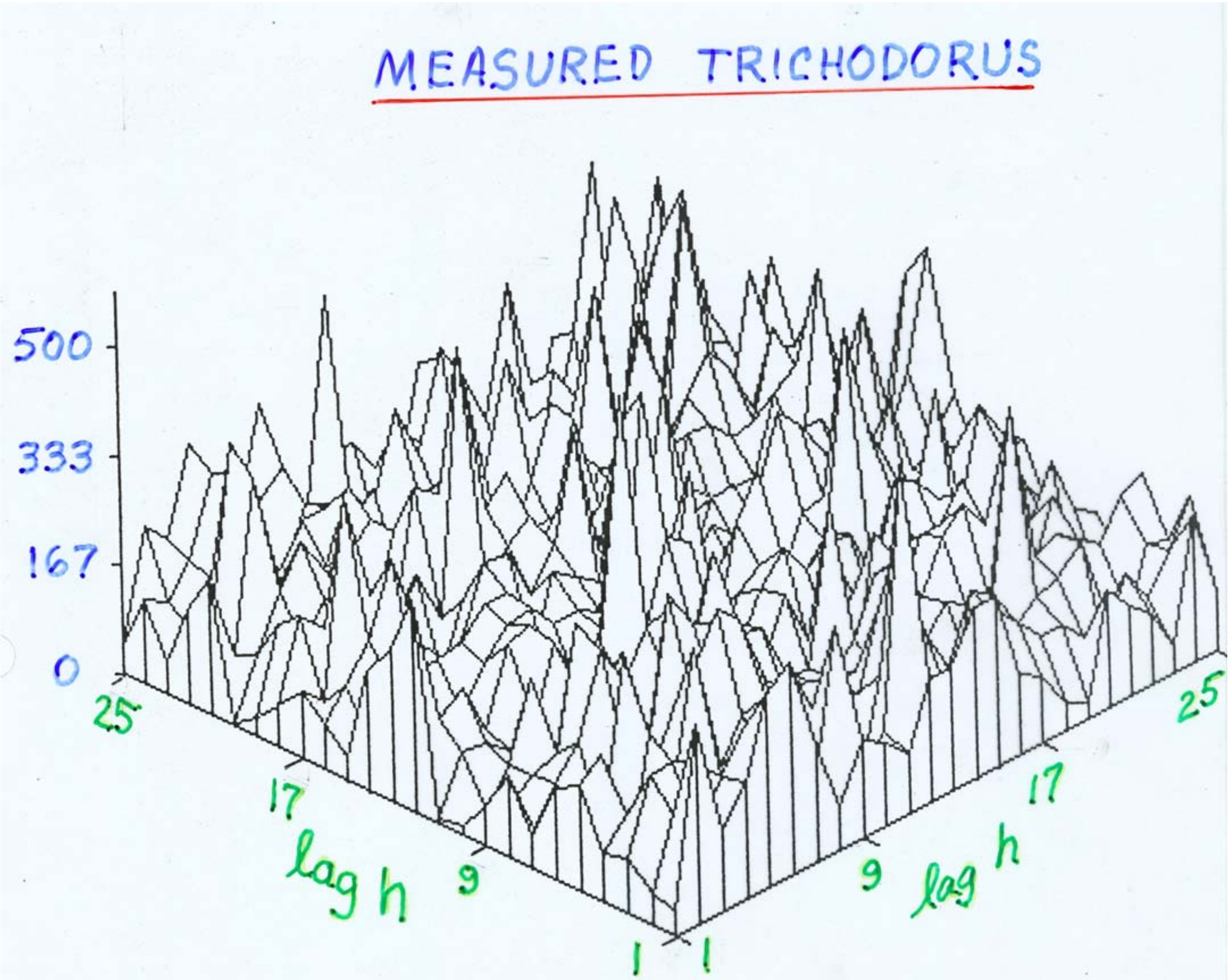


CROP YIELD AND NEMATODES

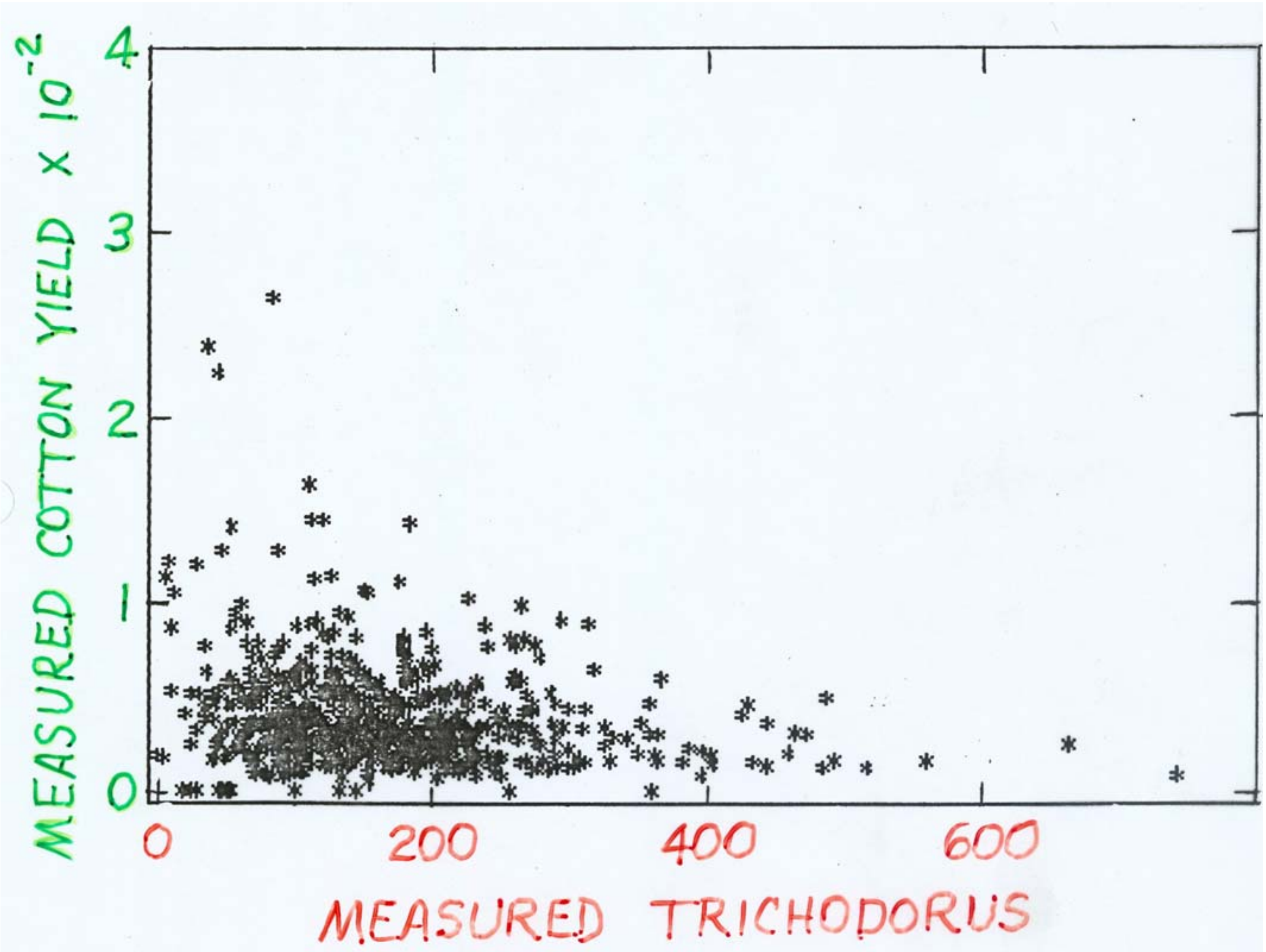
cotton yield (nematodes)



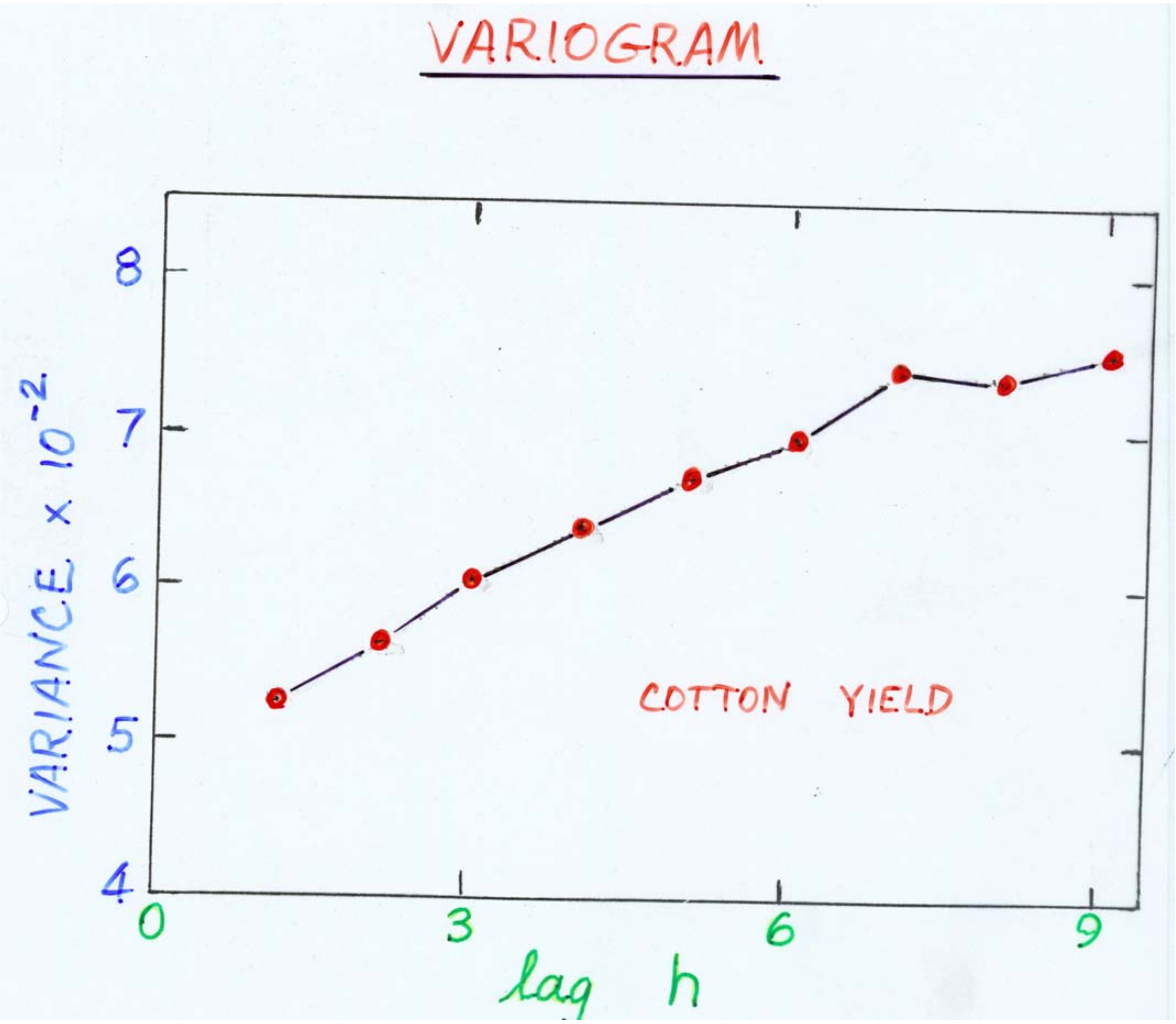
trichodorus (cotton)



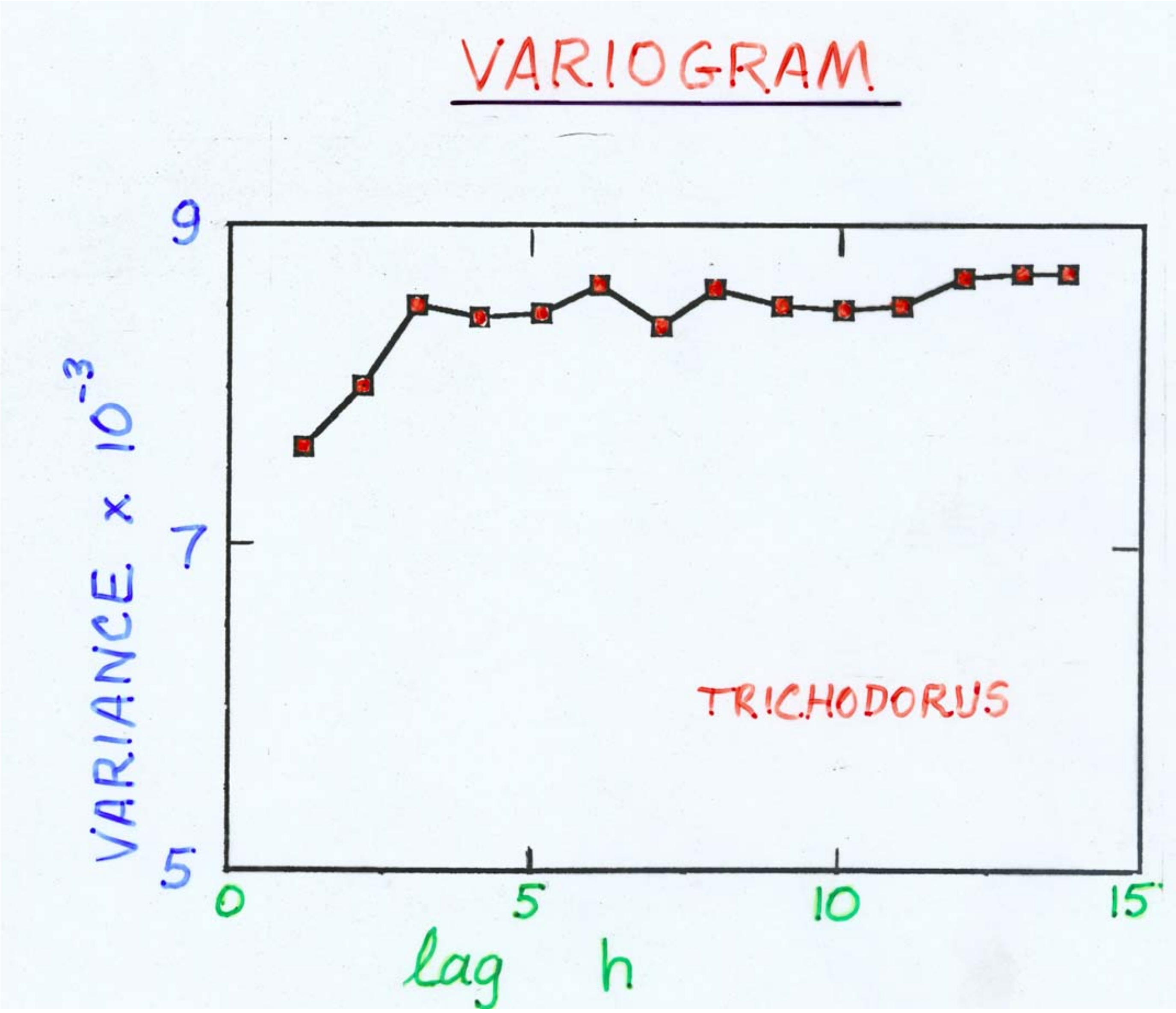
cotton yield vs trichodorus



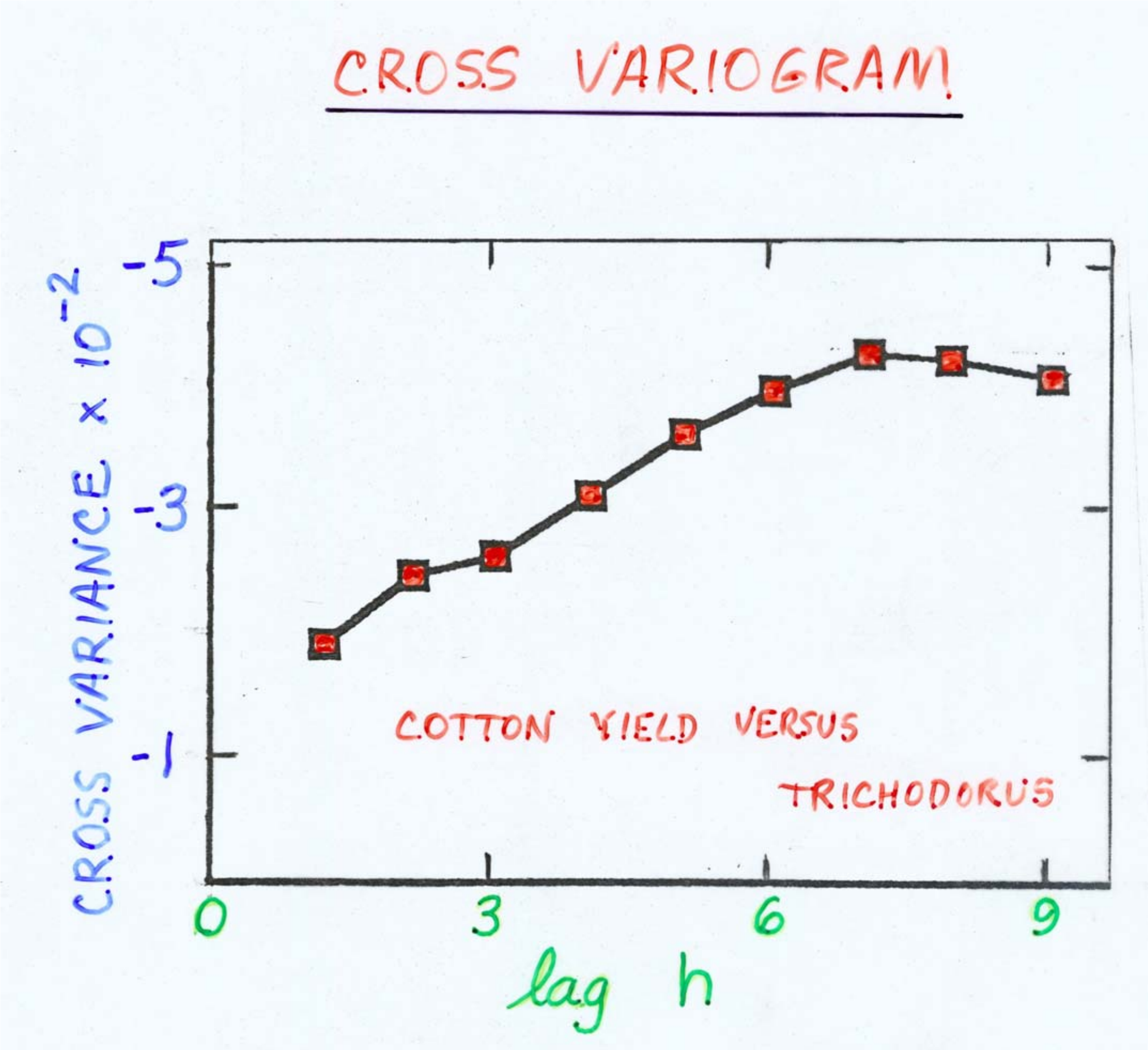
variogram cotton yld (nematodes)



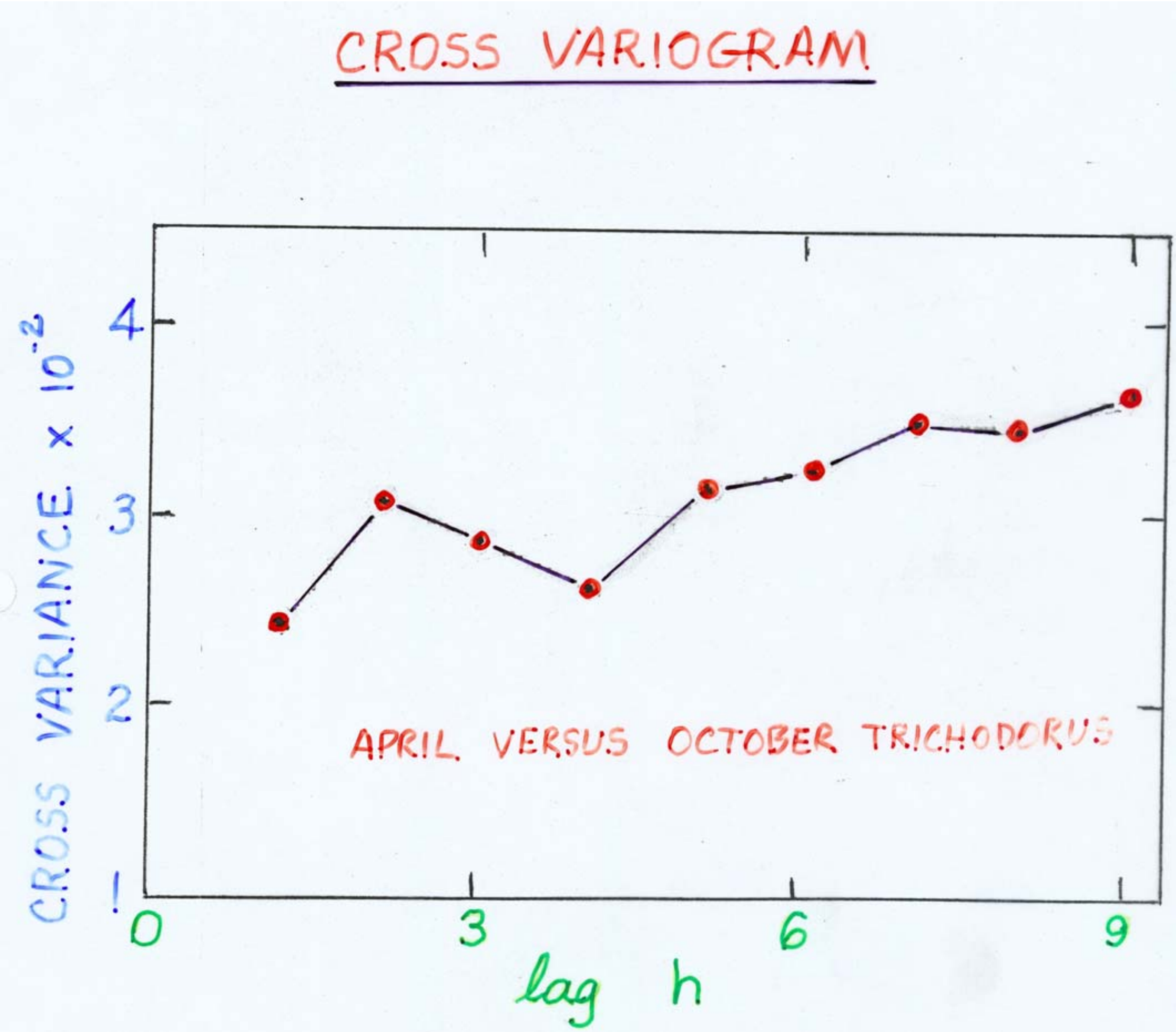
variogram nematodes (cotton yld)



cross variogram cotton vs nematodes

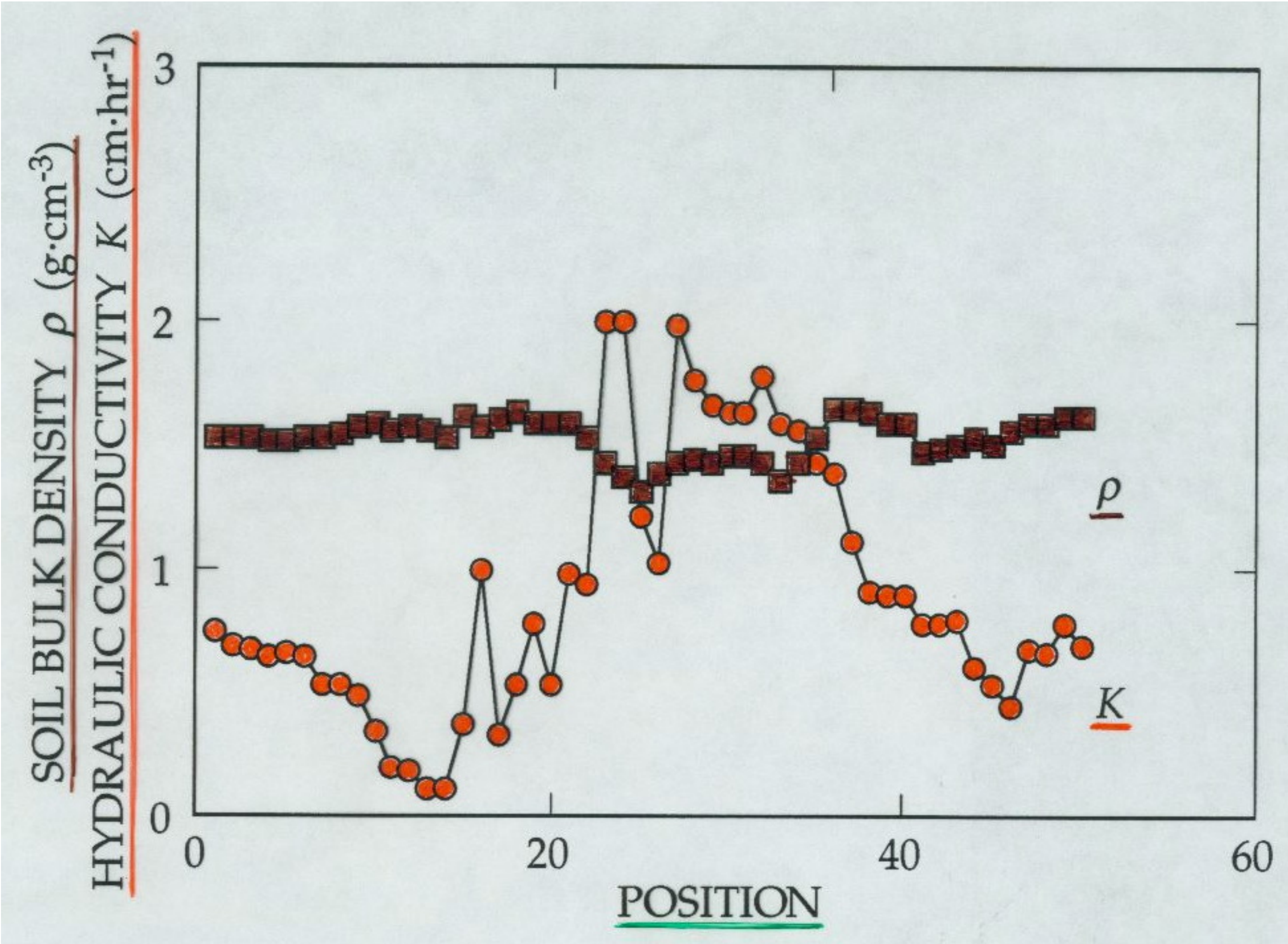


cross variogram April vs Oct nematodes

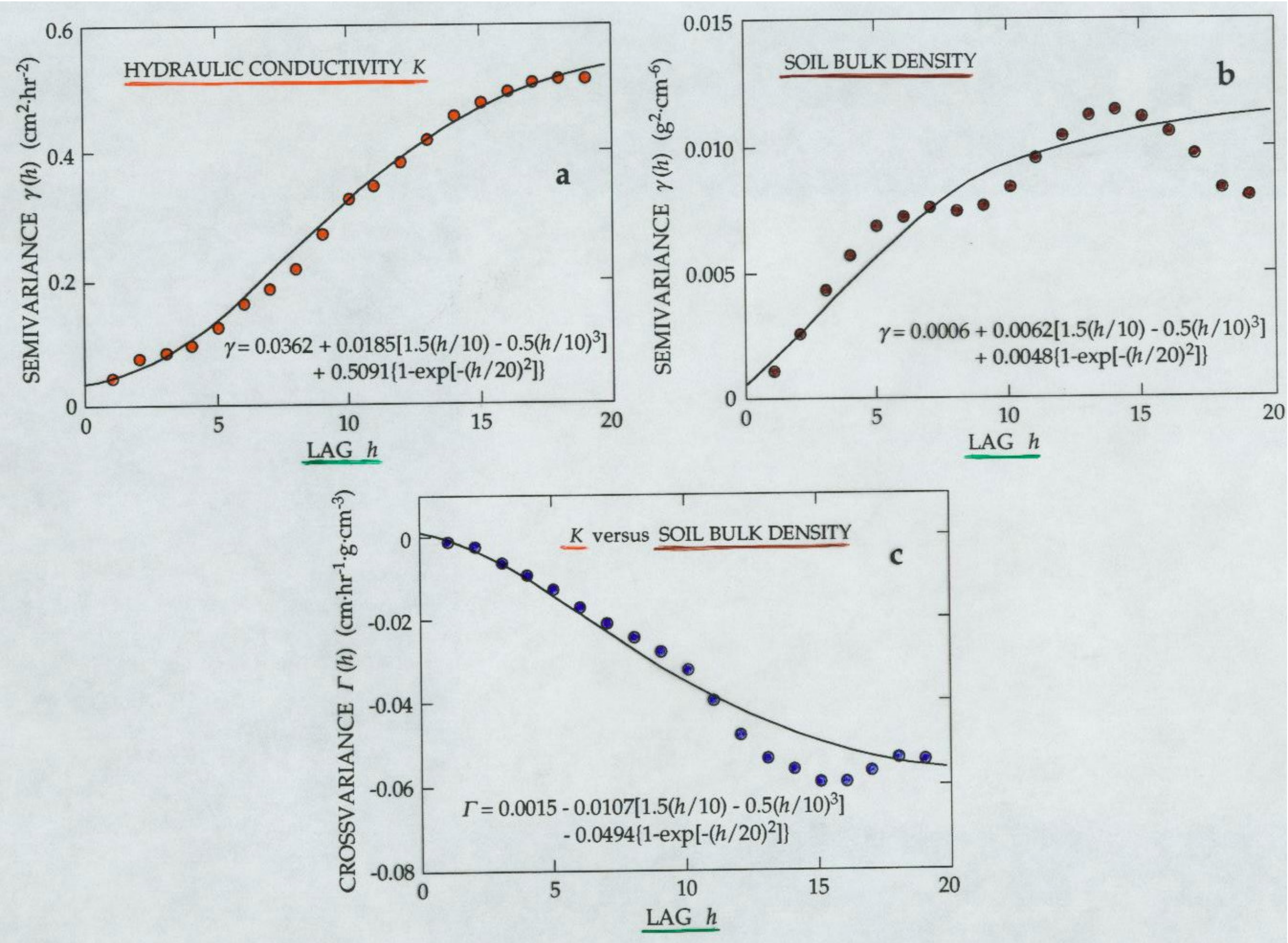


COKRIGING SOIL HYDRAULIC CONDUCTIVITY WITH SOIL BULK DENSITY

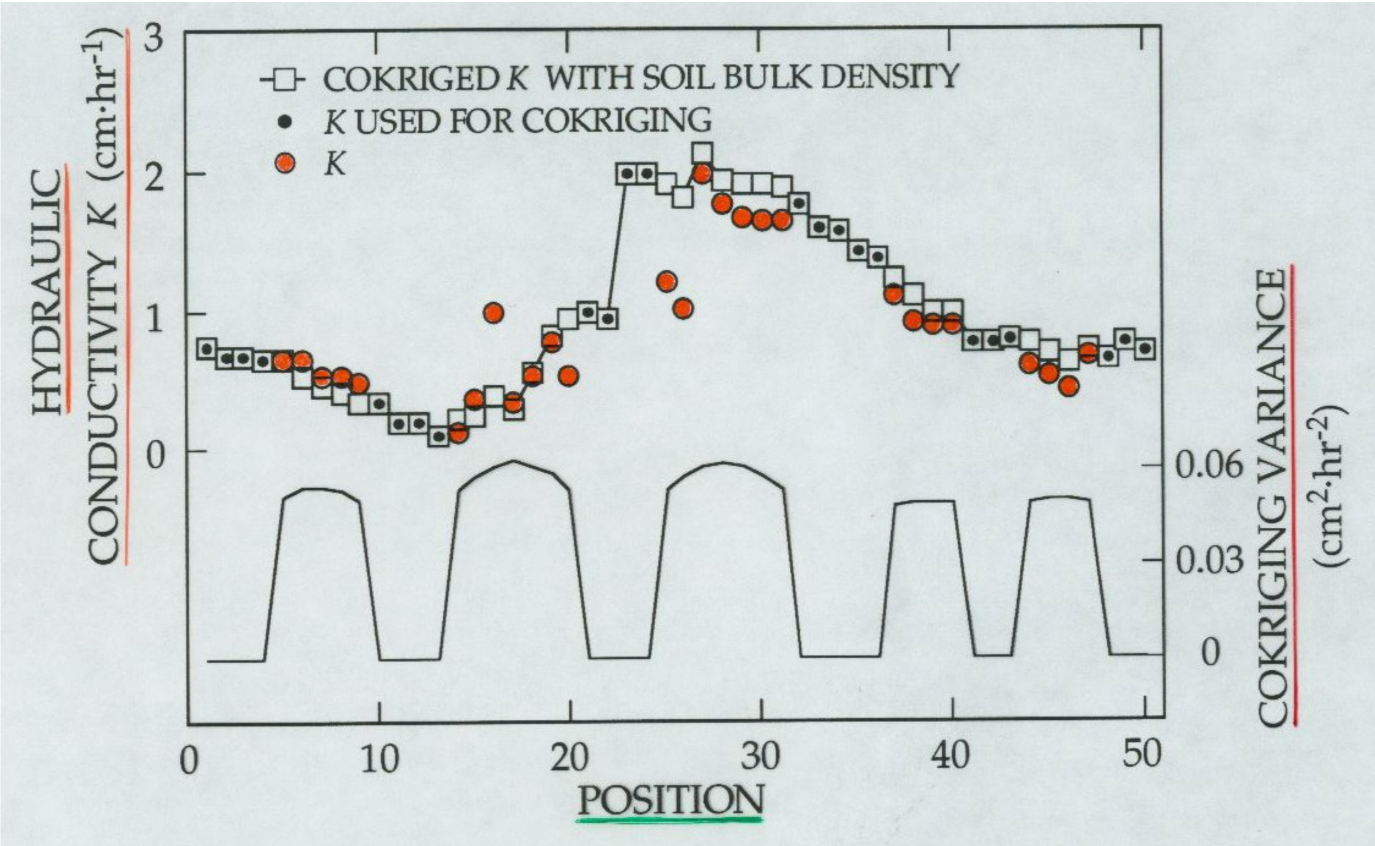
K and BD versus distance



variograms&covar
K&BD

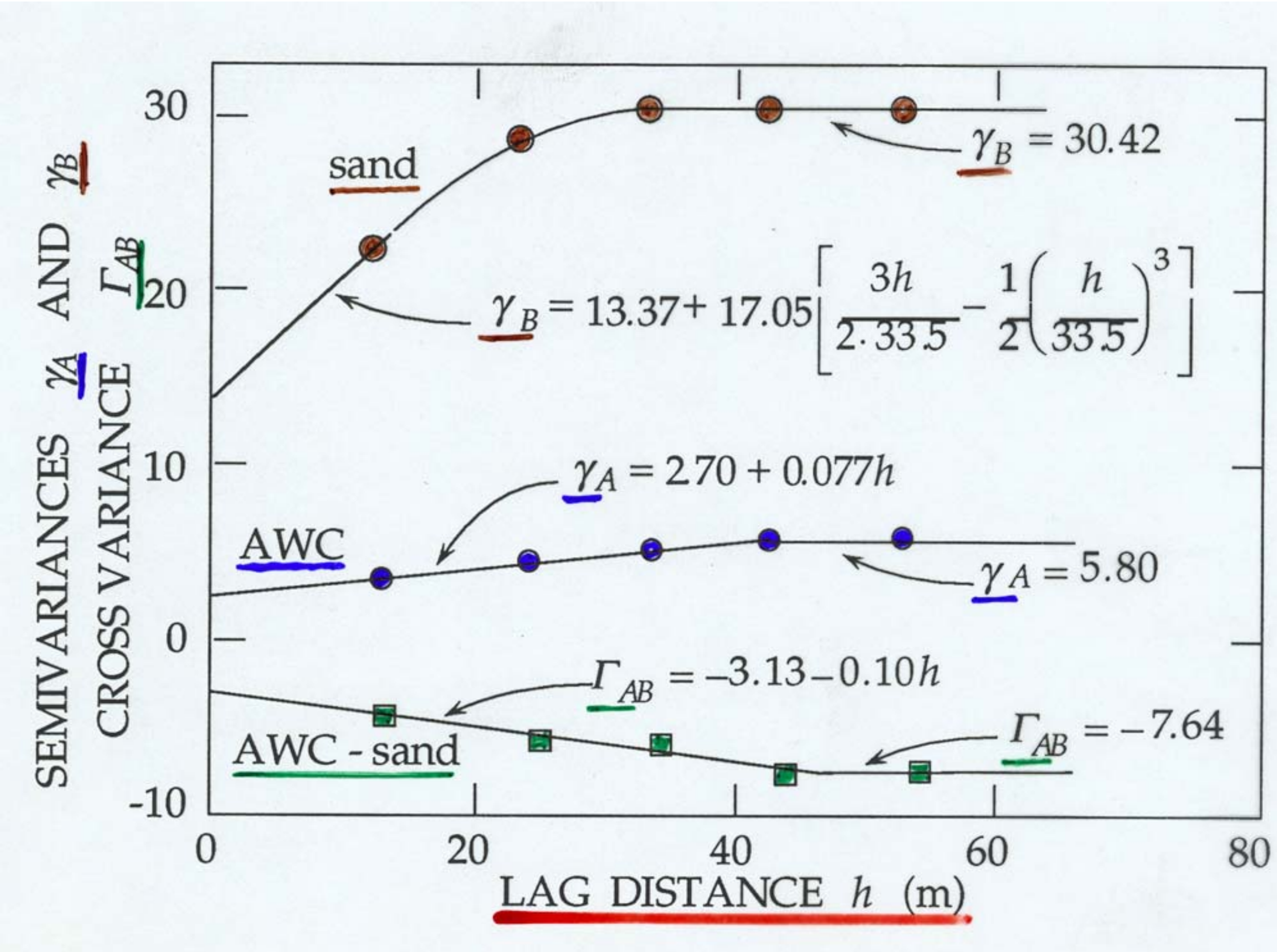


cokriged K with BD

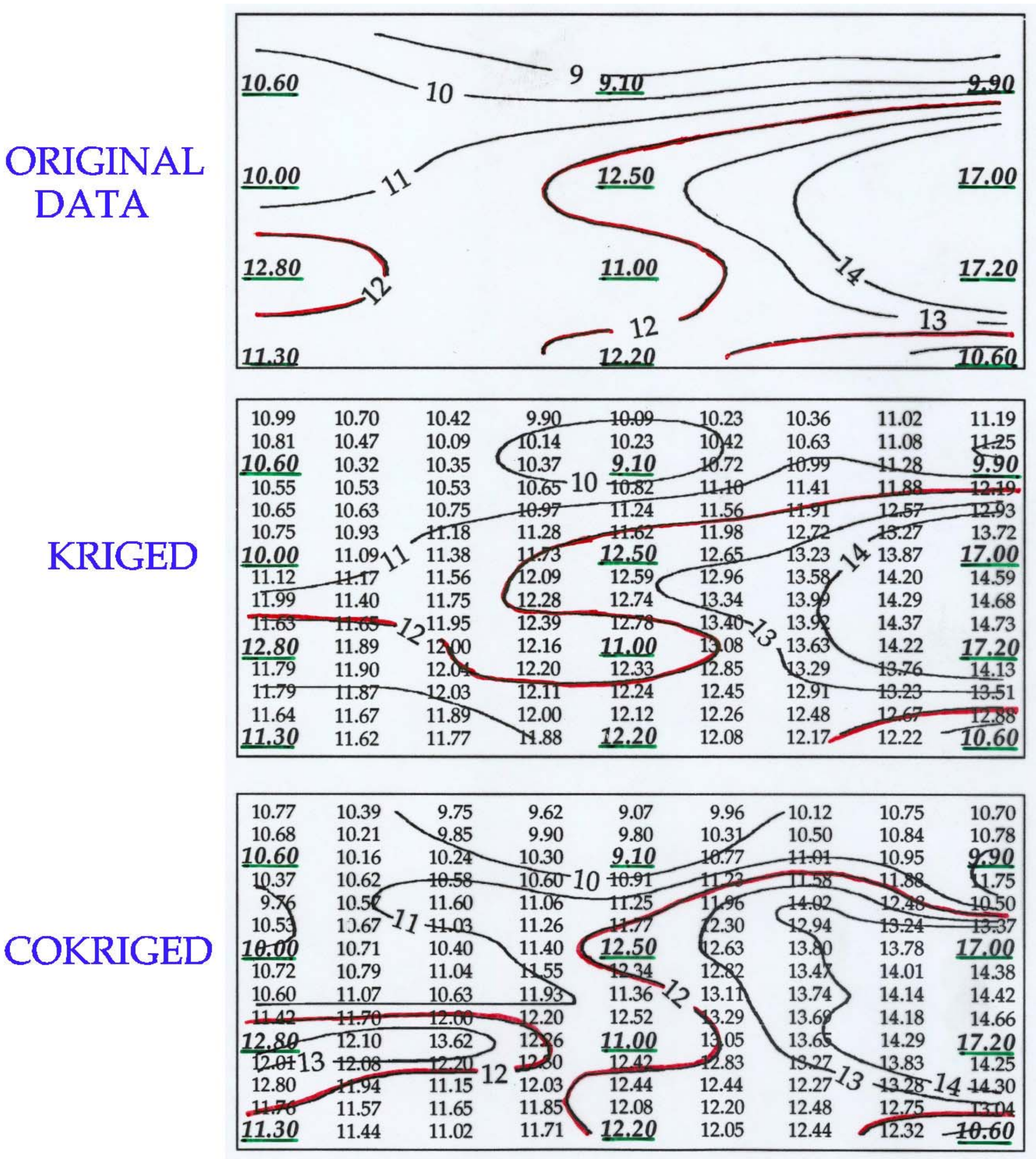


COKRIGING AVAILABLE WATER CONTENT WITH SAND CONTENT

variograms&covariogram of AWC&sand



original data, kriged & cokrige

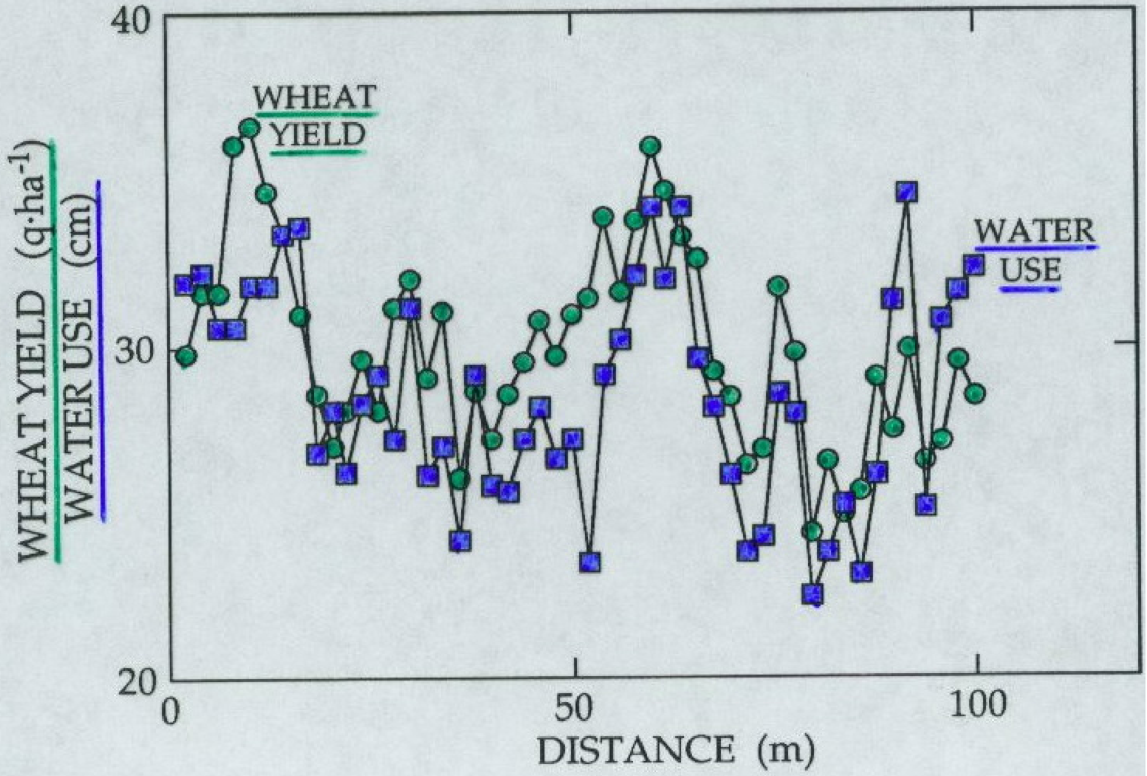


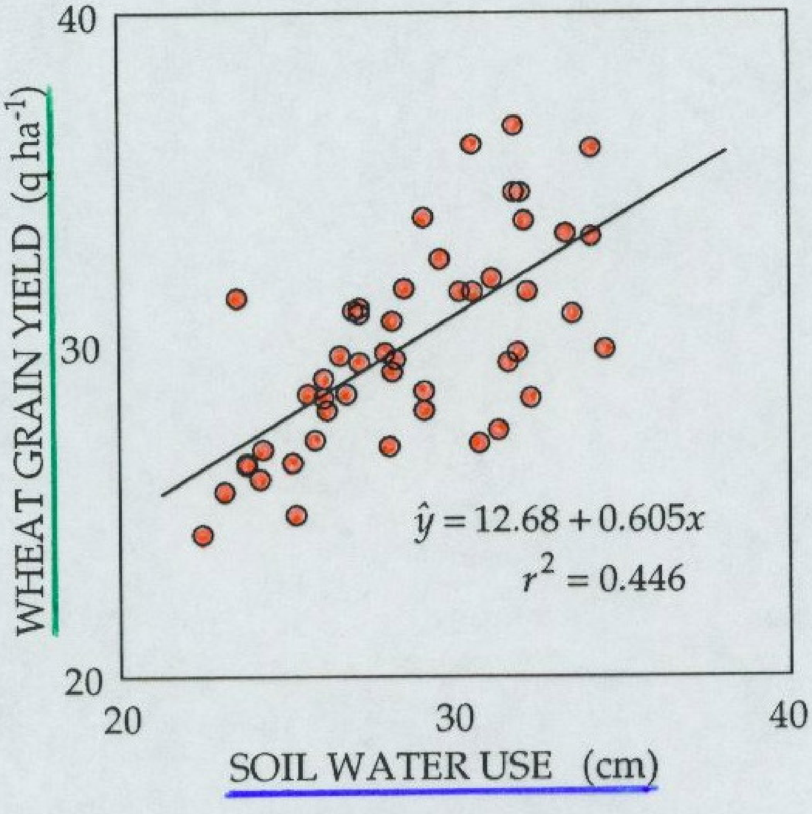
WHEAT YIELD

AND

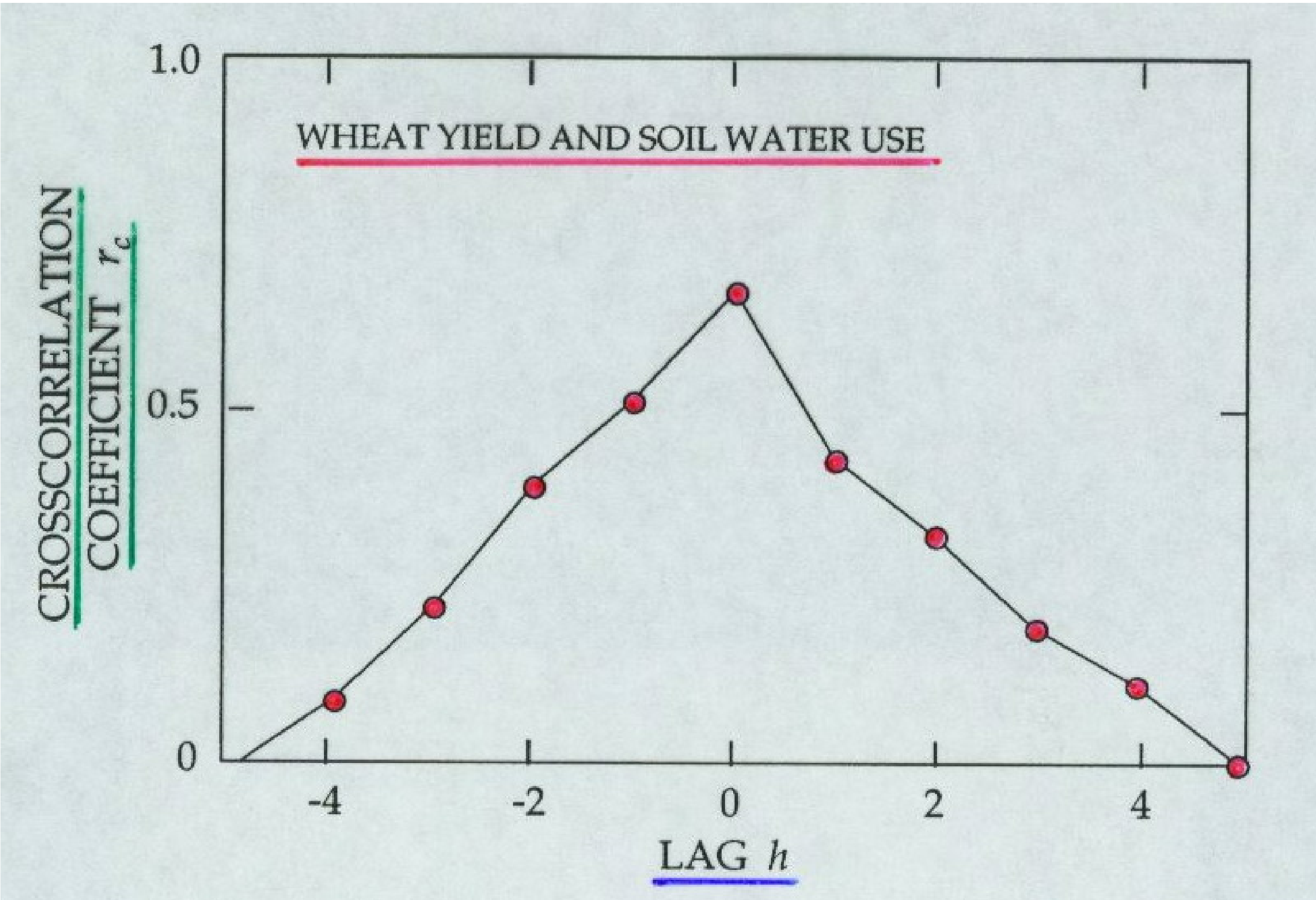
WATER USE

wheat versus water use

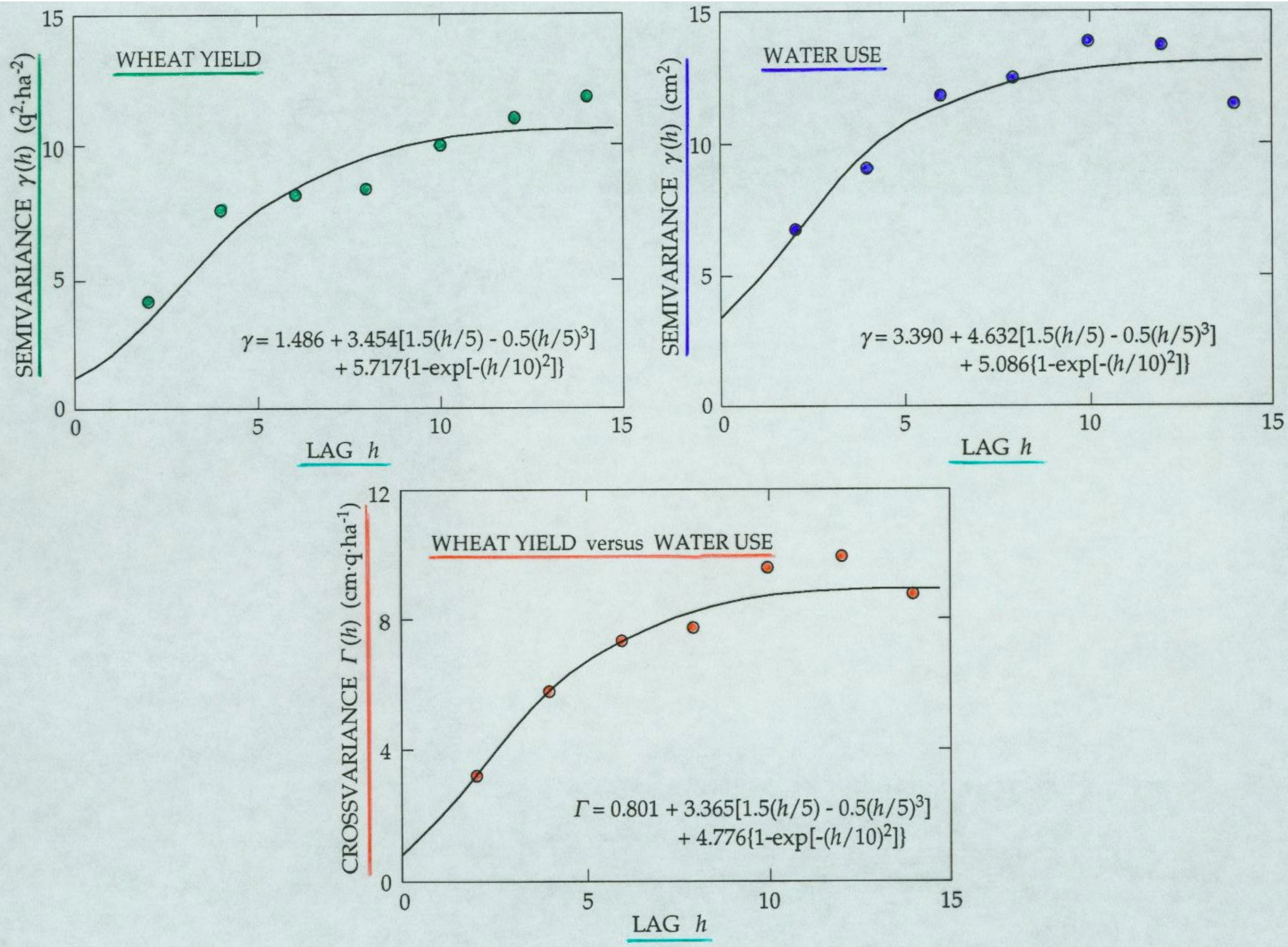




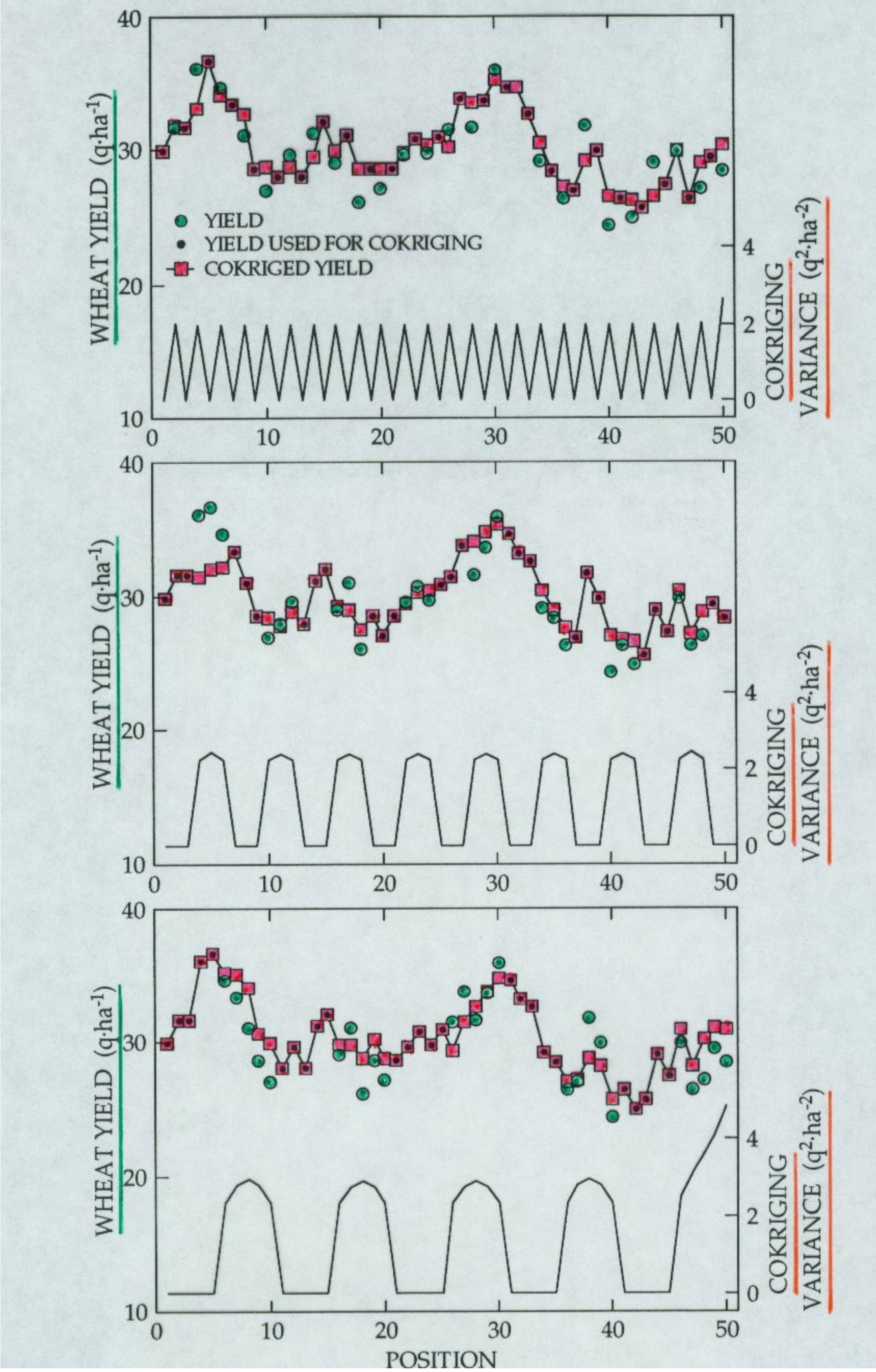
CCF wheat&water use



wheat & water use vario & covariogram



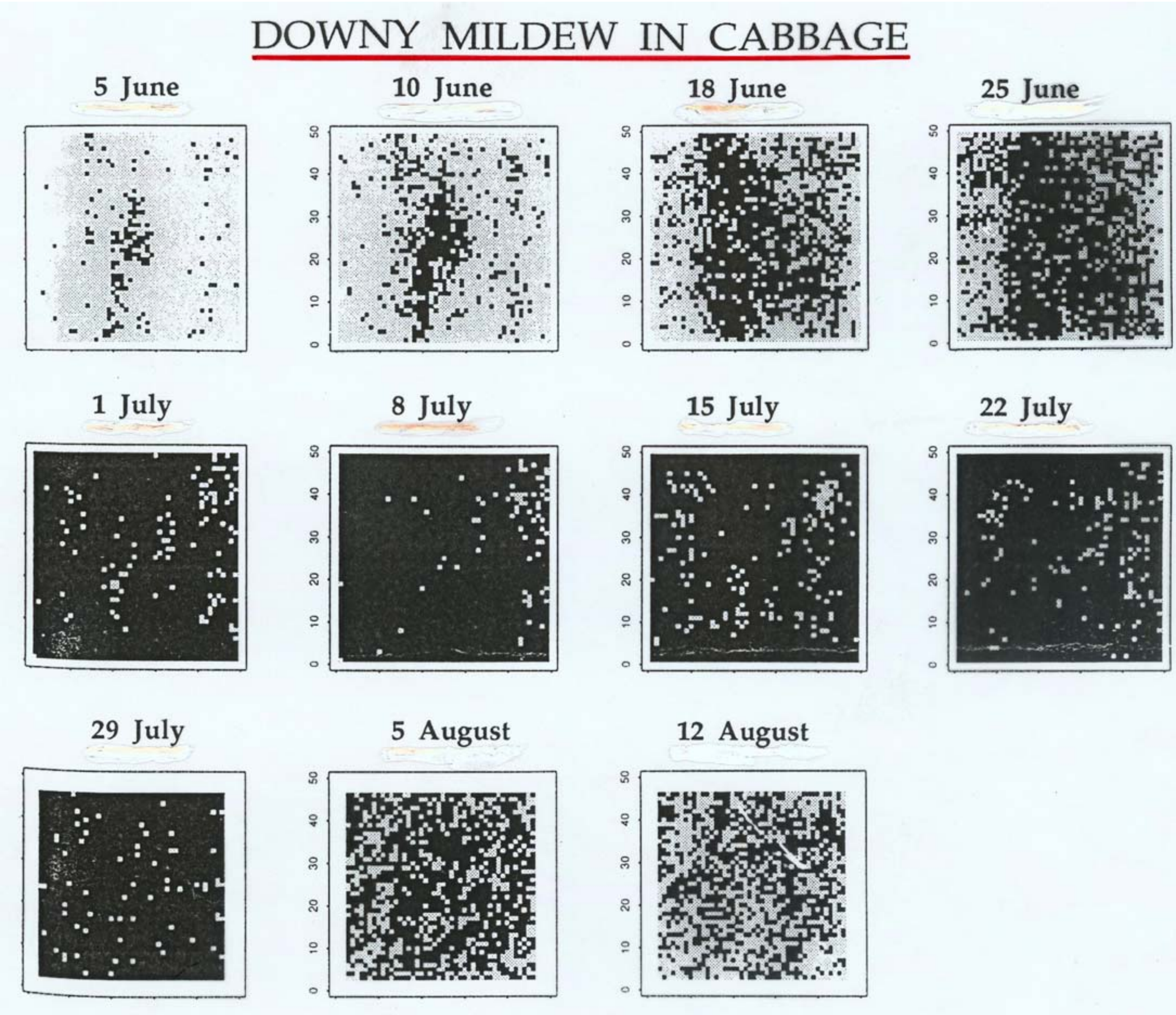
wheat&wateruse cokriging



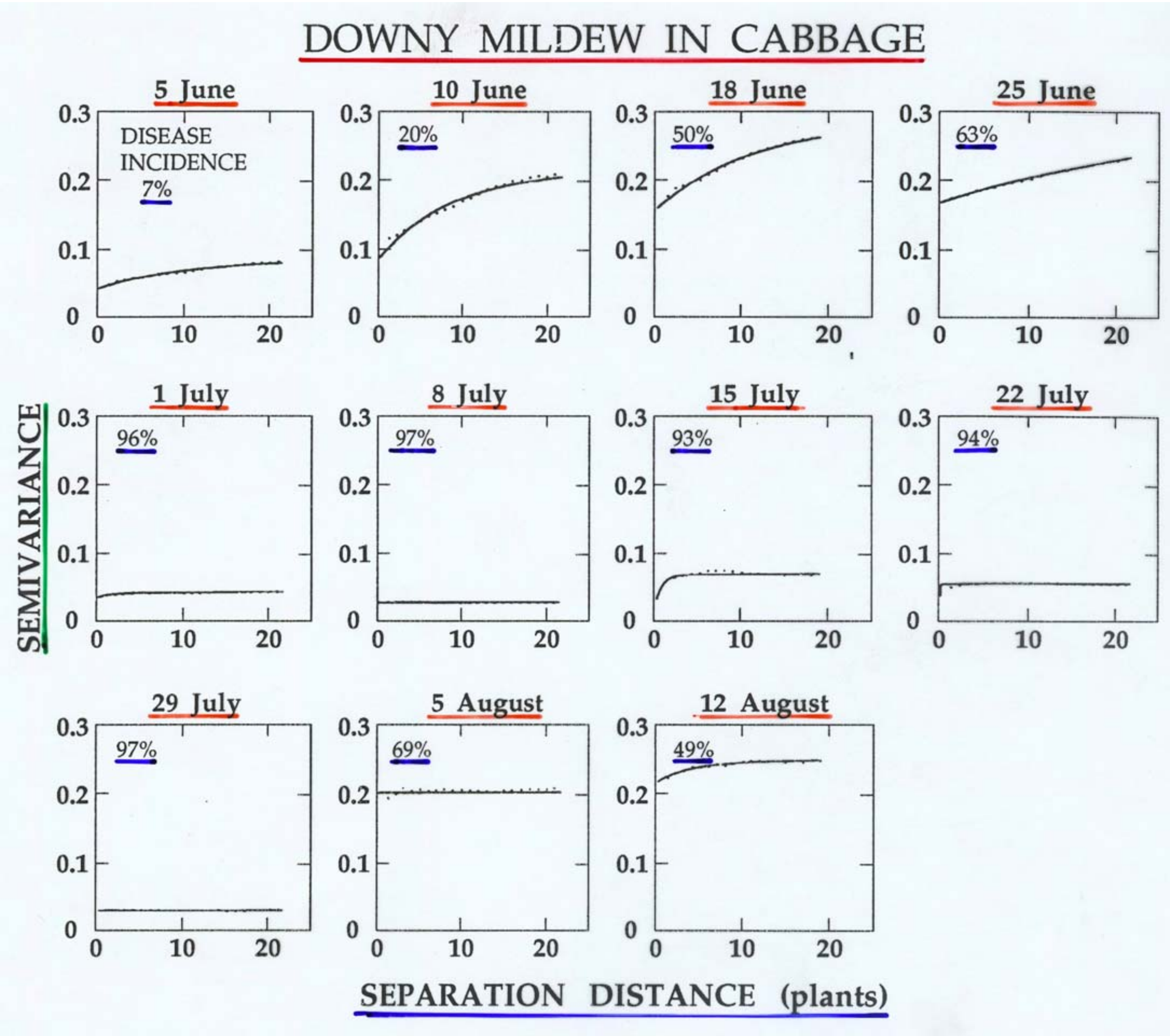
SPATIO-TEMPORAL ANALYSIS OF DOWNY MILDEW IN A FIELD OF CABBAGE

- MODELING AND PREDICTING THE SPATIAL PATTERN OF THE DISEASE AT ANY TIME
- DEVELOPING SAMPLING SCHEMES FOR FUTURE ASSESSMENT
- DETERMINING THE INITIAL LOCATION AND SPREADING RATE OF DISEASE

downy mildew in cabbage

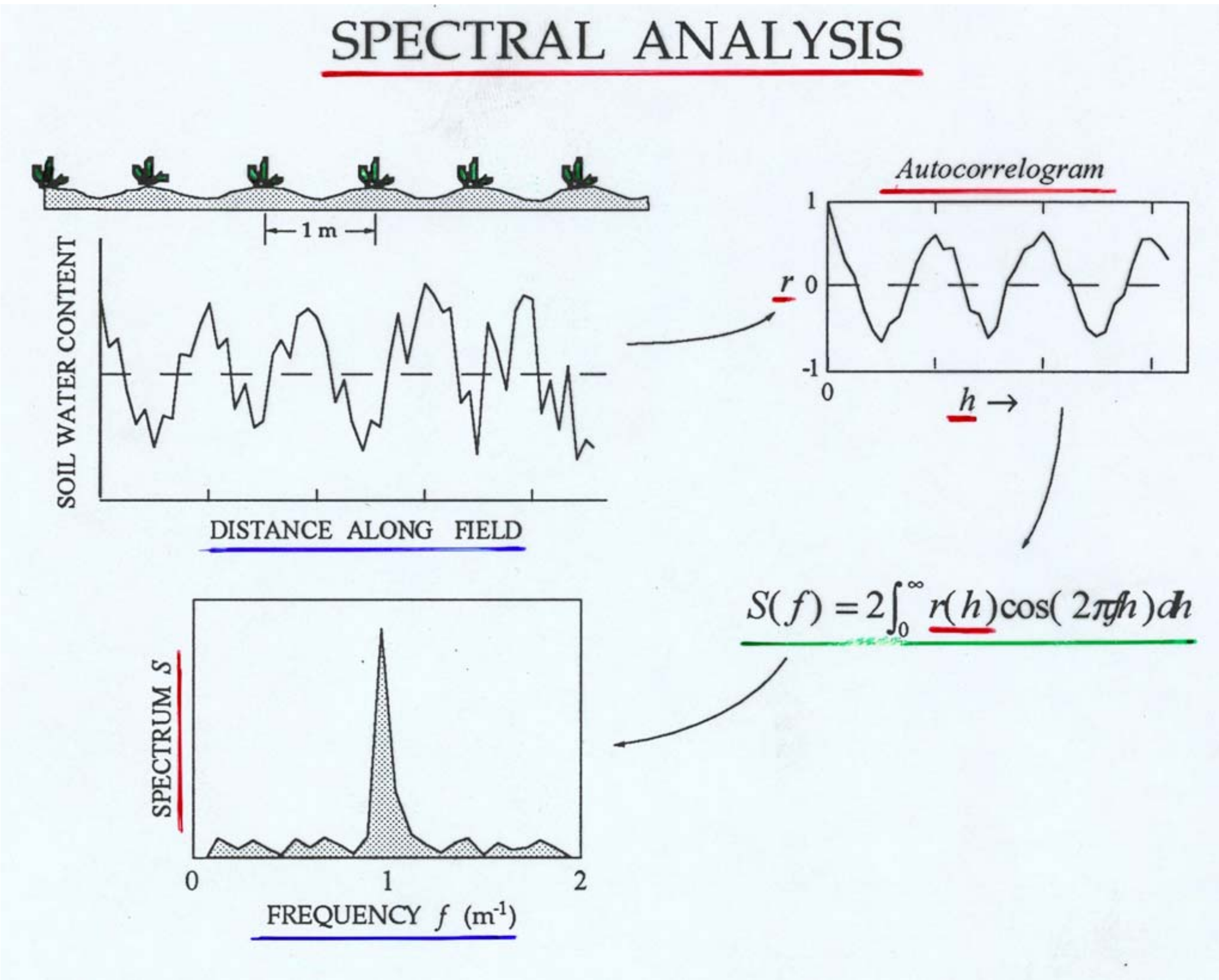


variograms downy mildew

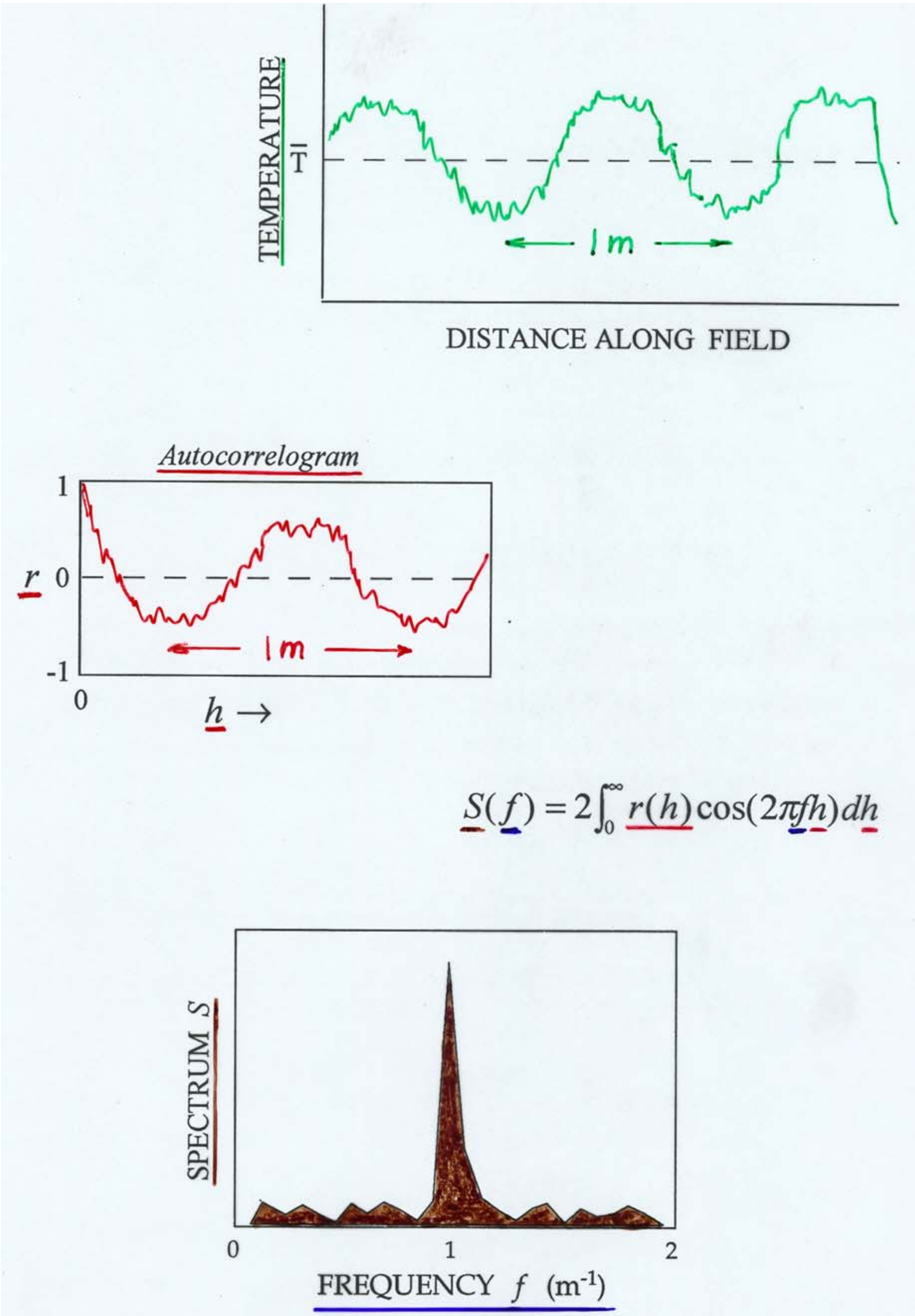


SPECTRAL ANALYSIS

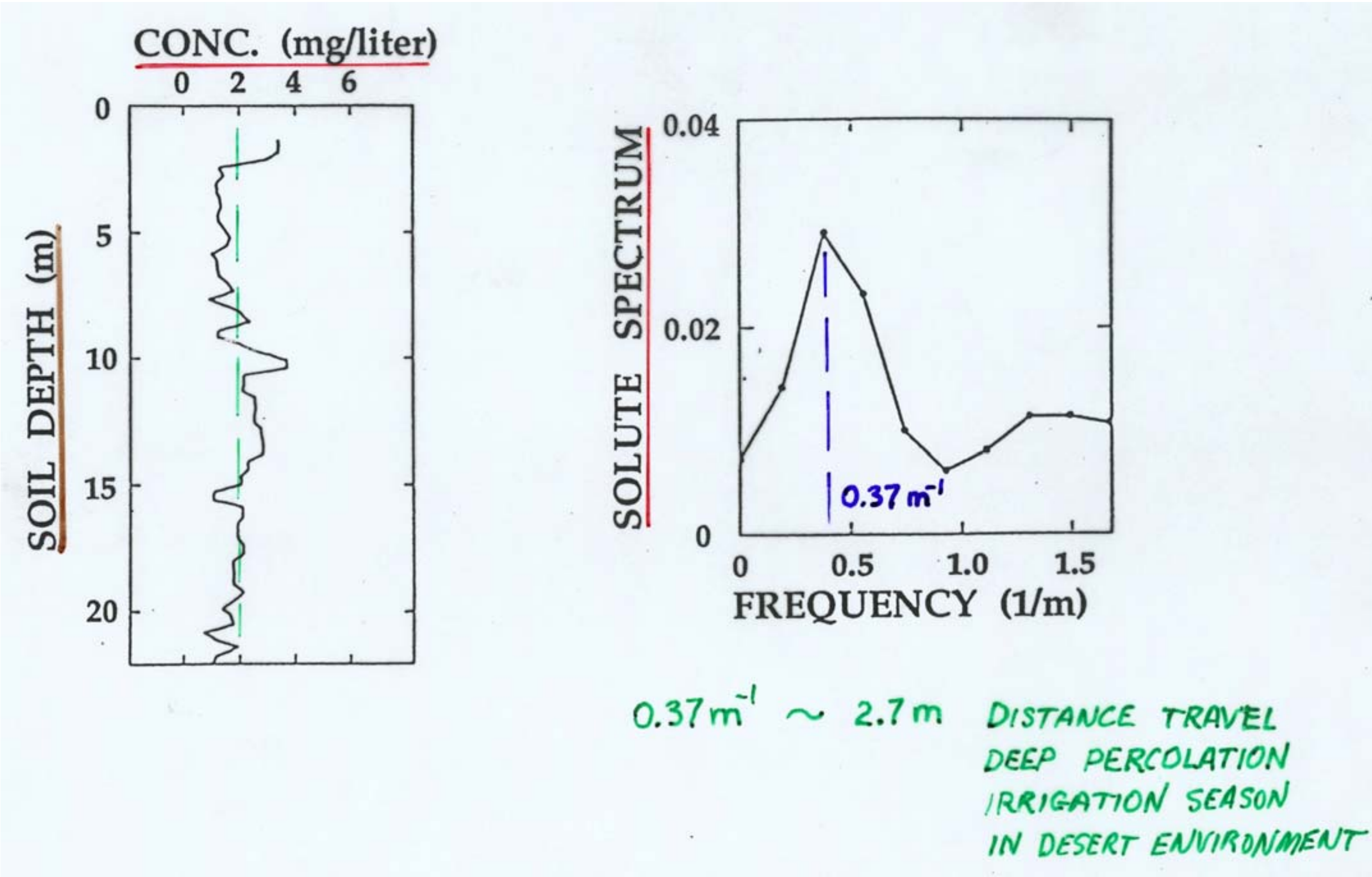
spectral analysis illustration



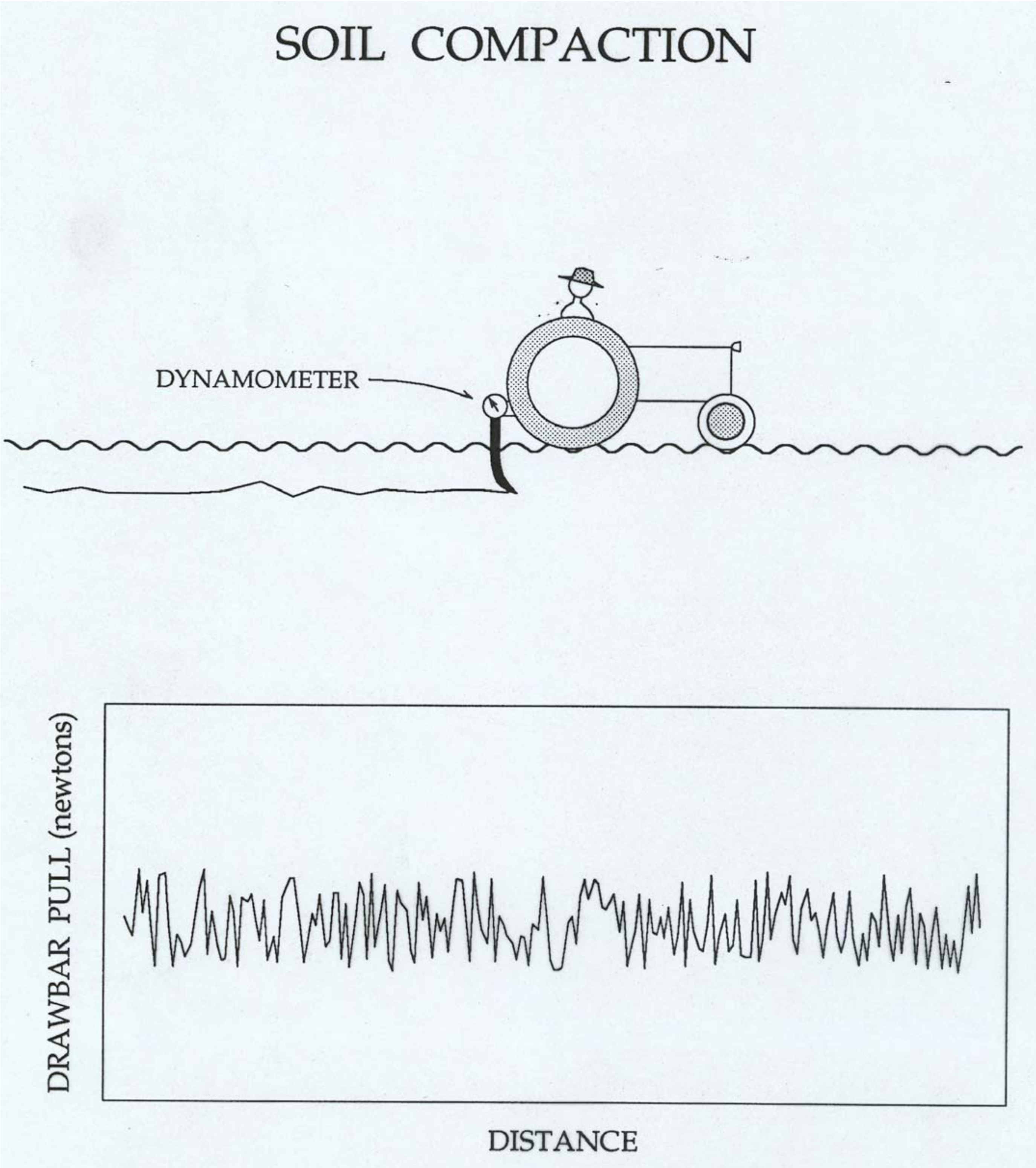
spectral analysis concept calc



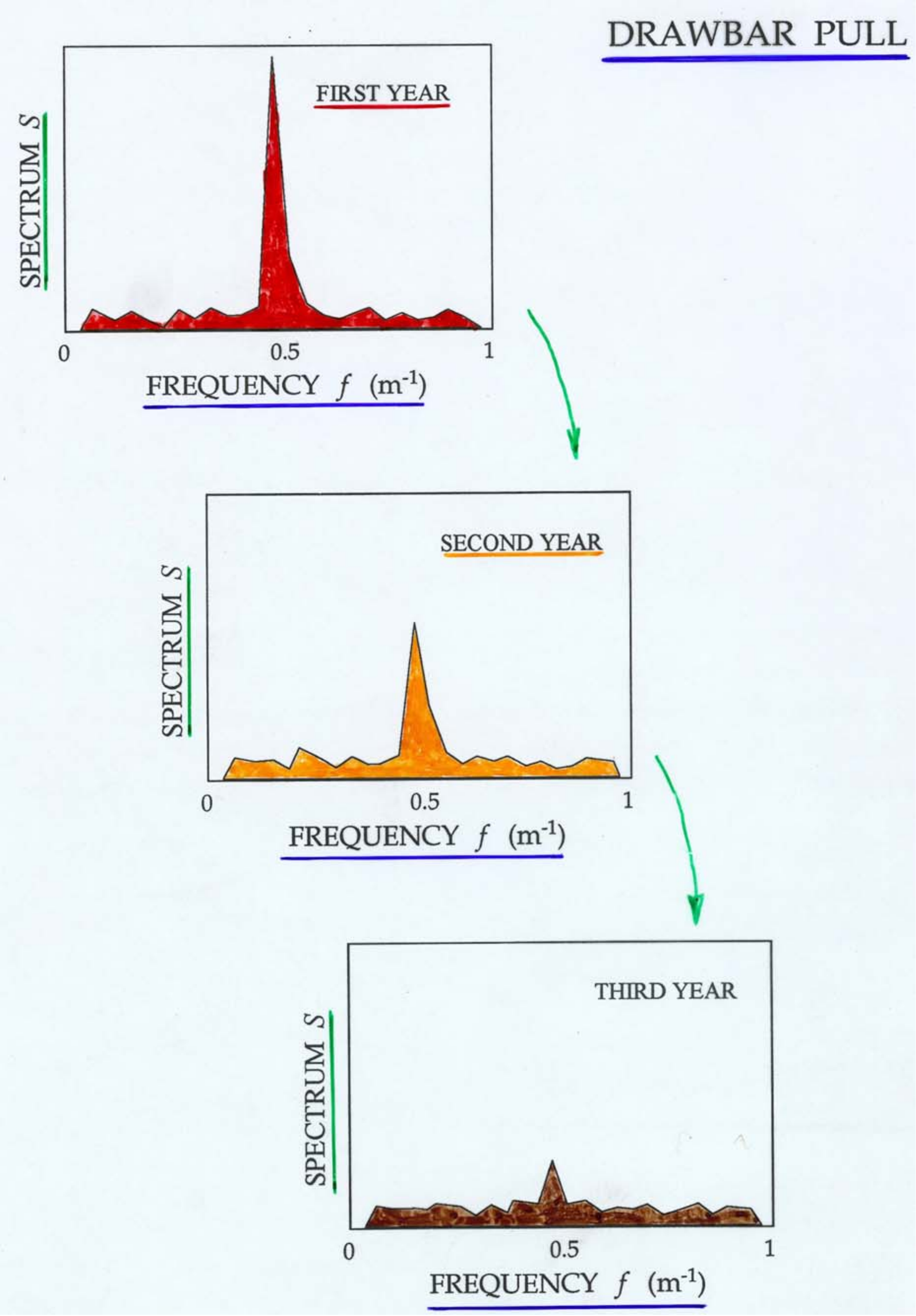
soil depth solute spectrum NM



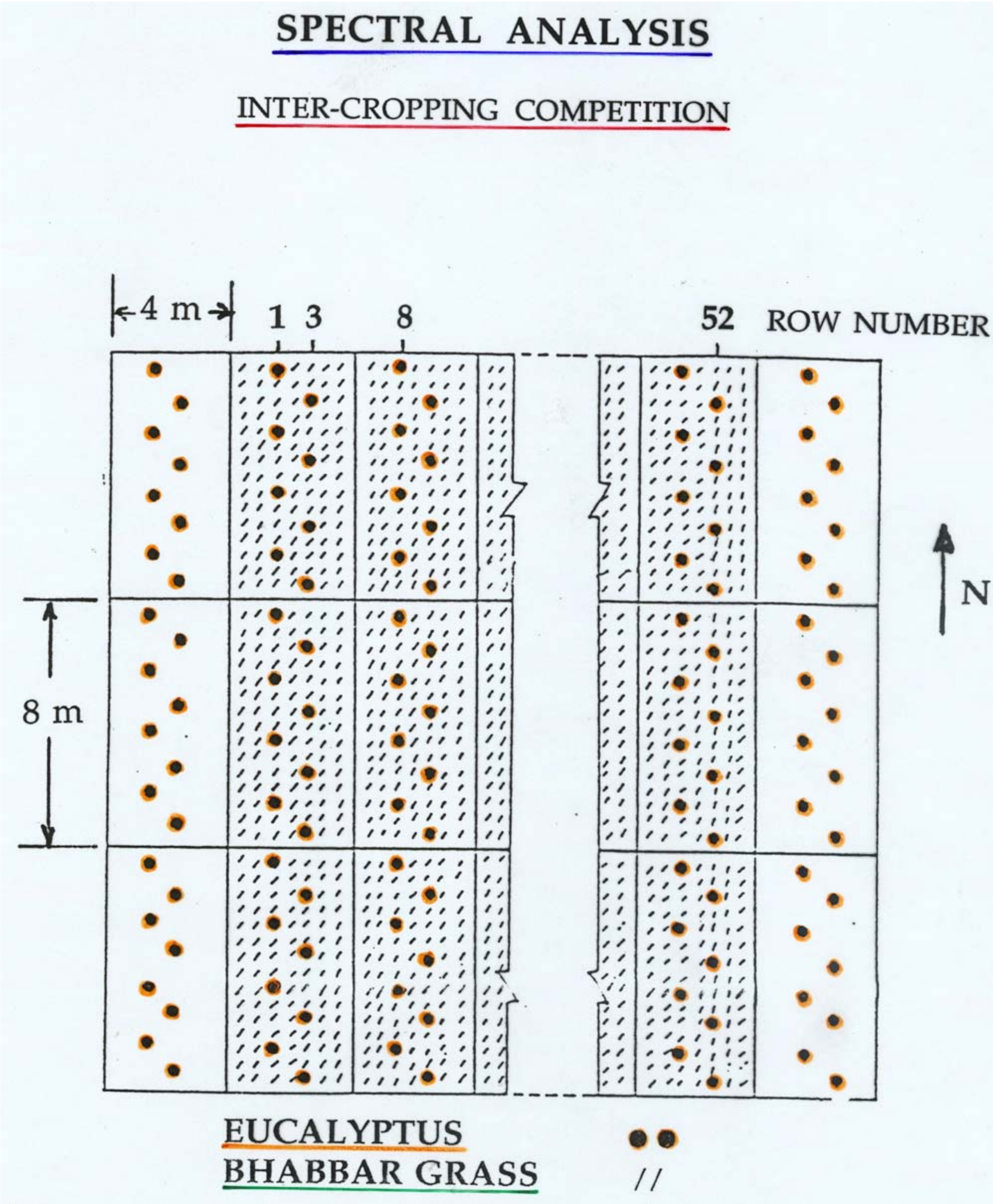
soil compaction
dynamometer



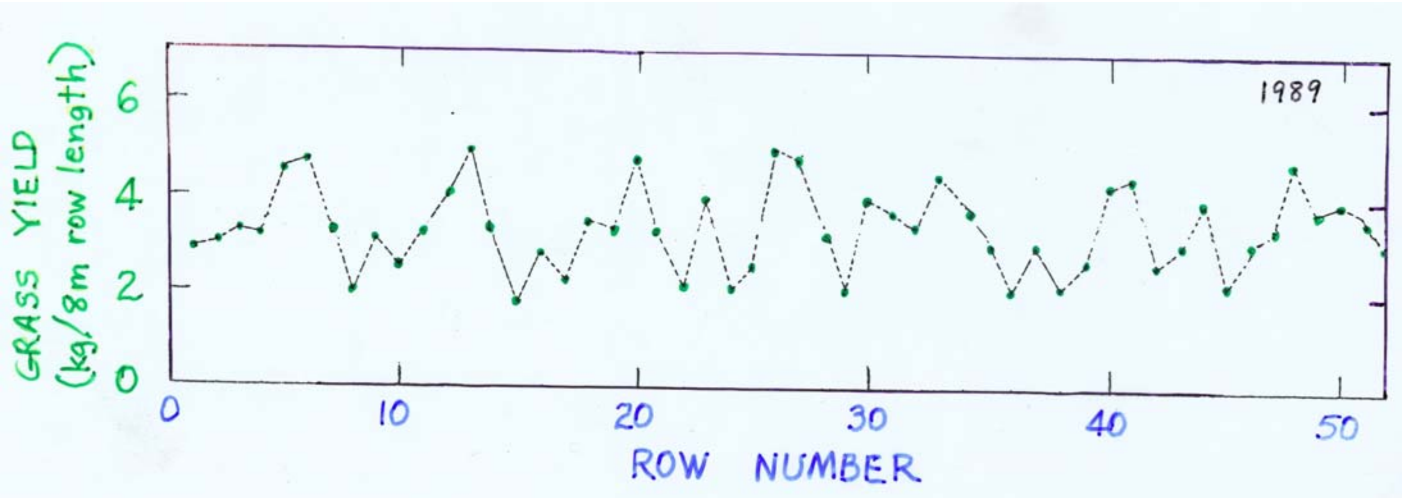
drawbar pull spectra 3 yrs



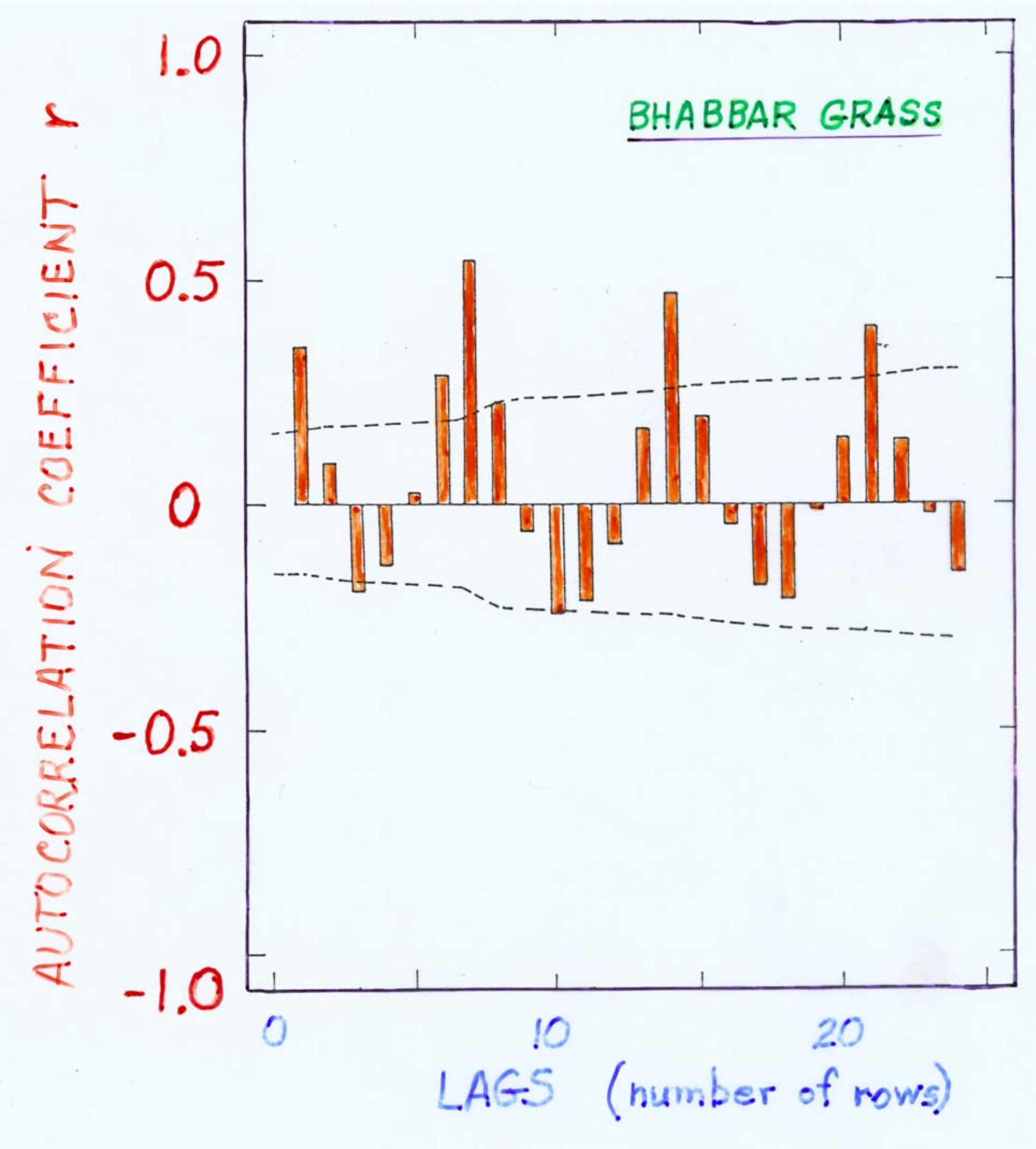
spectral analysis bhabbar grass



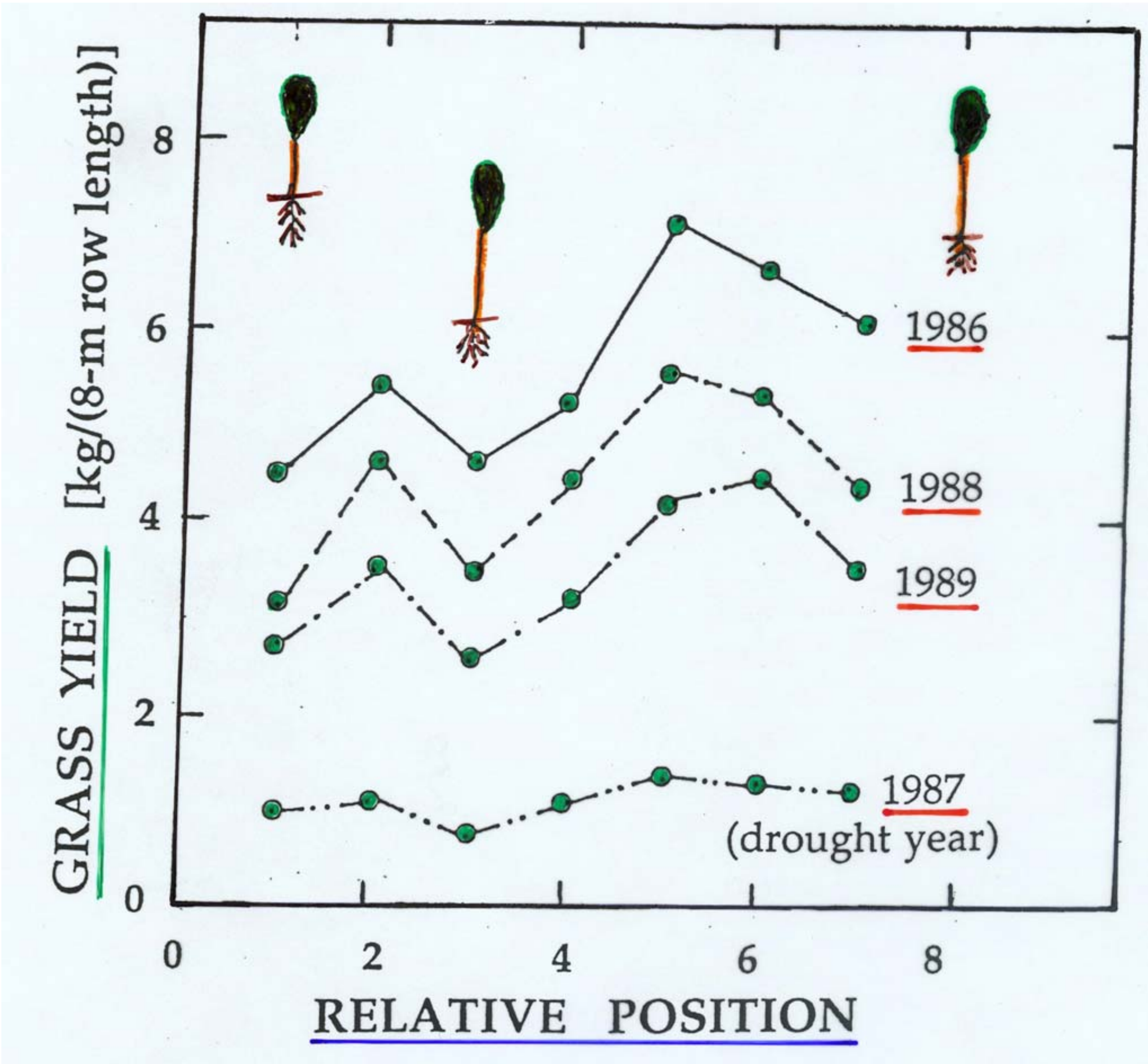
bhabbar grass yield vs location



ACF bhabbar grass



bhabbar grass vs location



bhabbar grass&eucalyptus conclusions

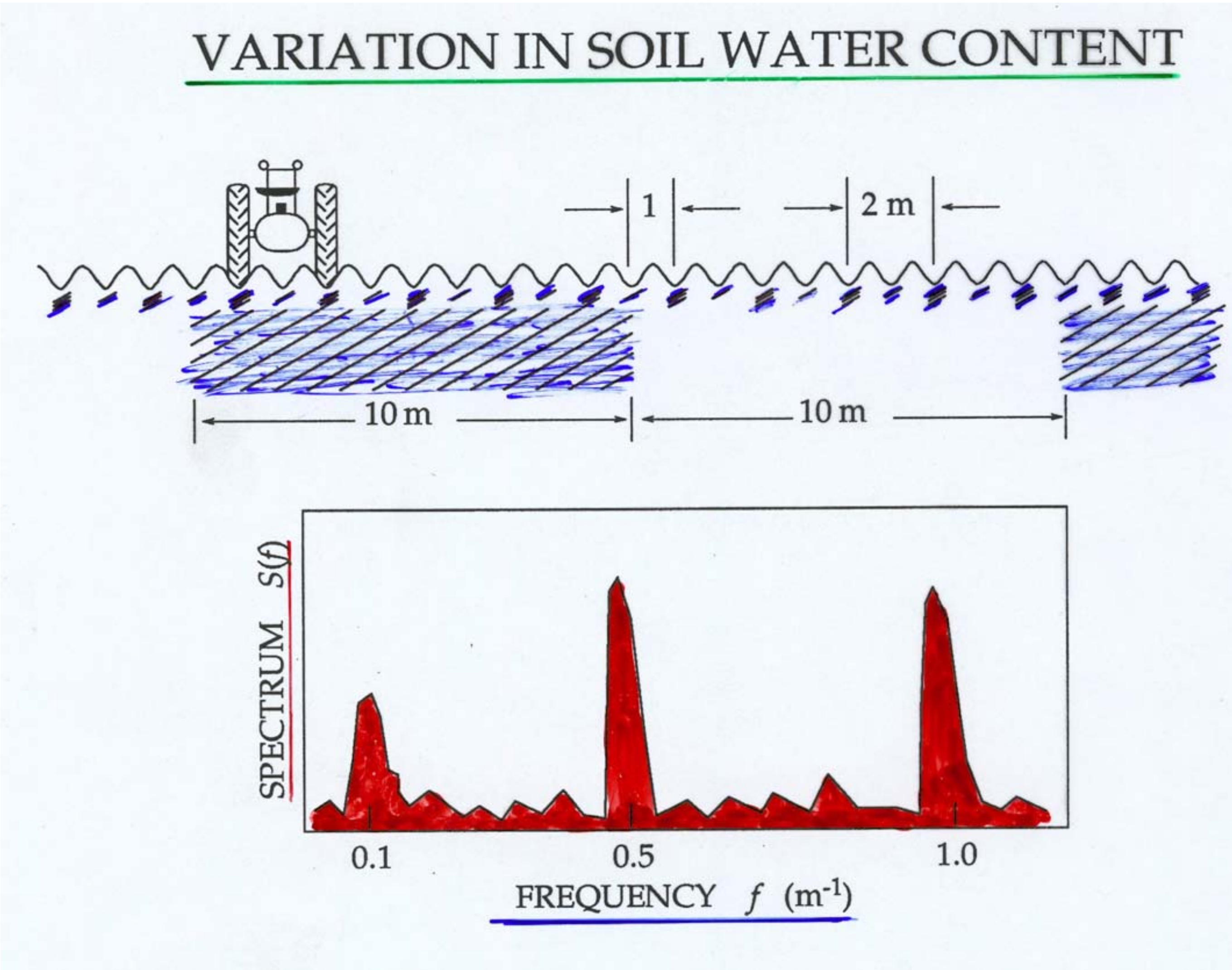
CONCLUSIONS

- VARIATION IN GRASS PRODUCTION AT A FREQUENCY CORRESPONDING TO 3.5m IS RELATED TO EUCALYPTUS TREES DURING THE FIRST YEAR.

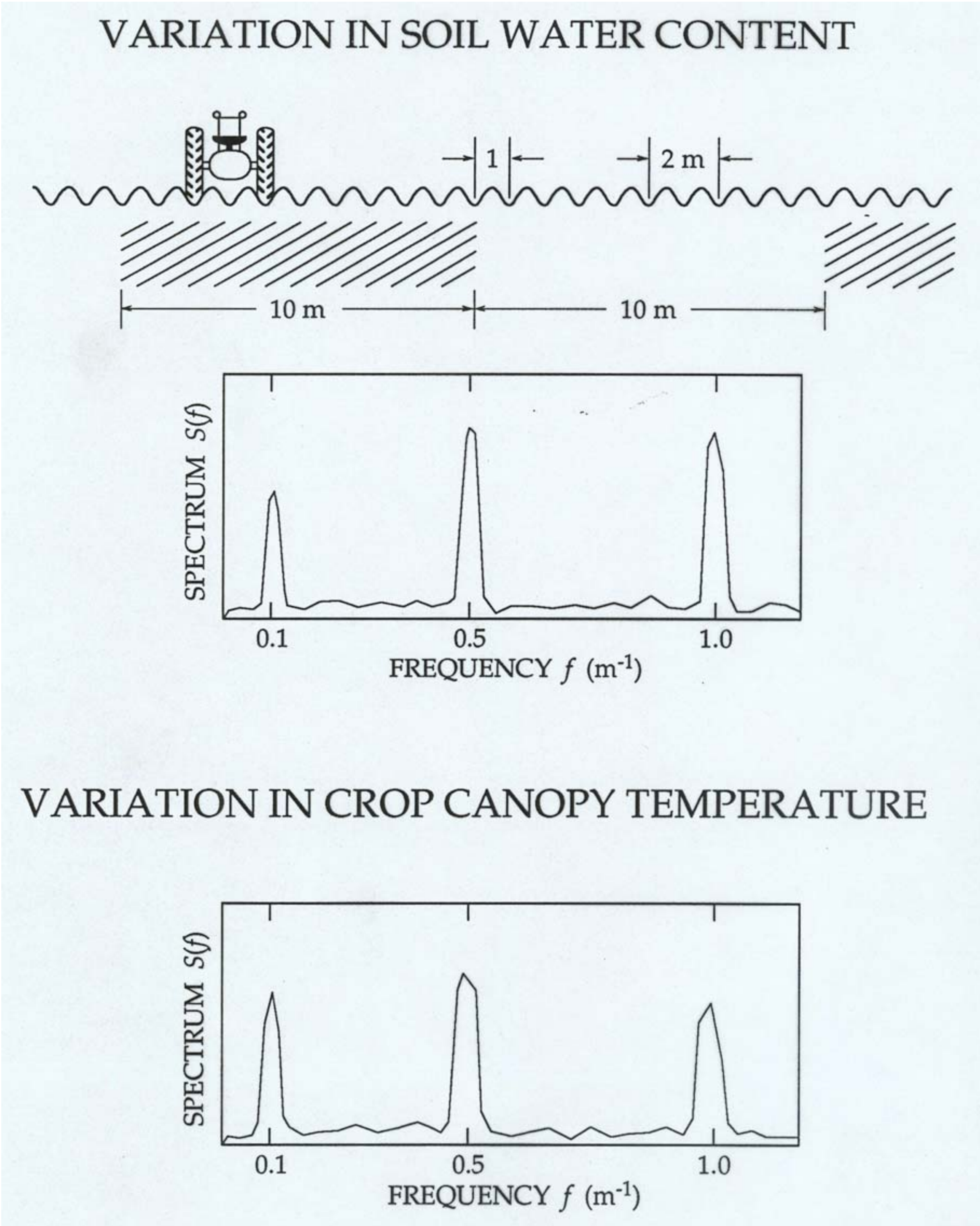
- ADDITIONAL VARIATION IN GRASS PRODUCTION AT A FREQUENCIES CORRESPONDING TO 1.75 AND 1.17m DURING OTHER YEARS AS TREES GREW TALLER.

CO-SPECTRAL ANALYSIS

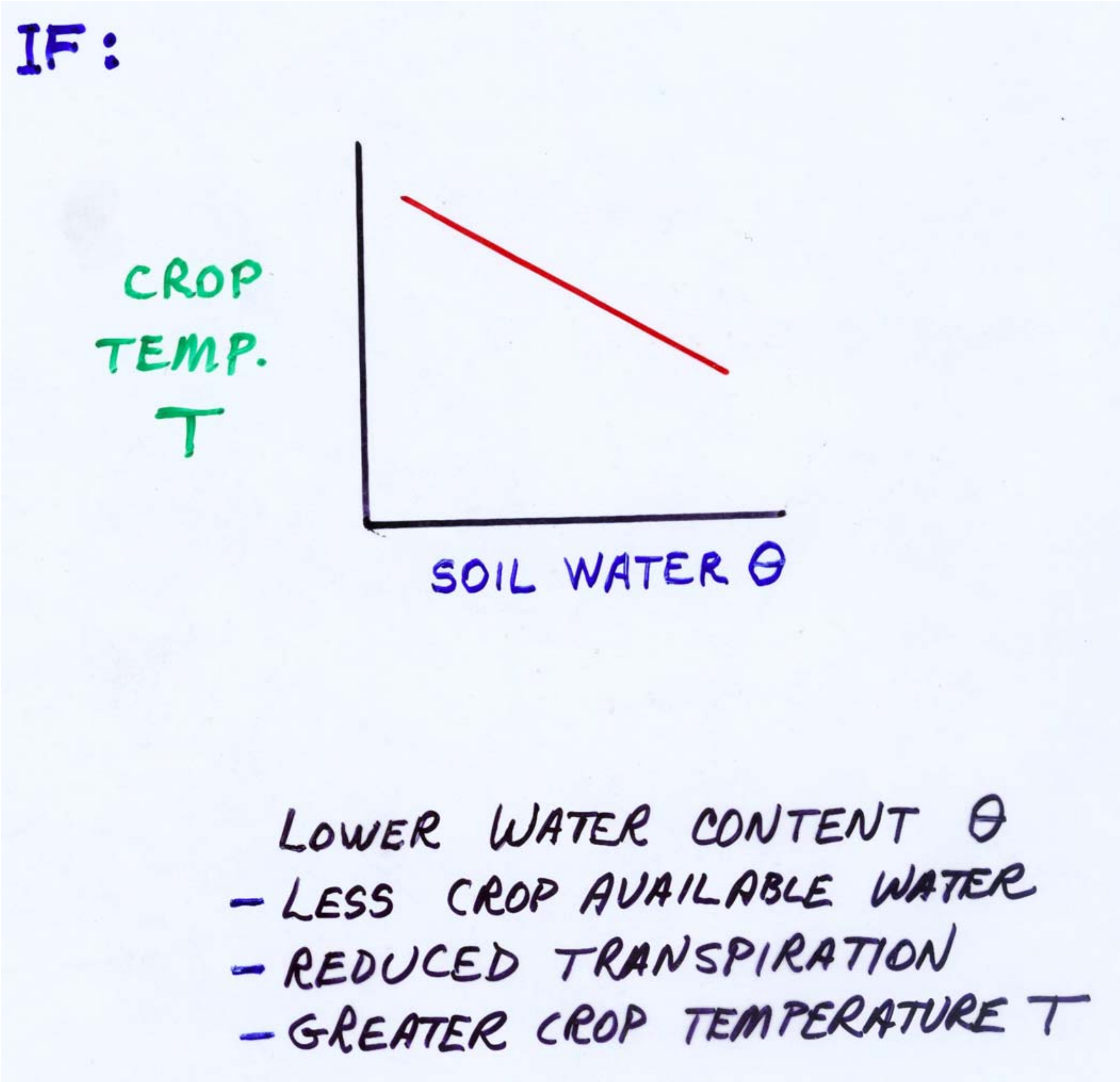
variation in water soil content



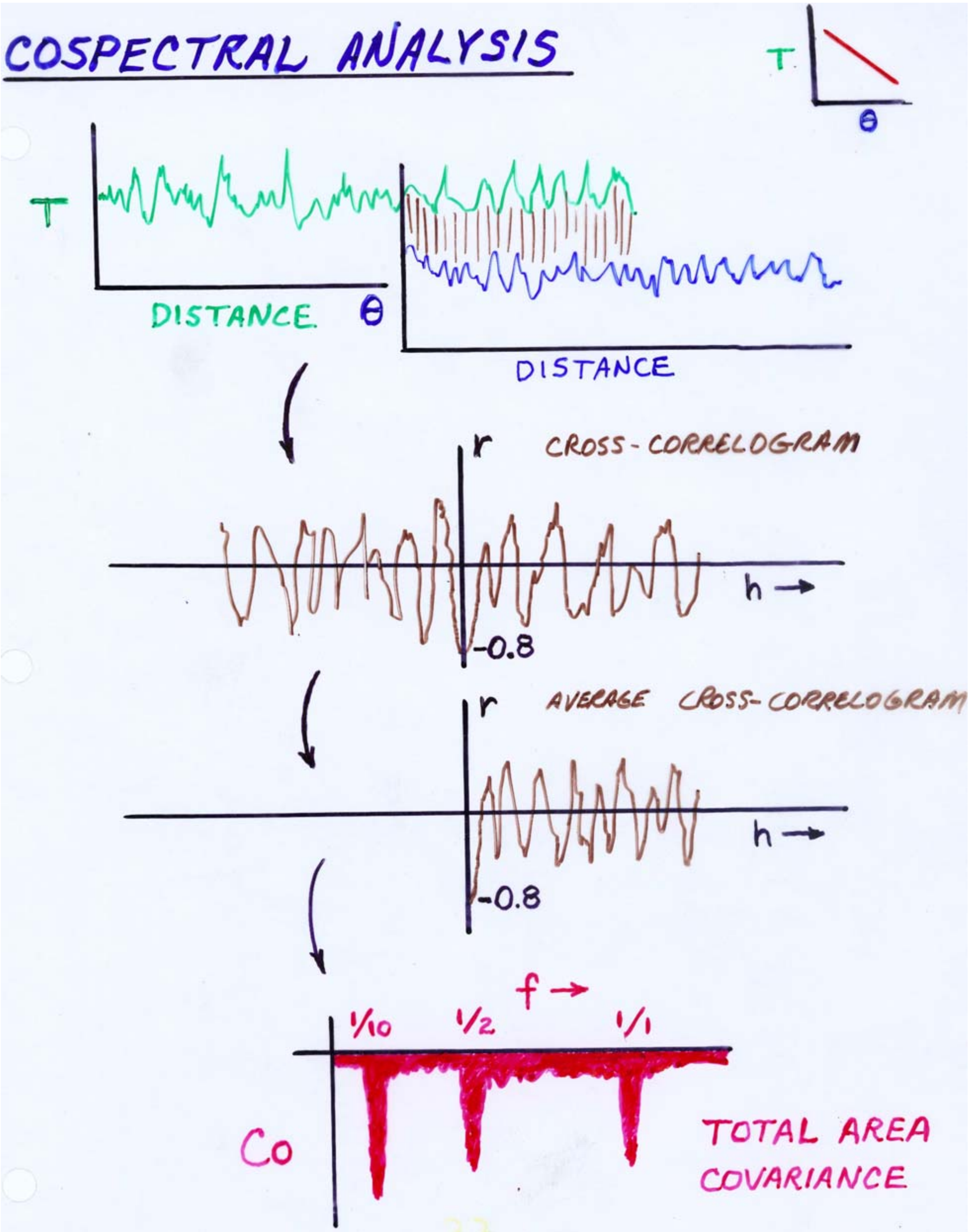
161 variation in soil water content &crop temp



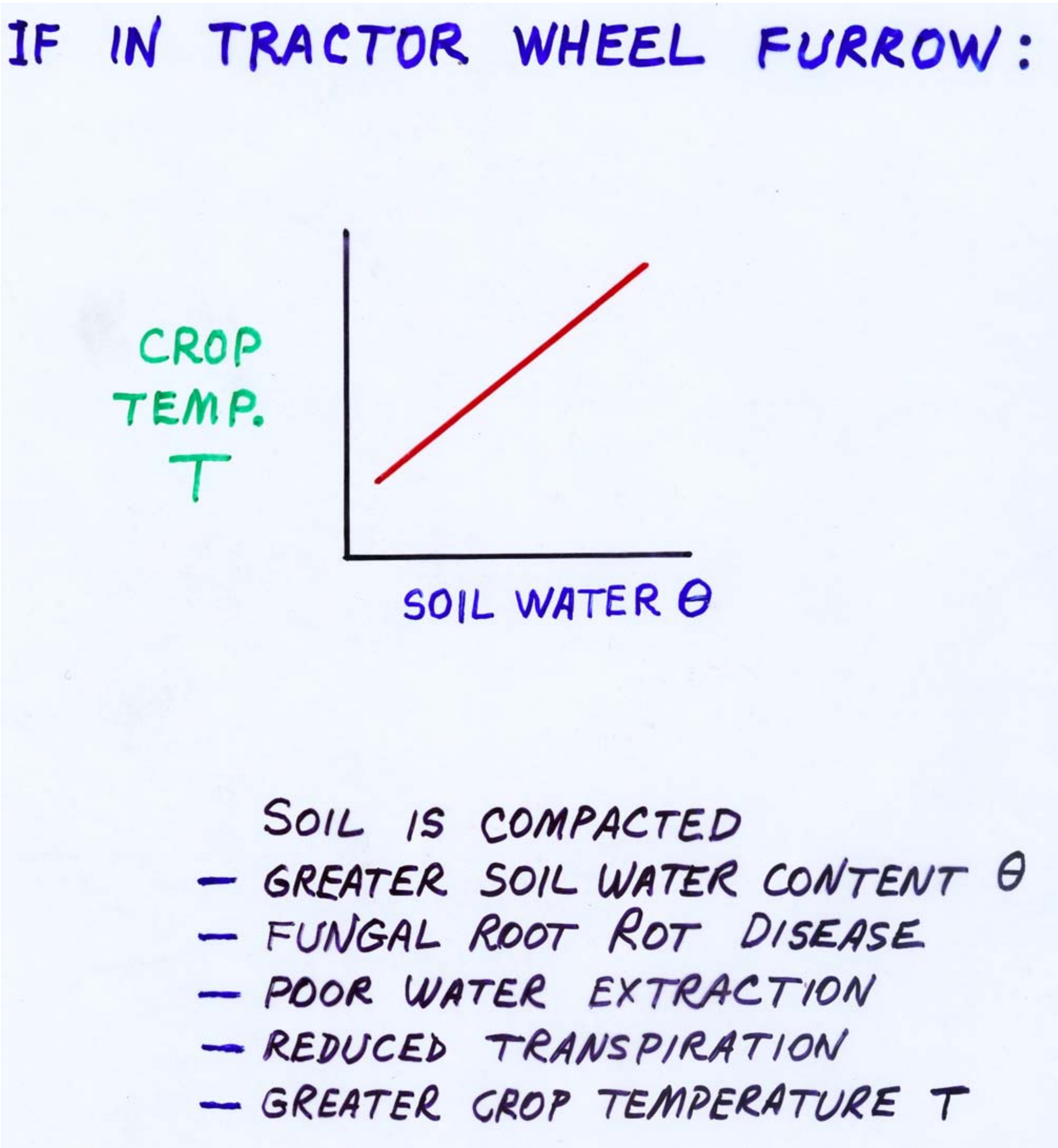
if crop T inversely related to theta



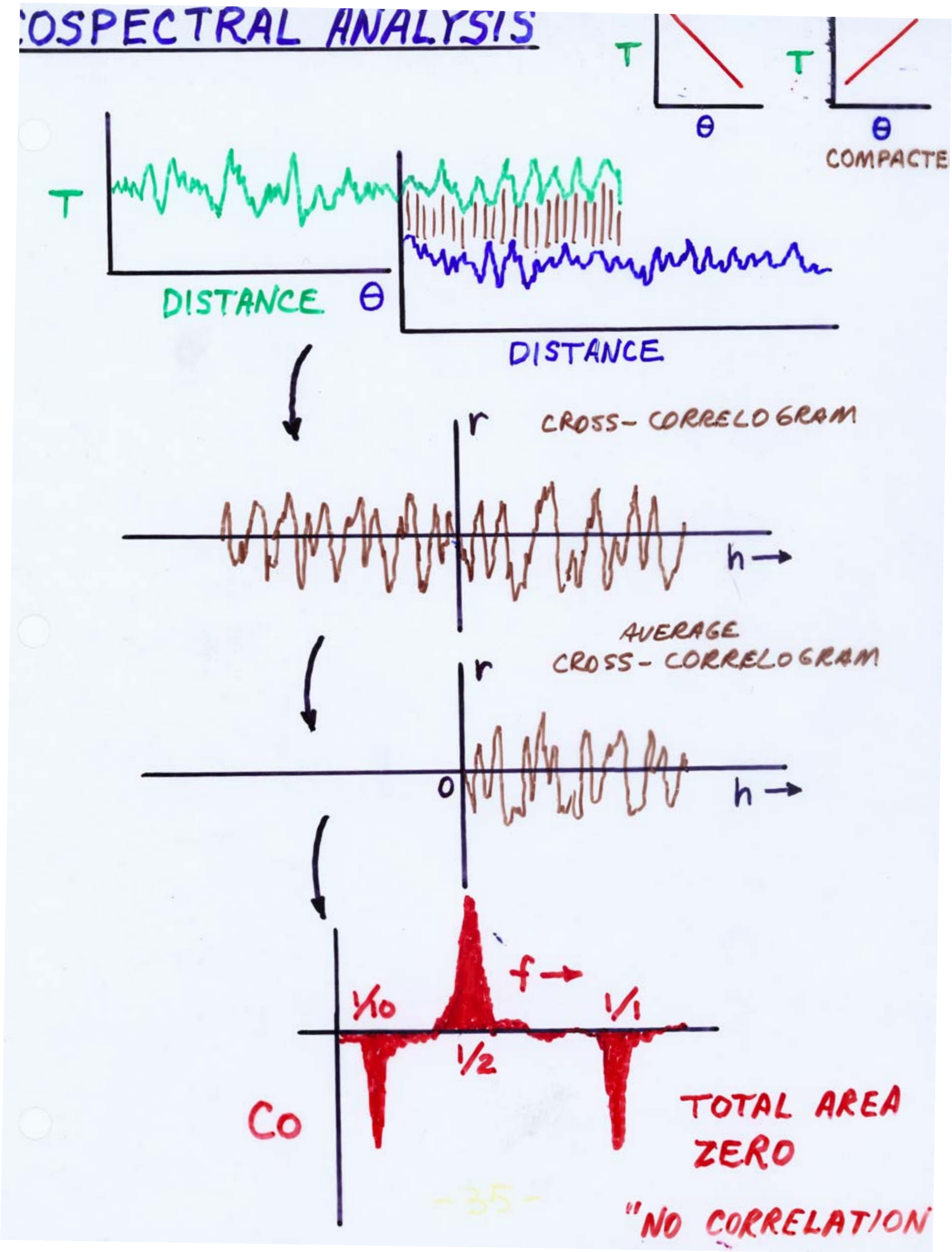
cospectral analysis diag no compaction



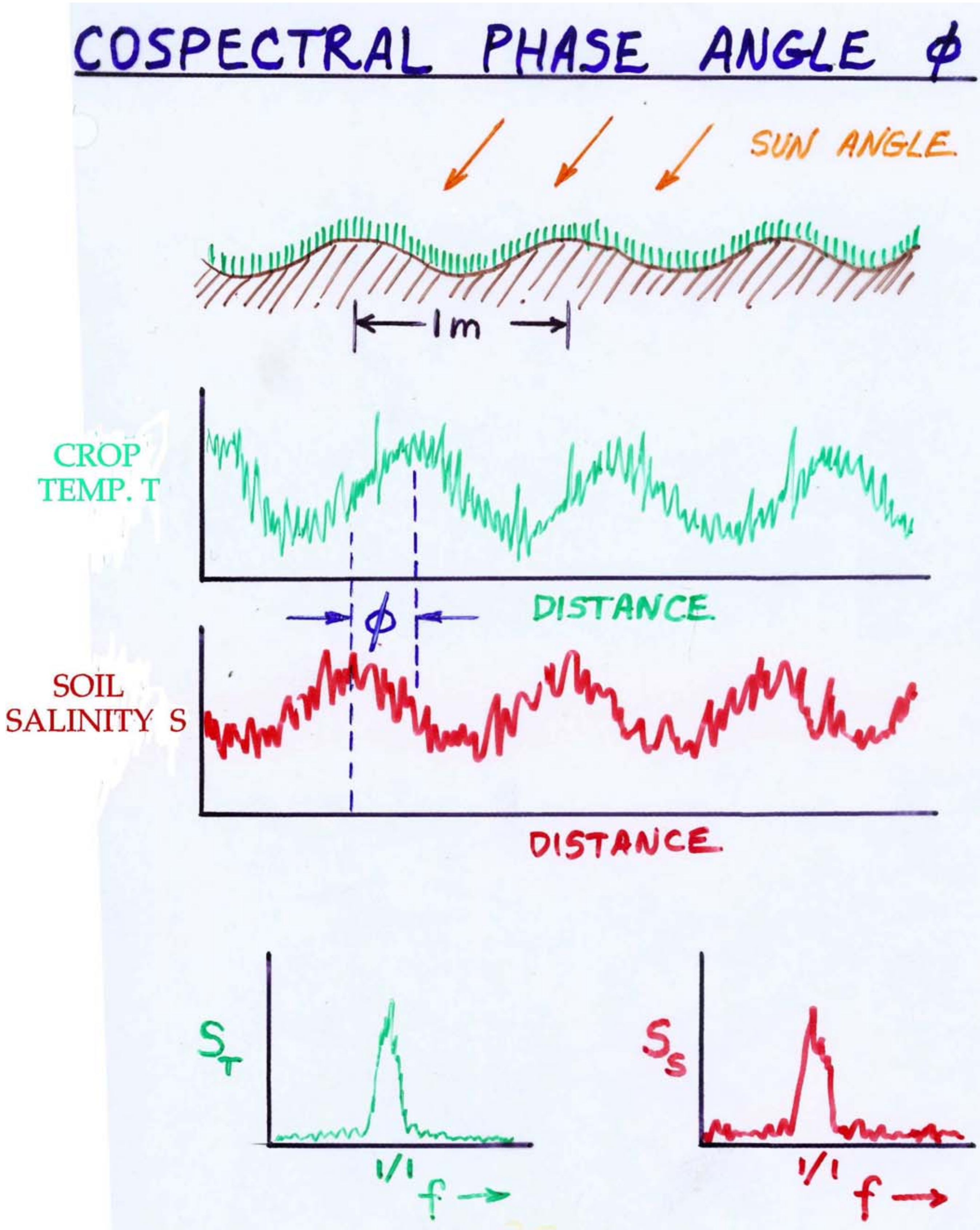
if compaction in tractor wheel furrow



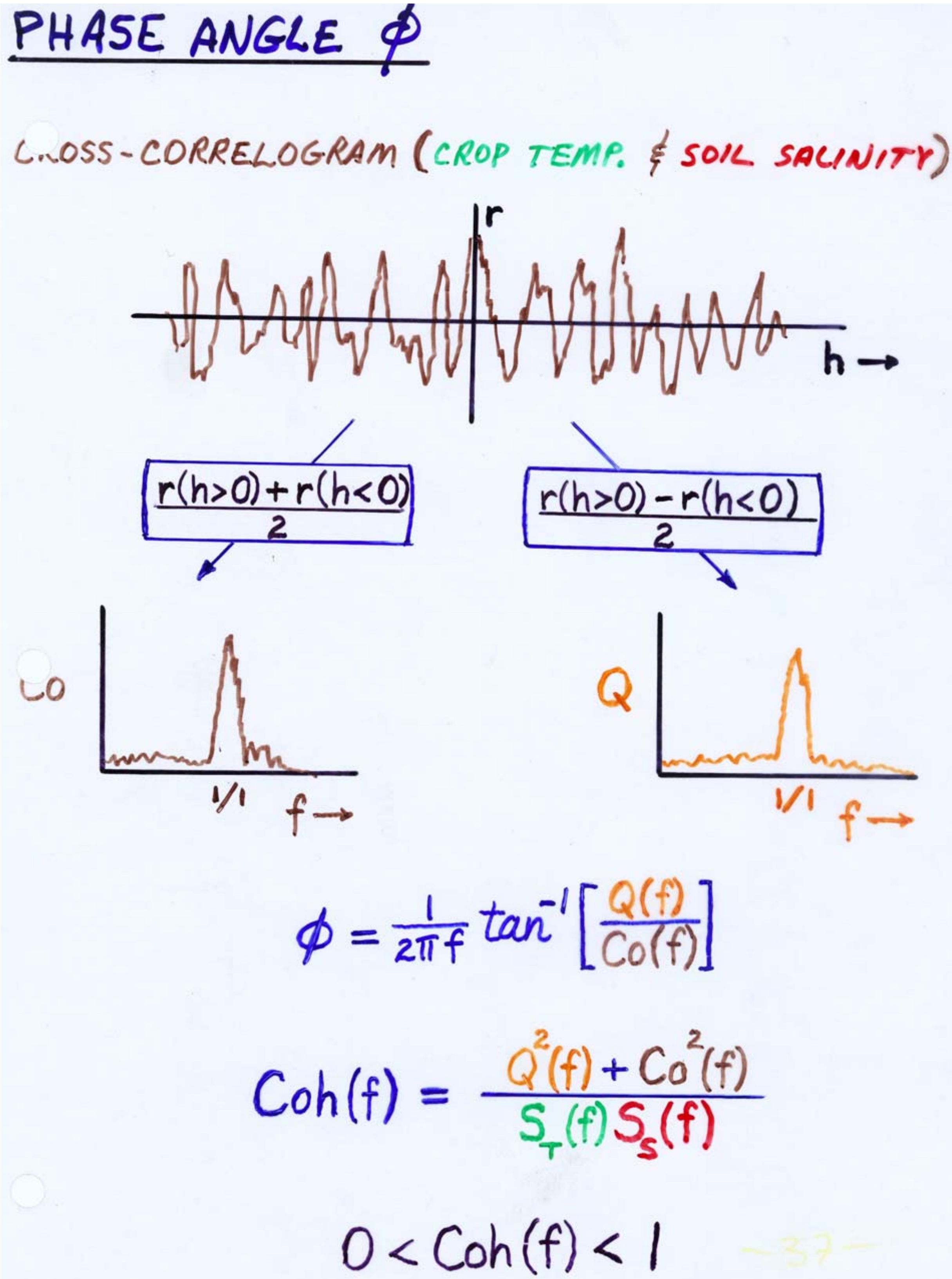
cospectral analysis diag compaction



cospectral phase angle

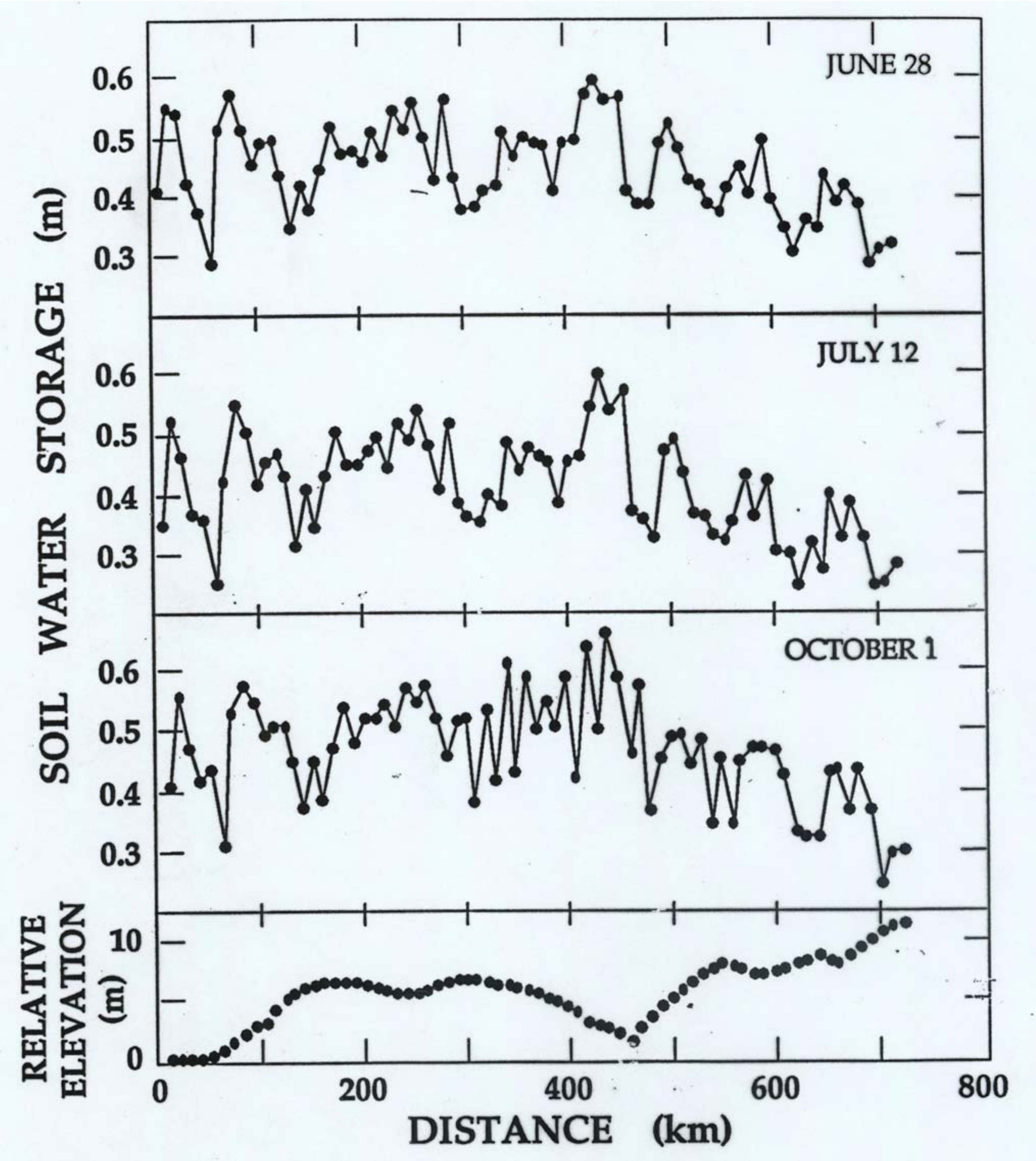


phase angle illustration

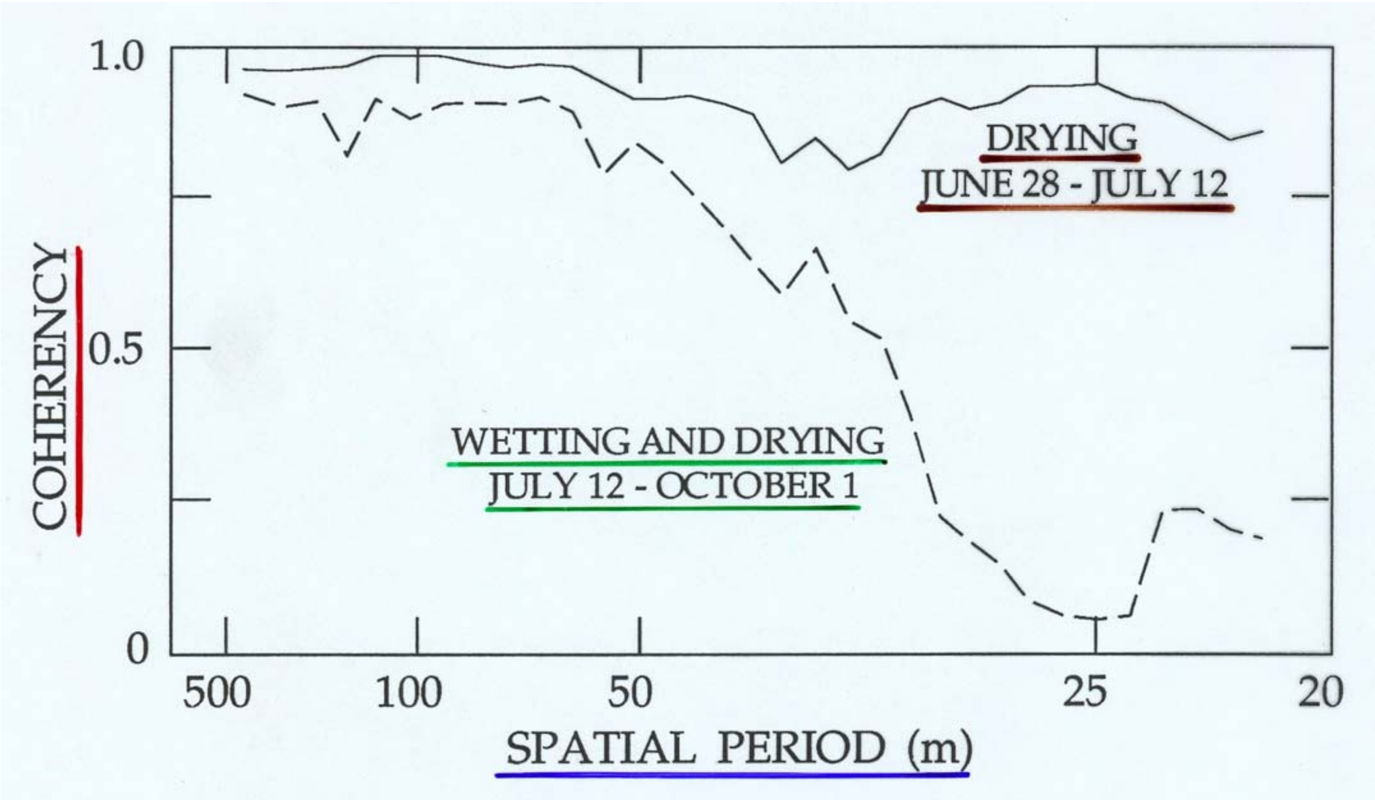


COHERENCY OF SOIL WATER STORAGE AT DIFFERENT TIMES

soil water storage vs distance

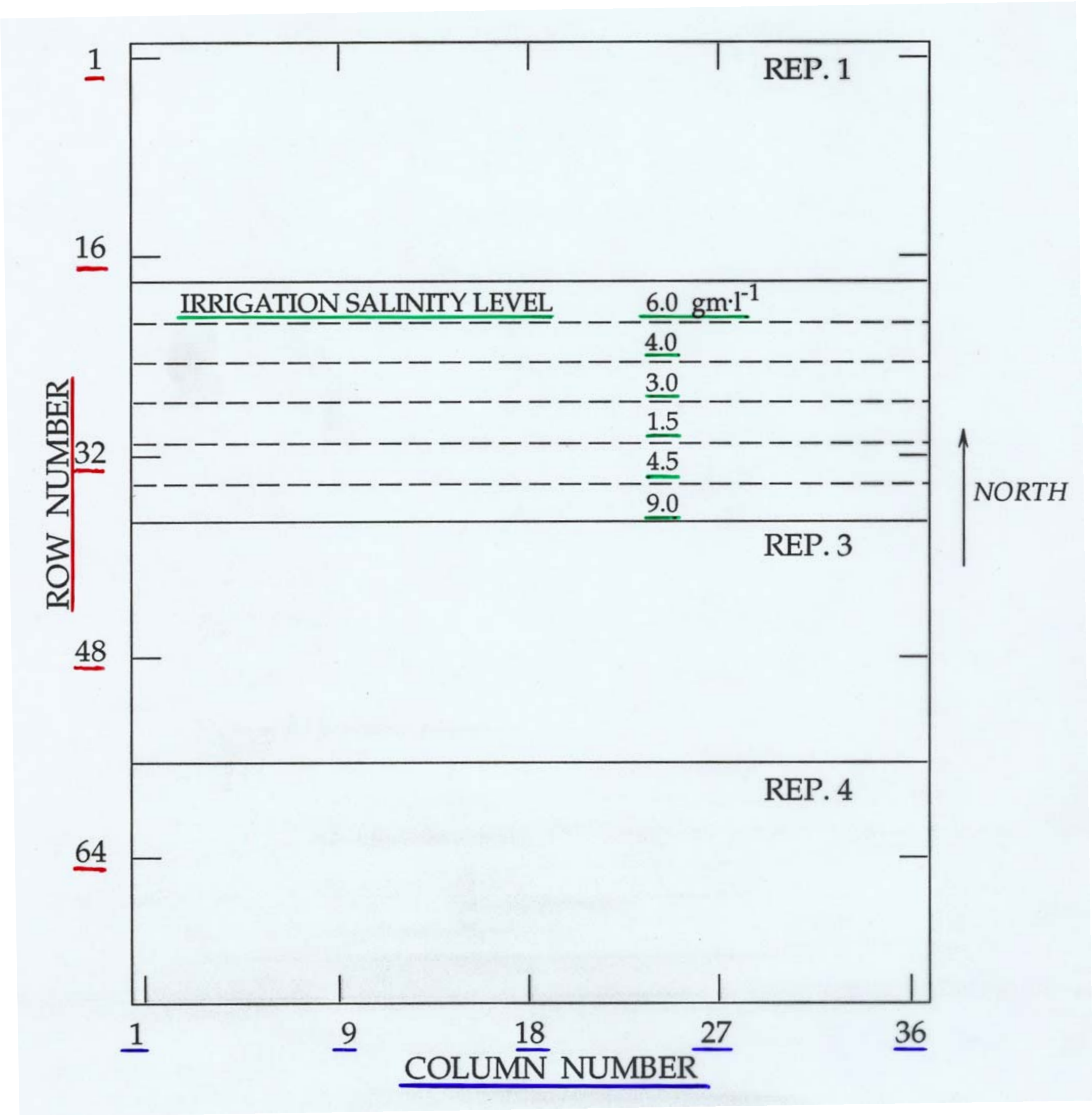


coherency vs spatial period

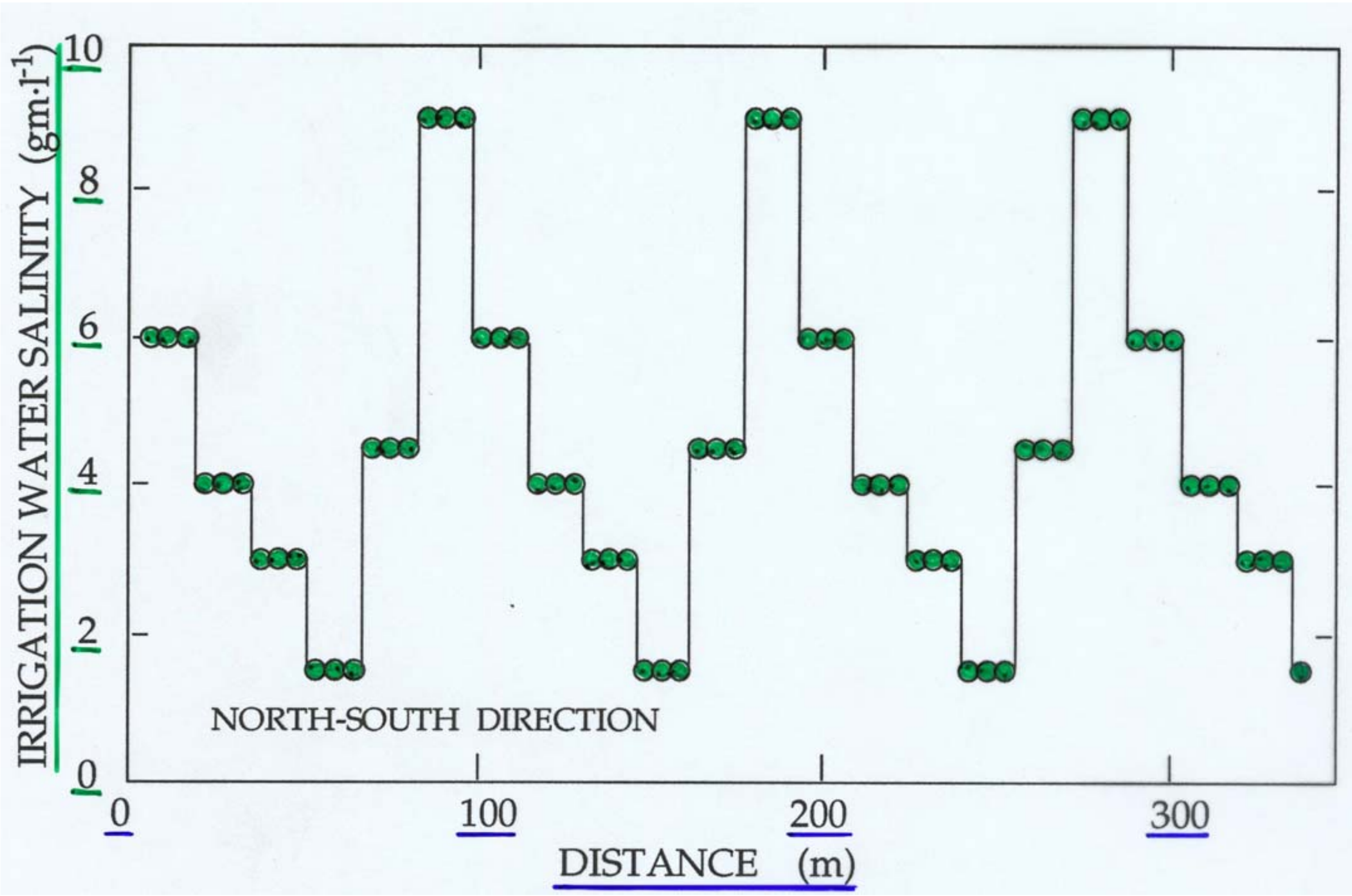


QUALITY OF IRRIGATION WATER RELATED TO SOIL TEMPERATURE

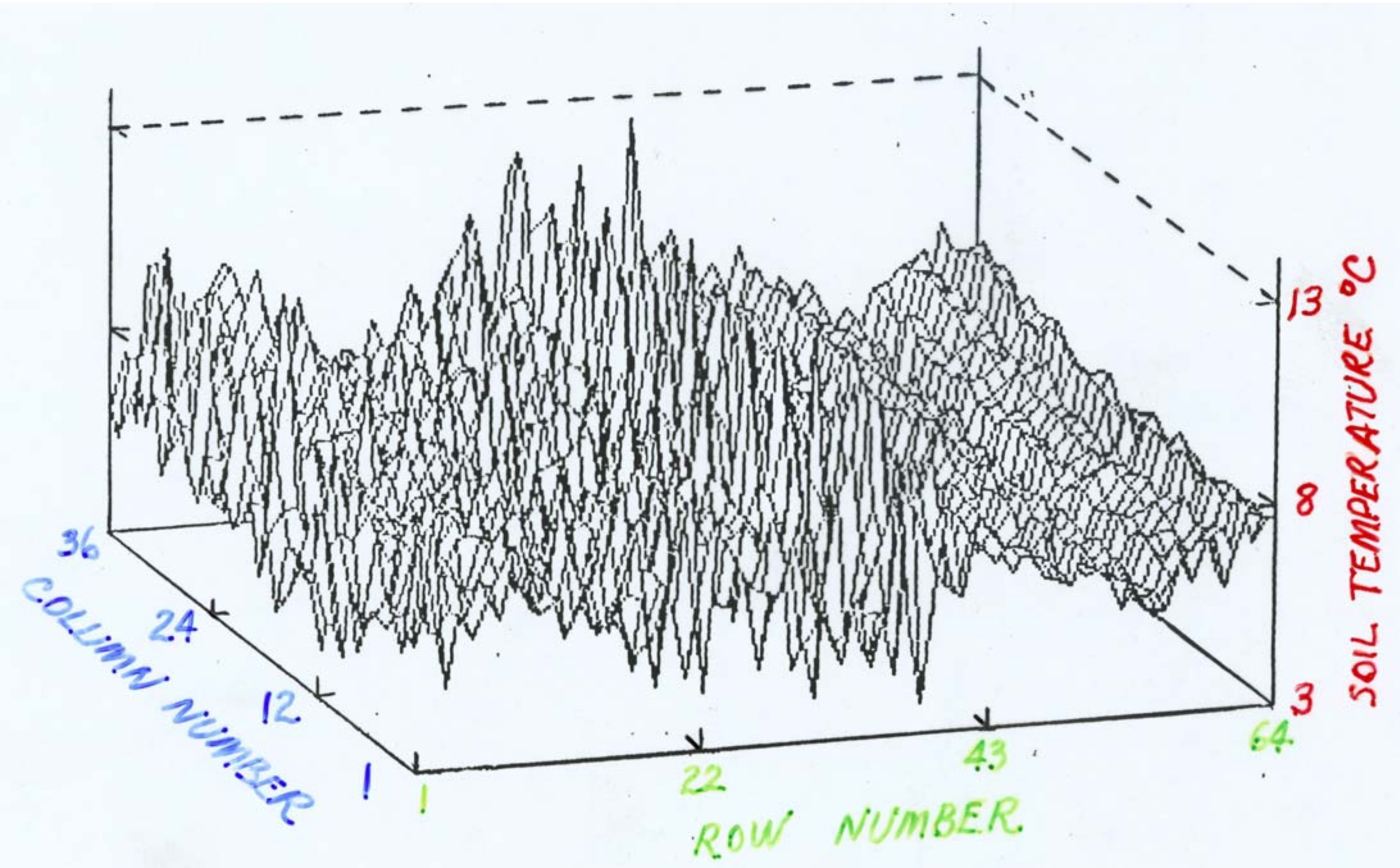
row and column number irrig&salinity



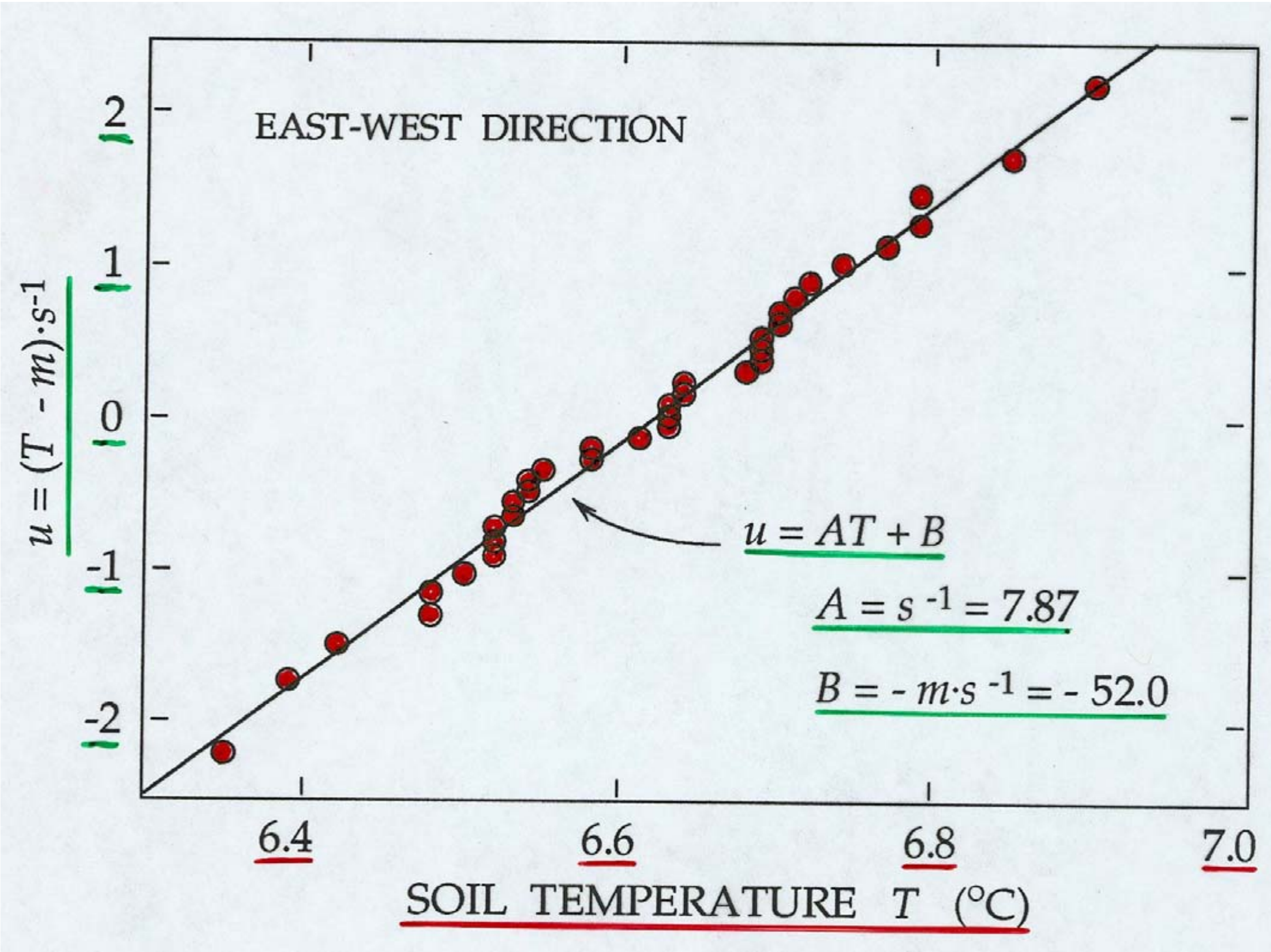
irrig water salinity vs distance



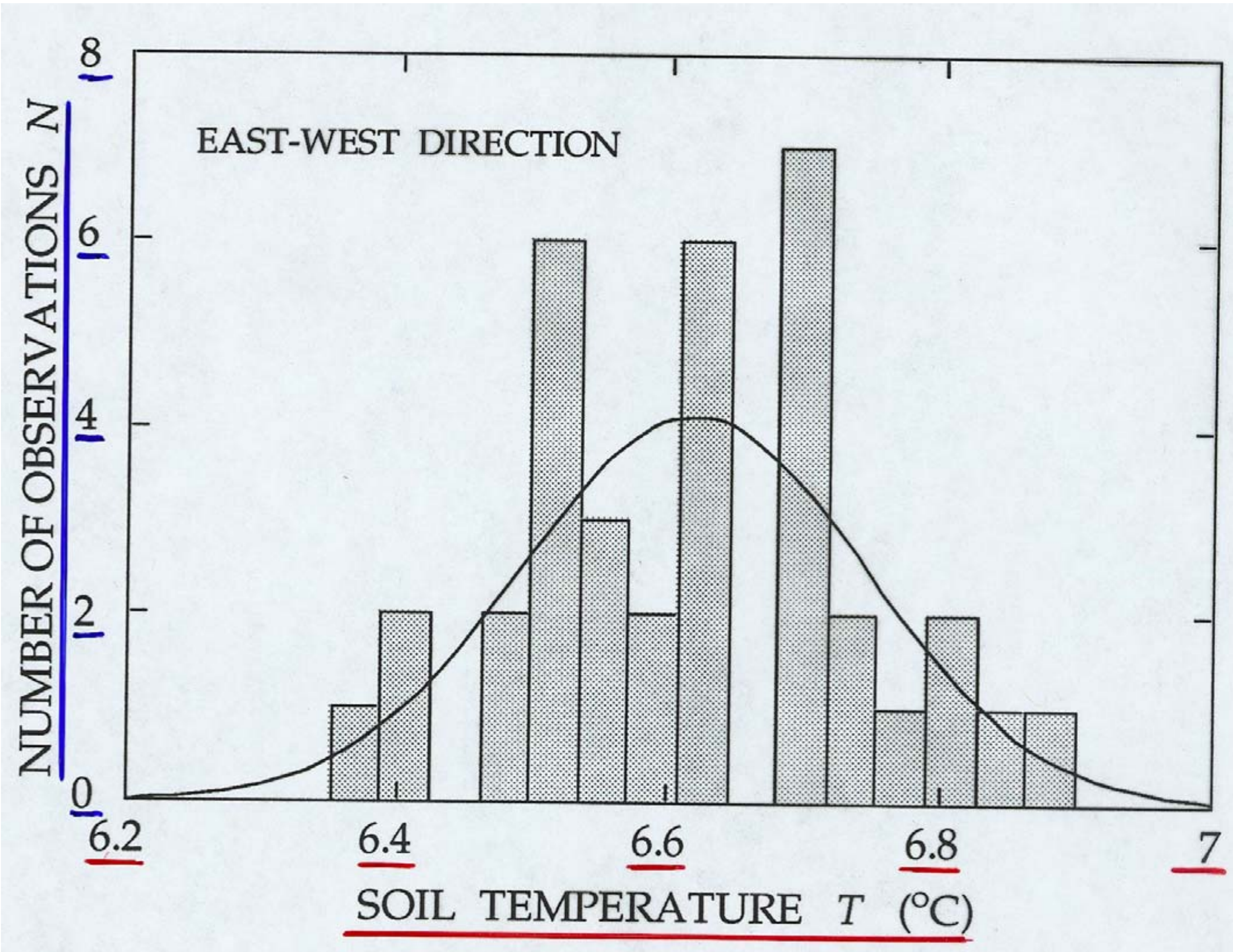
soil temp vs row & column numbers



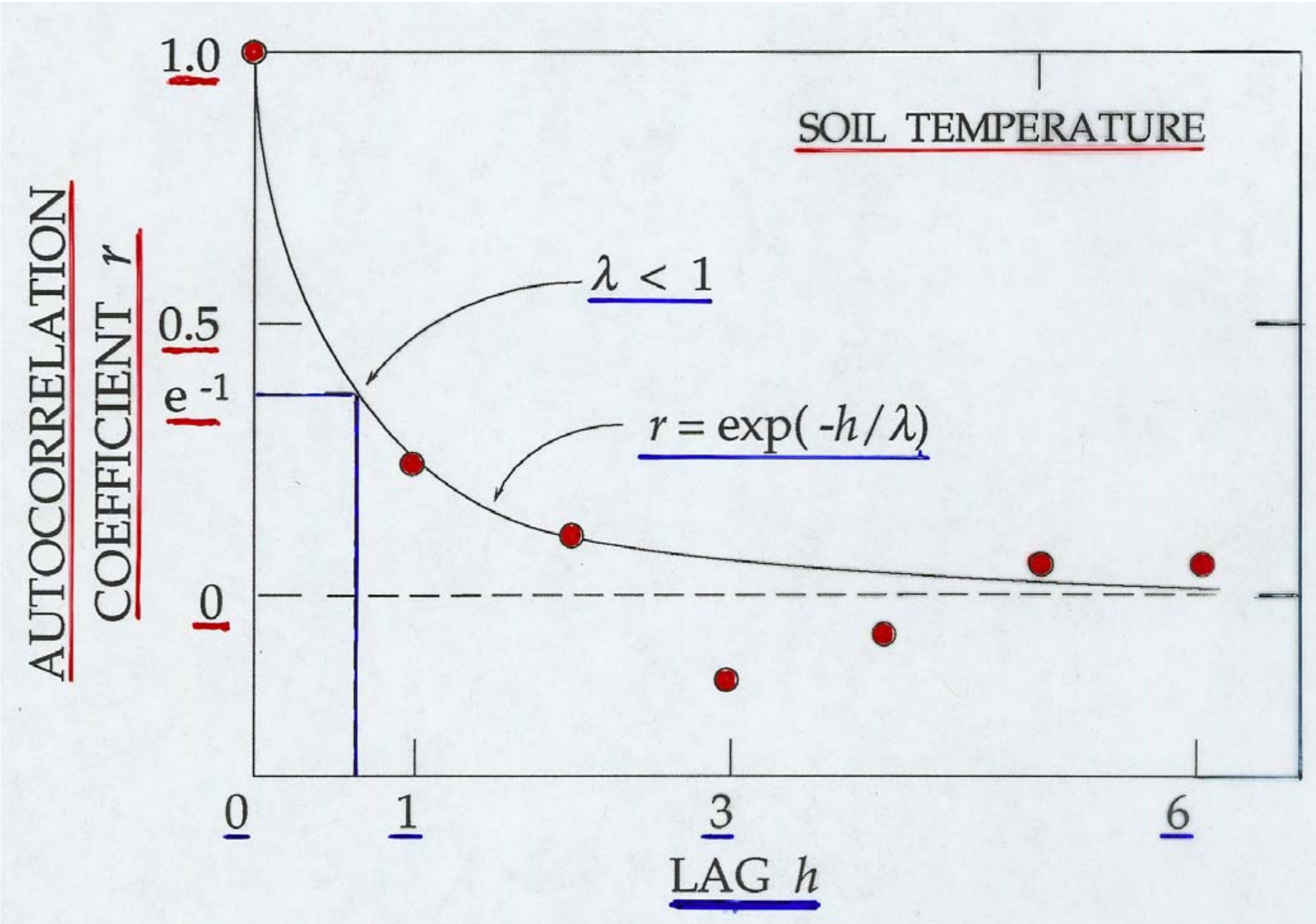
fractile diagram soil temp (E-W)



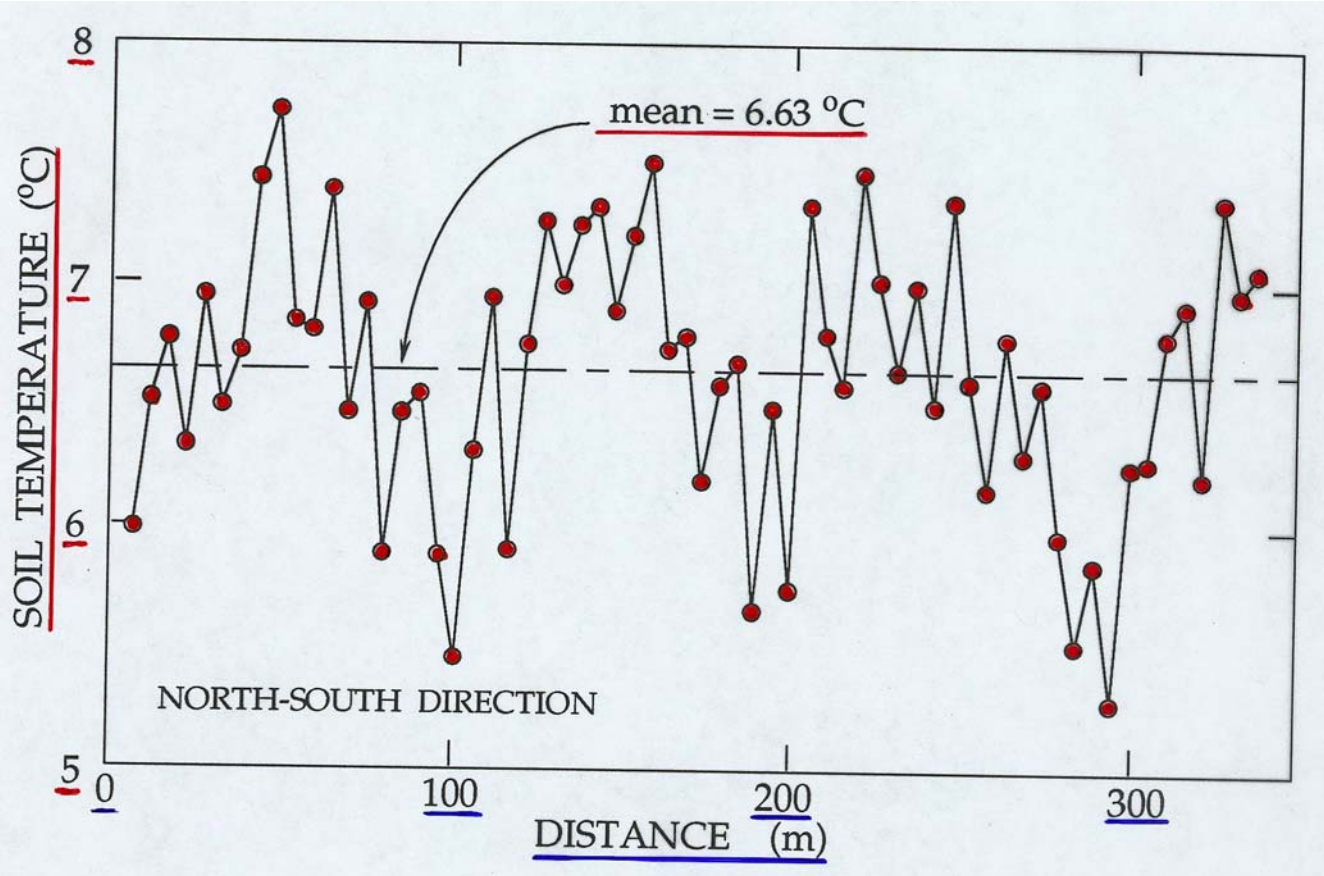
pdf soil temperature (E-W)



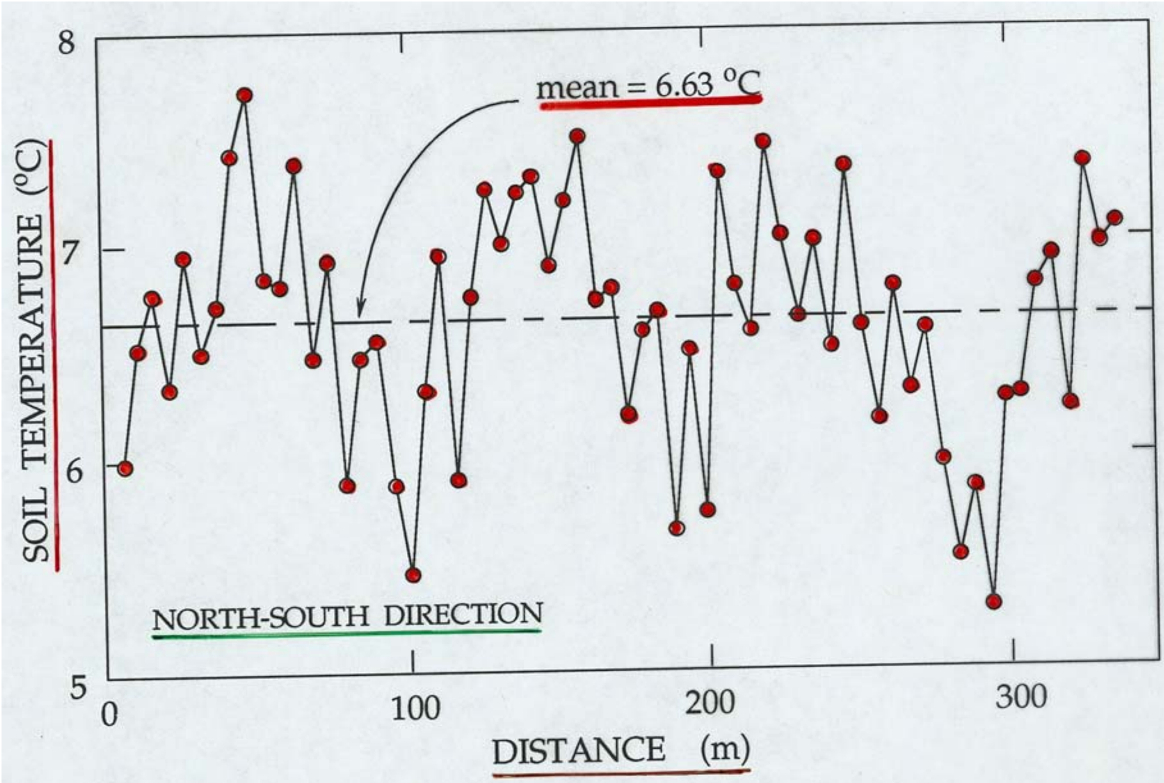
autocorrelogram E-W soil temp.

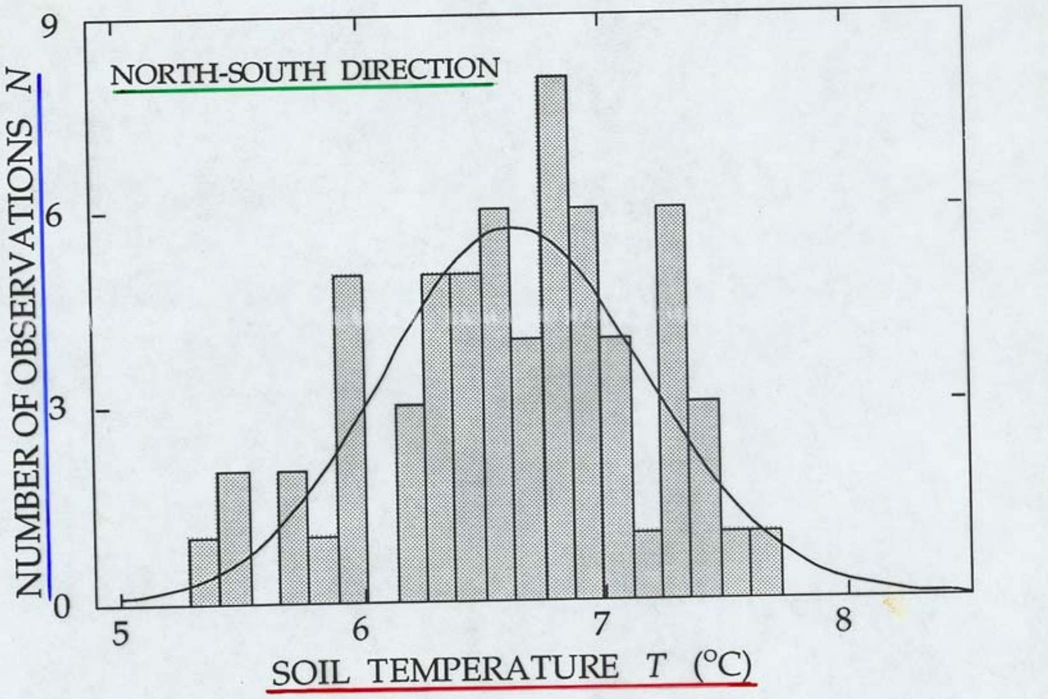


soil temperature vs distance (N-S)

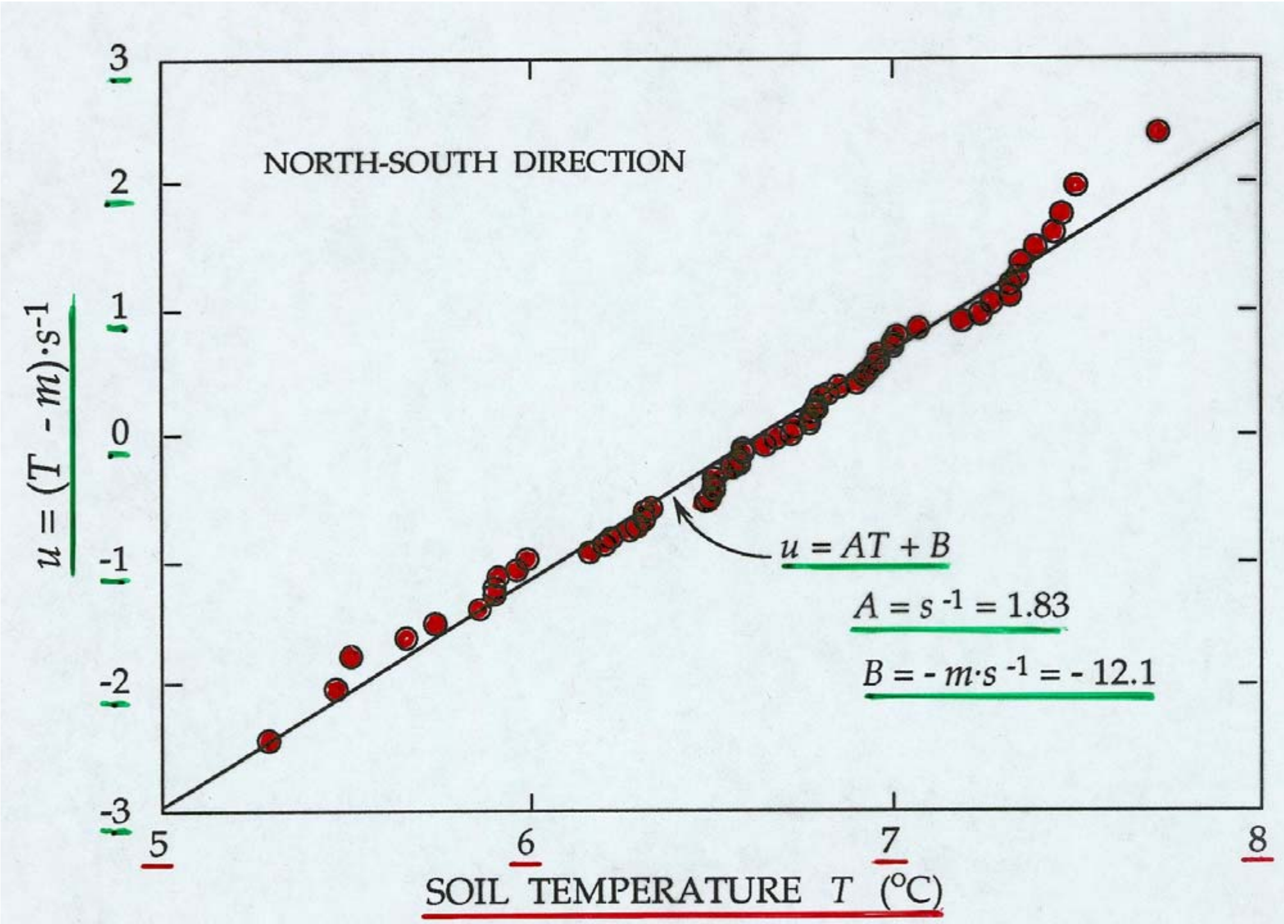


soil temperature vs distance & pdf (N-S)

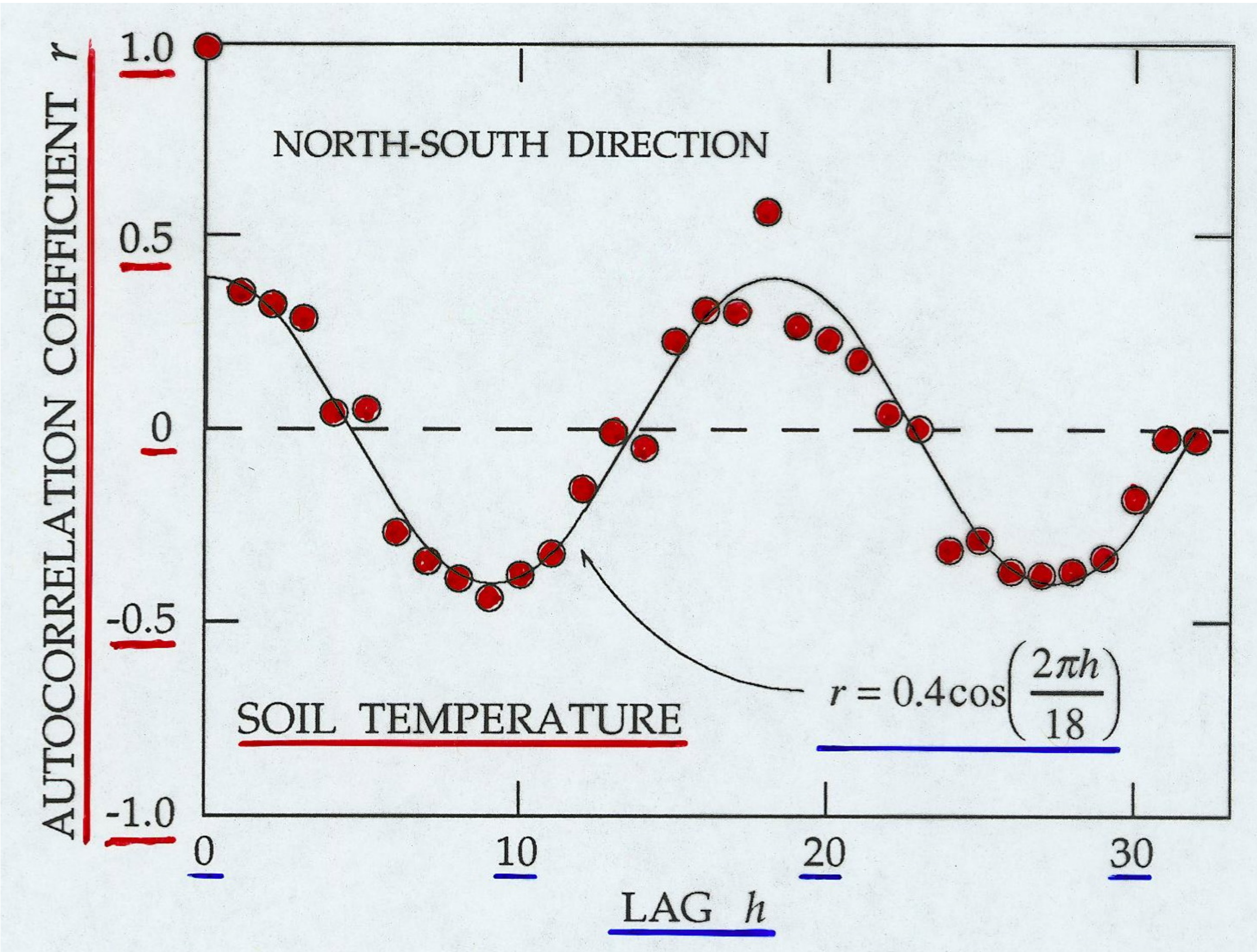




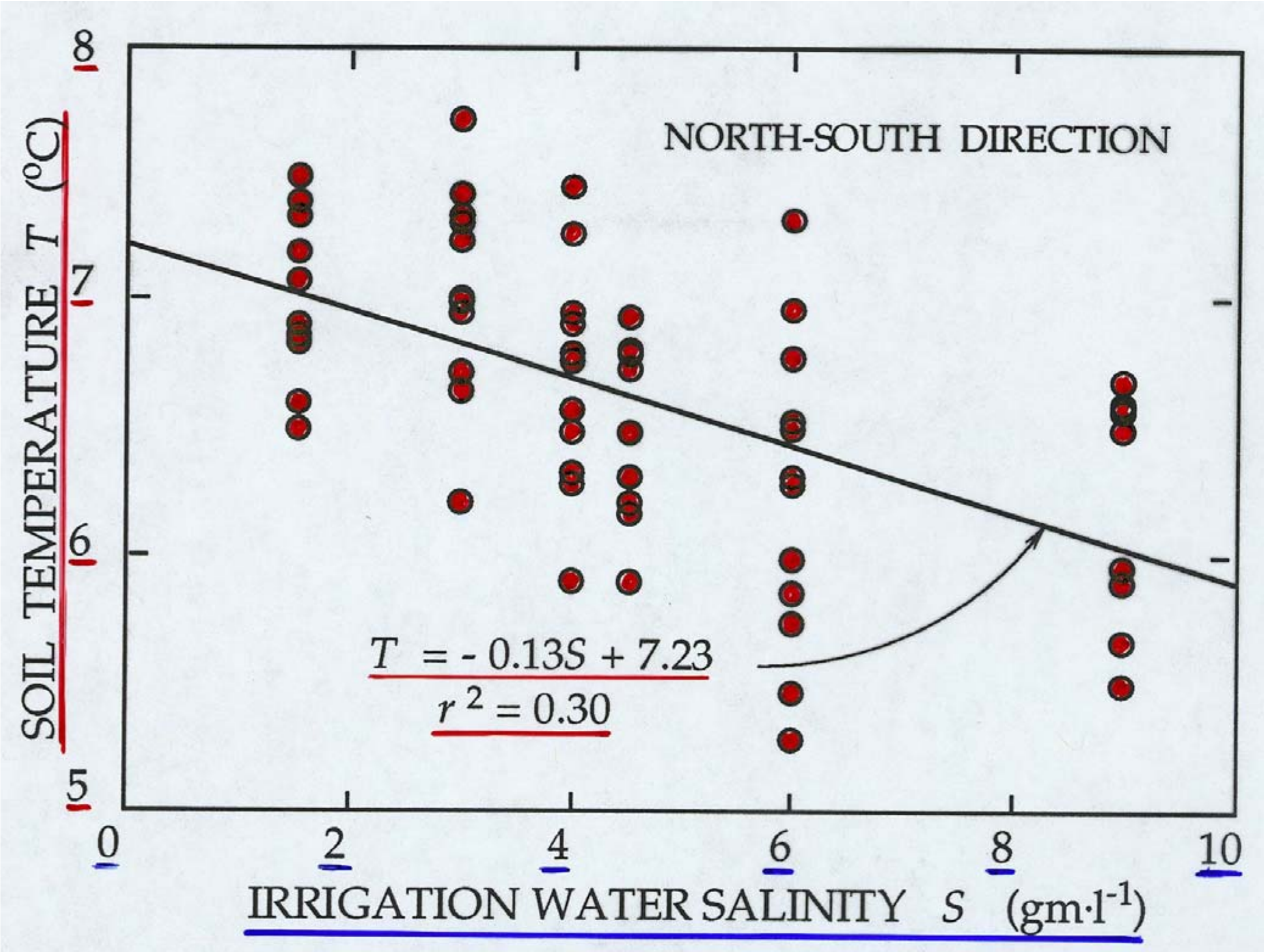
fractile diagram soil temperature (N-S)



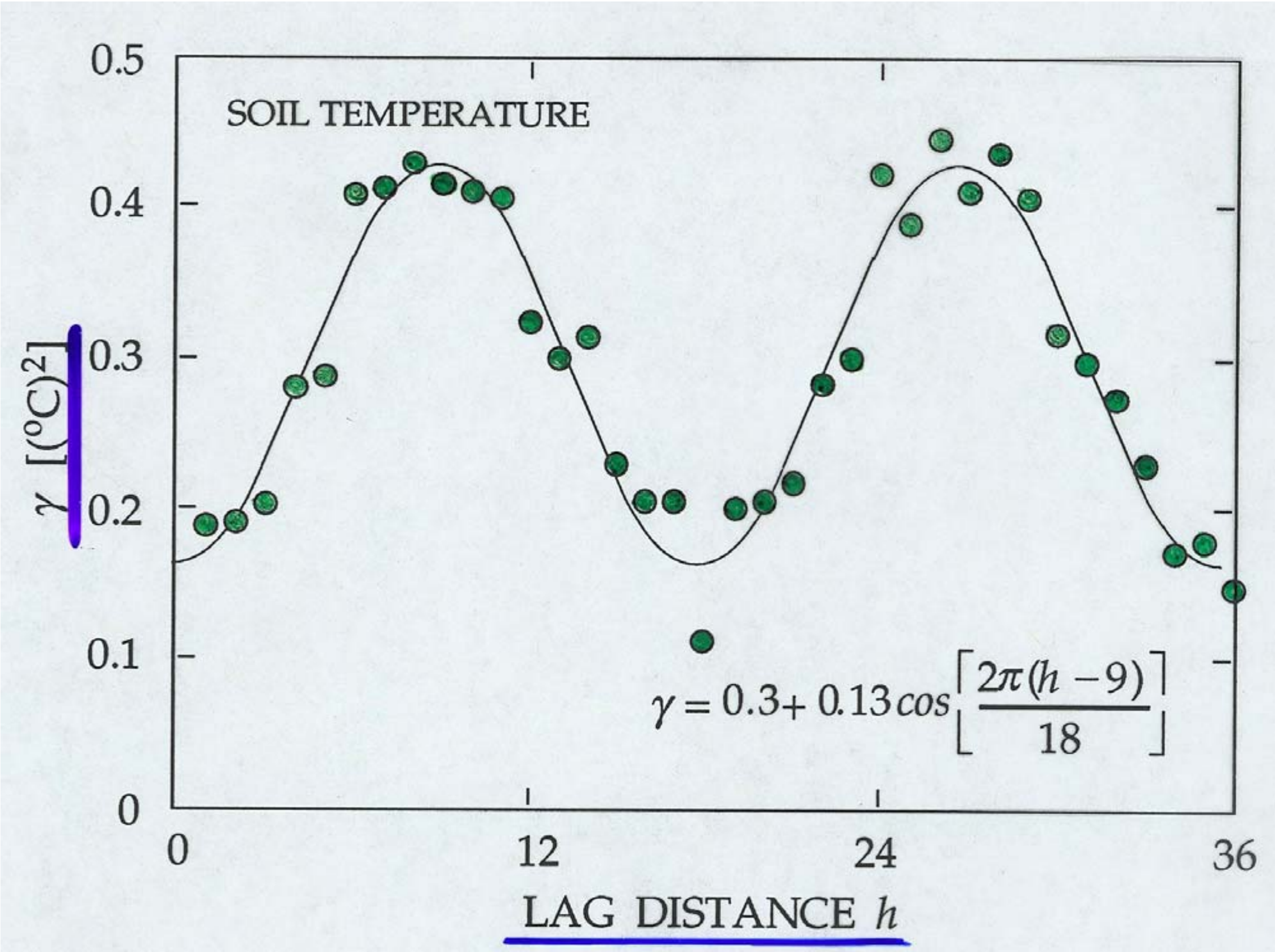
ACF N-S soil temp



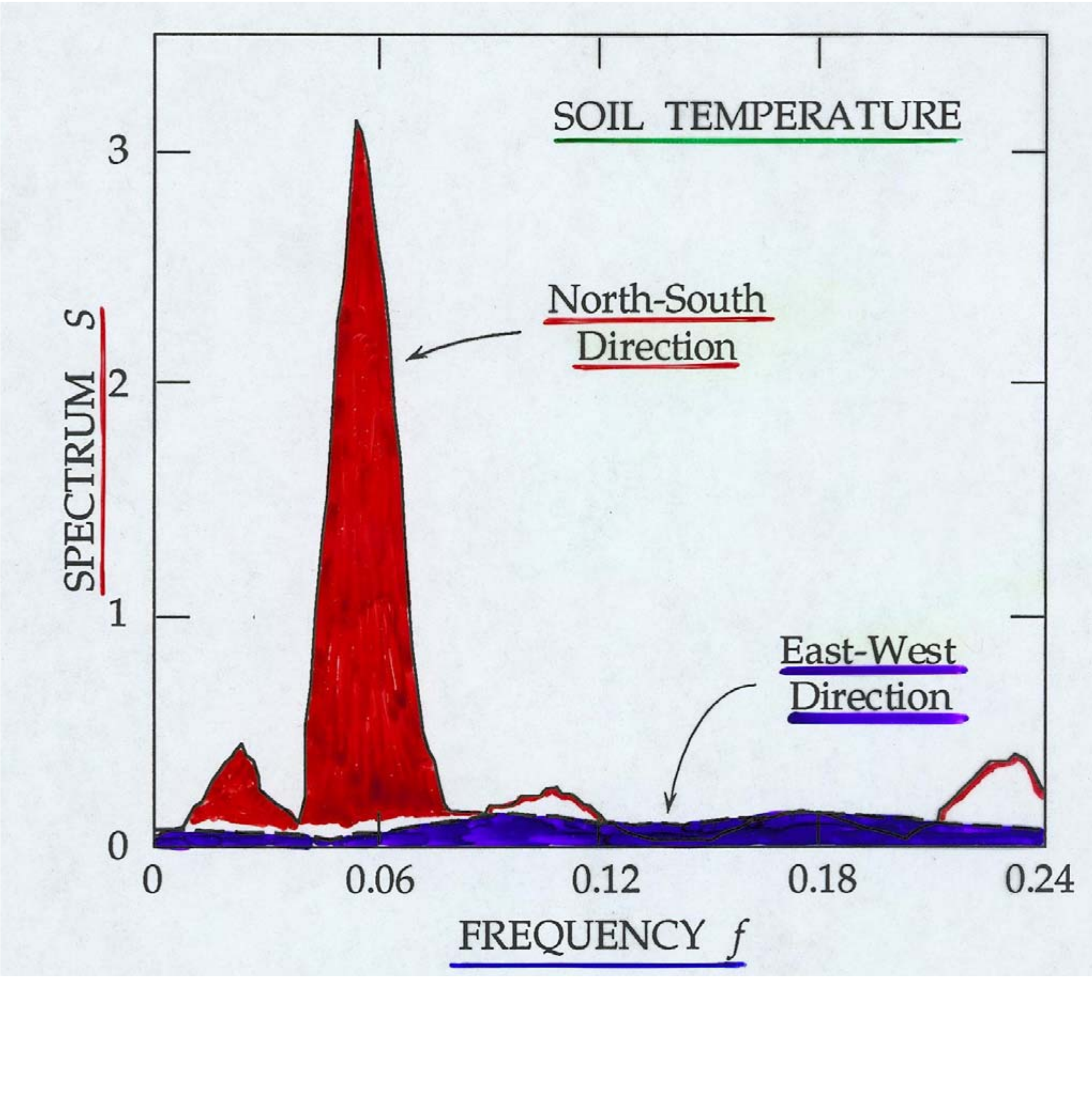
linear regress soil temp vs irrig salinity



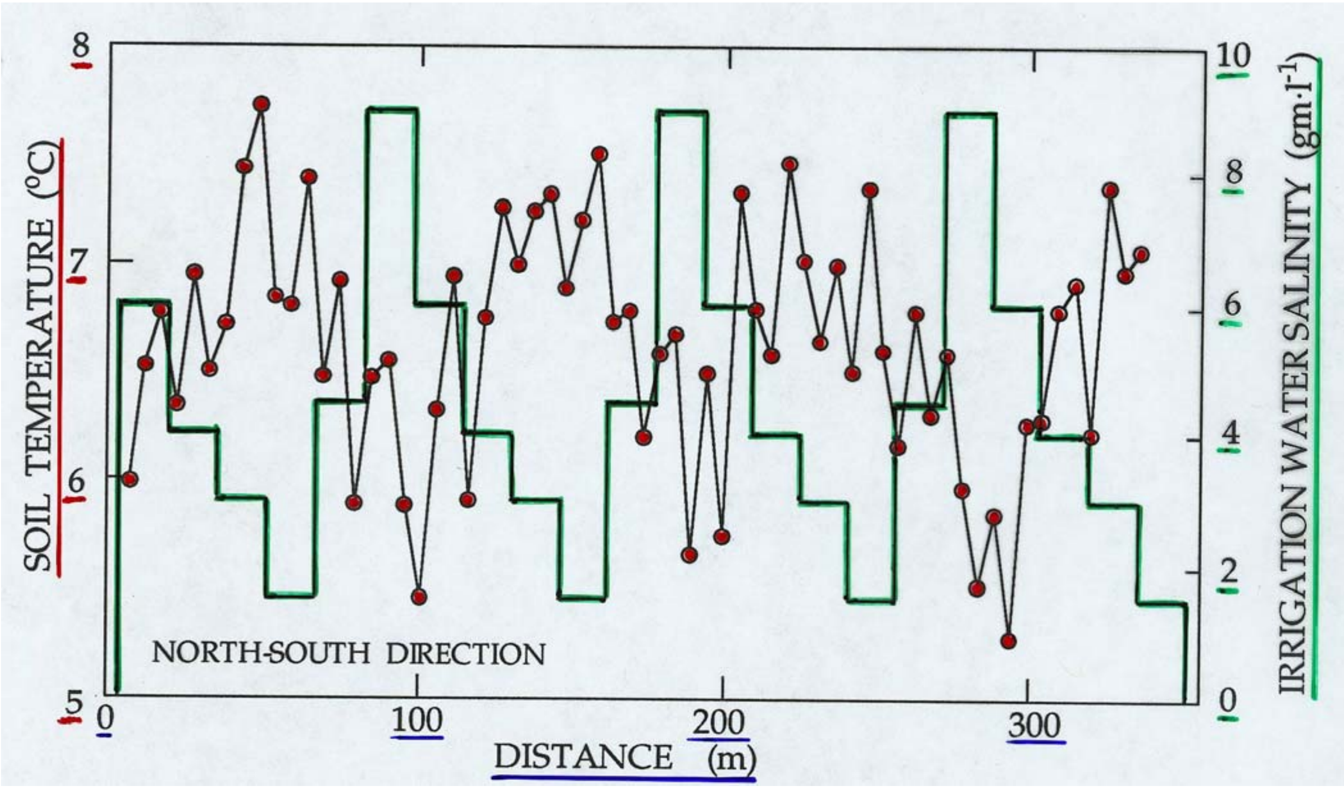
variogram soil temperature (cosine)



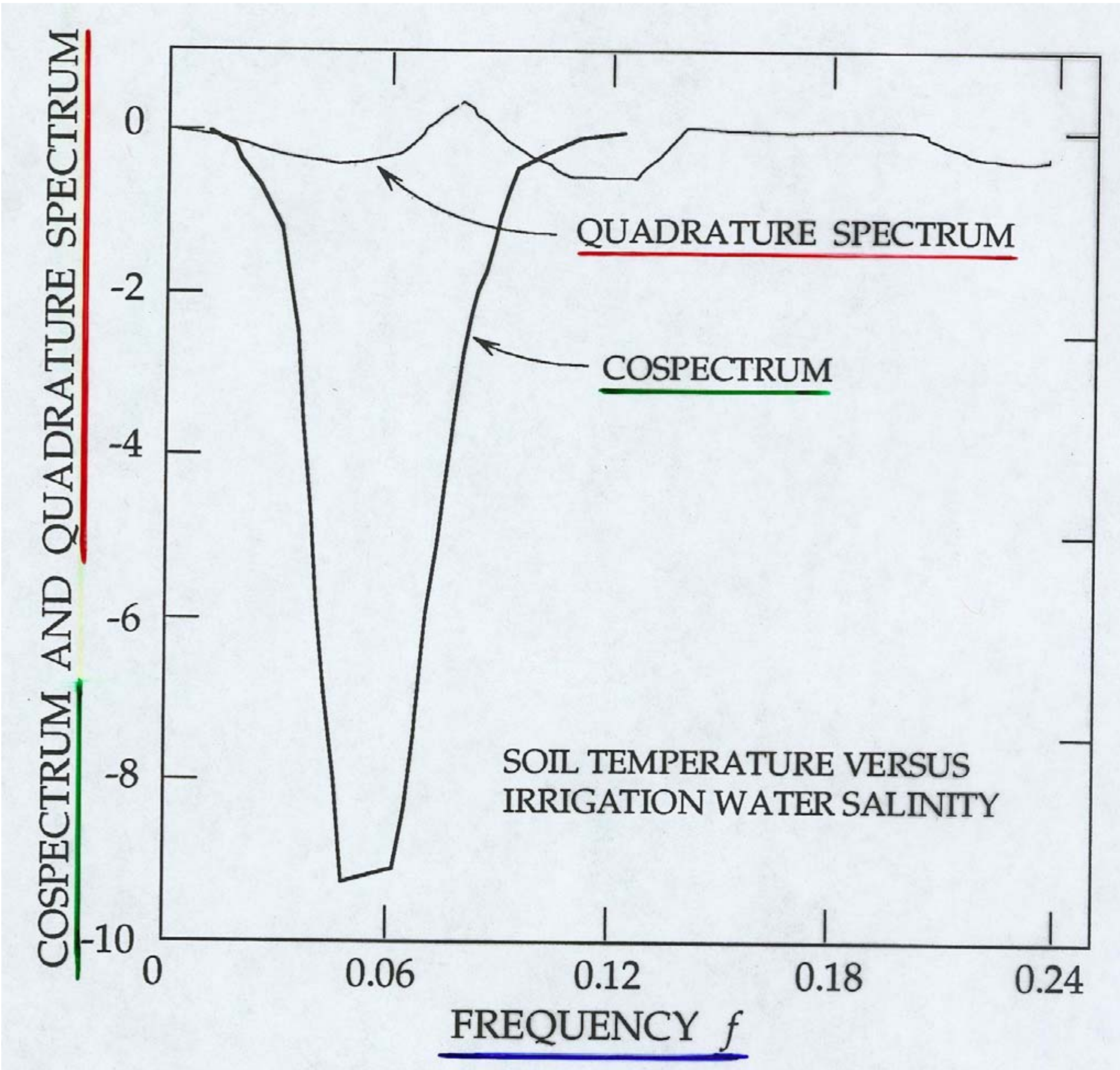
spectra soil temp (N-S & E-W)



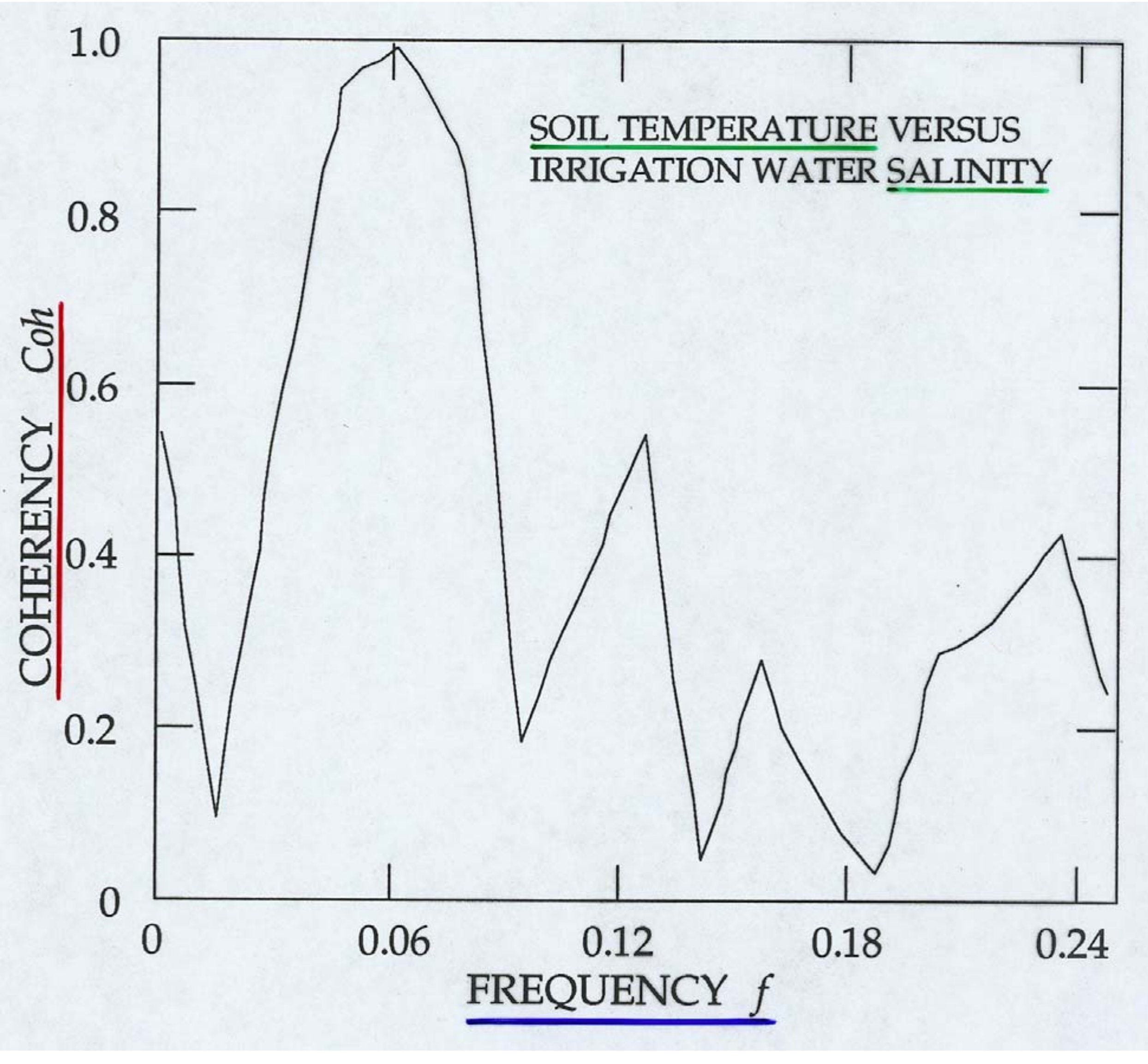
soil temp & irrigation salinity vs distance



co-& quad-spectra temp vs water salinity

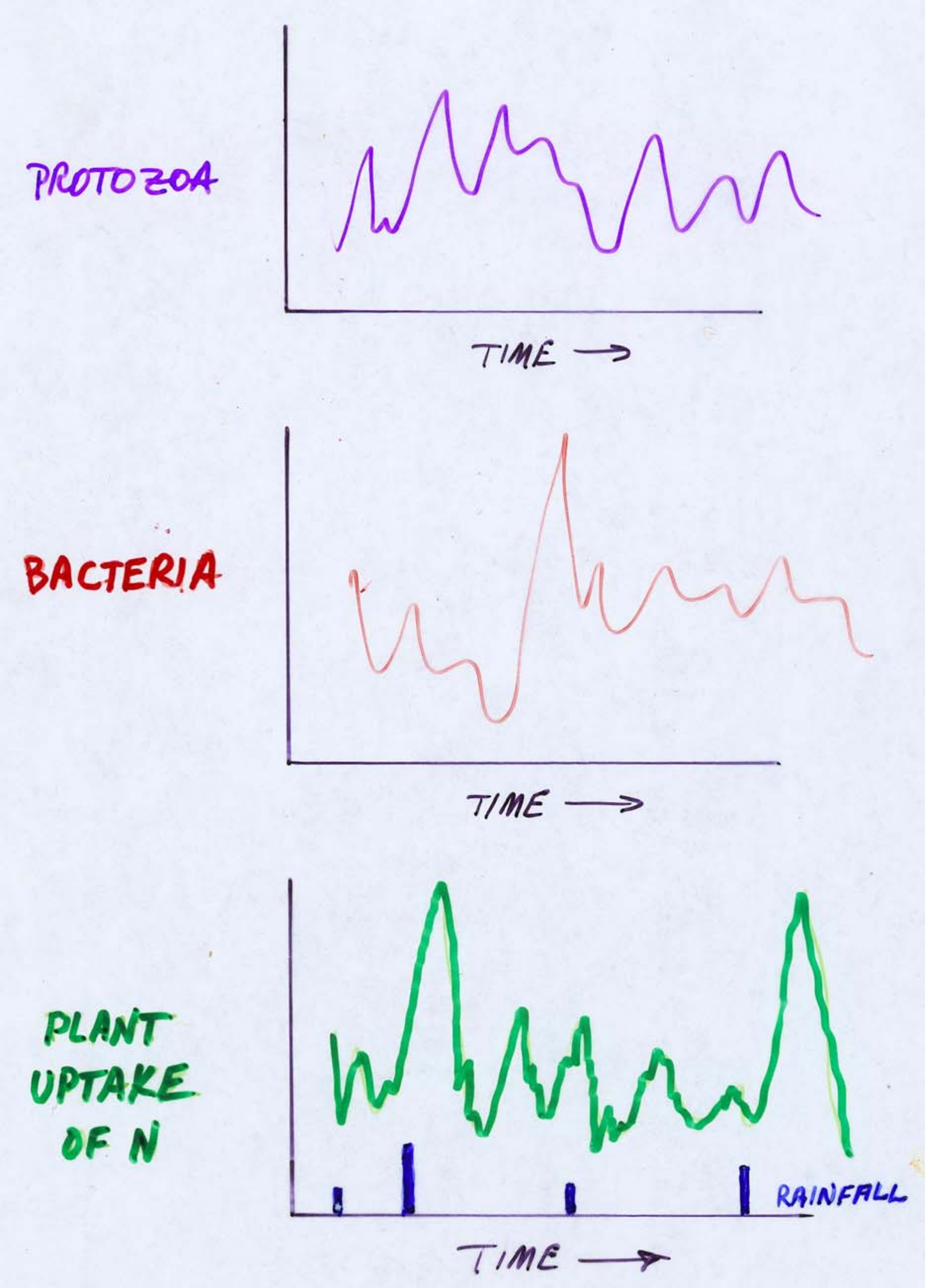


coherency soil temp vs irrig water salinity

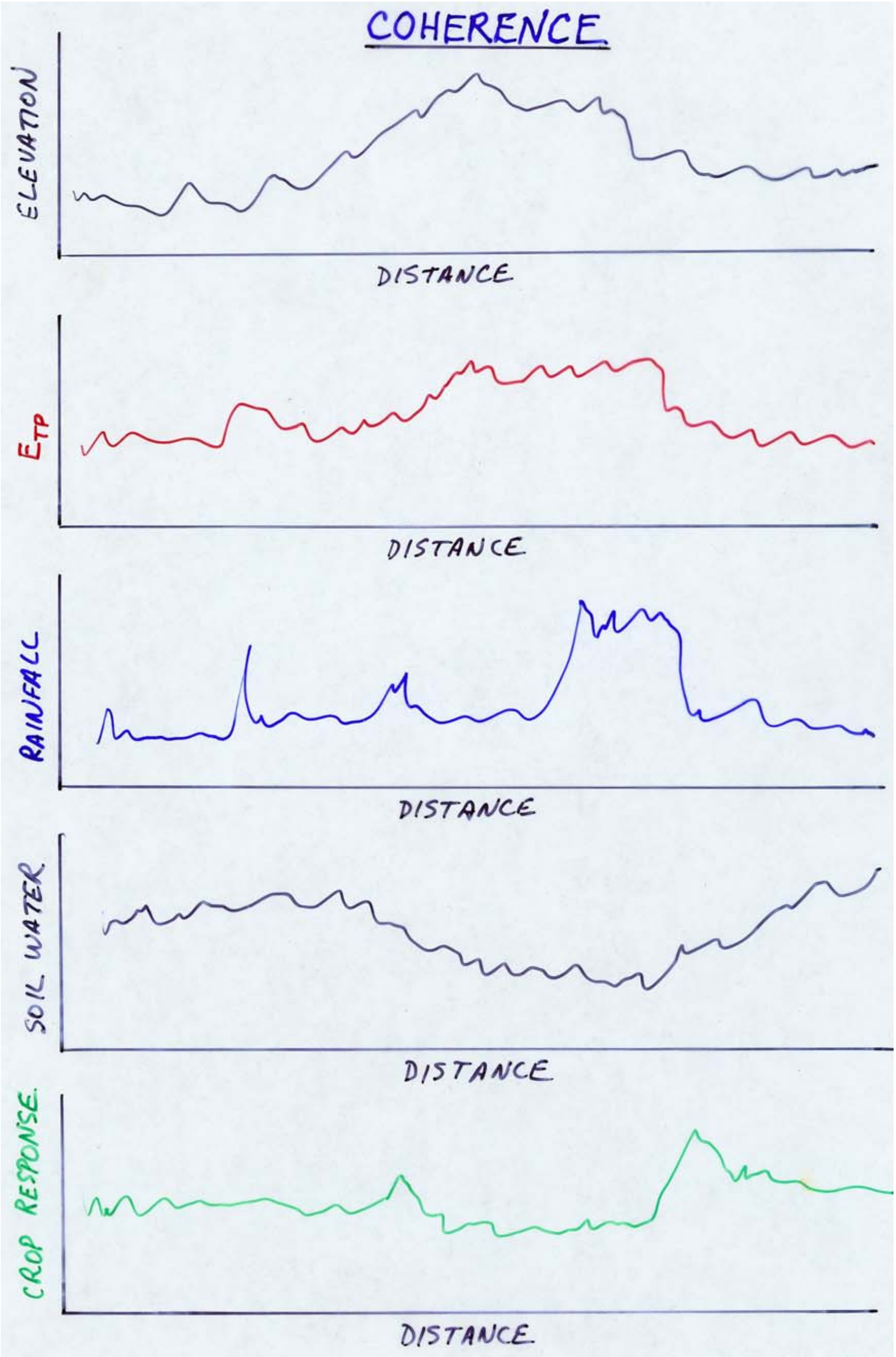


conclusions

protozoa vs time, etc.

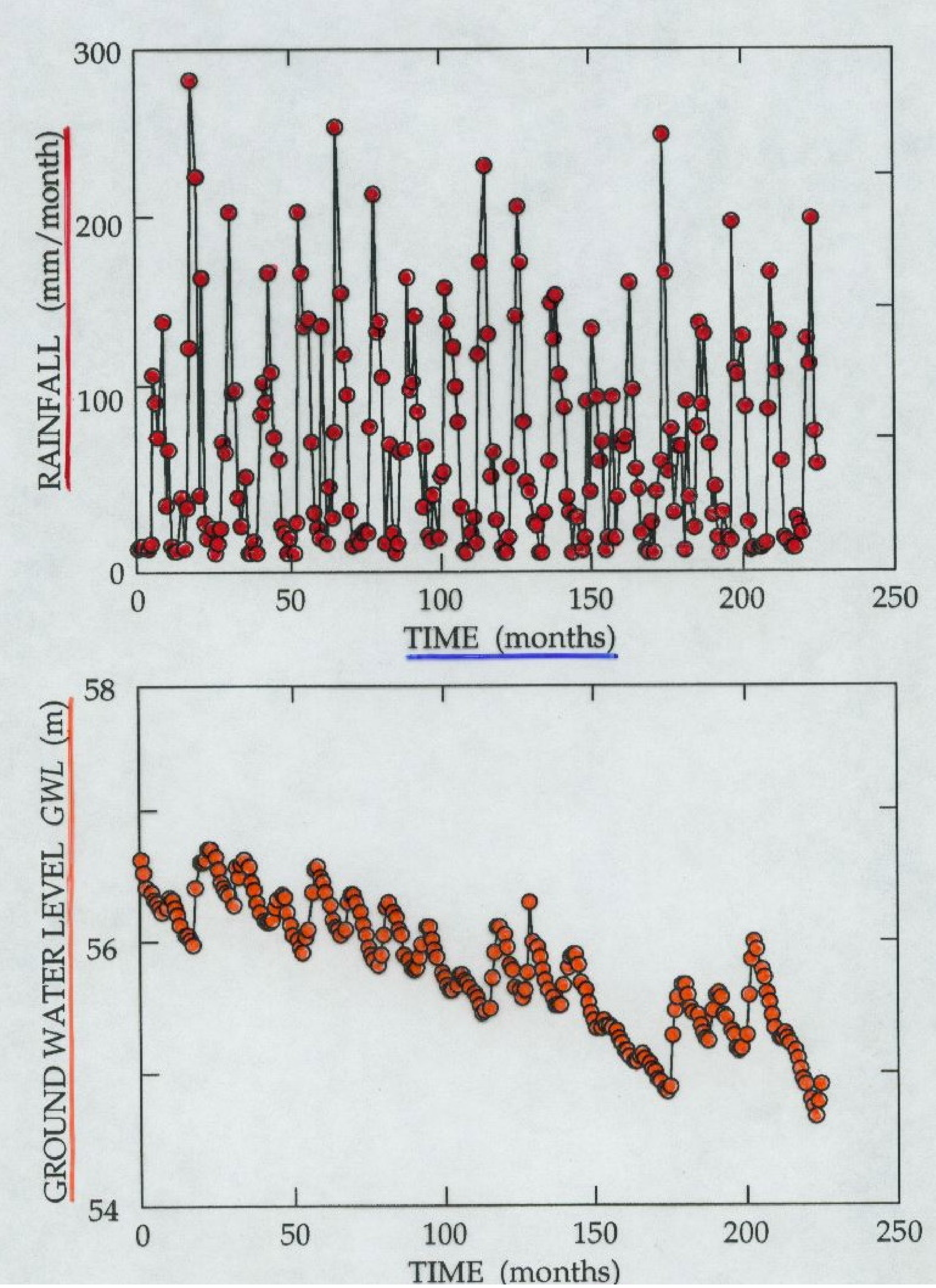


coherence across landscape

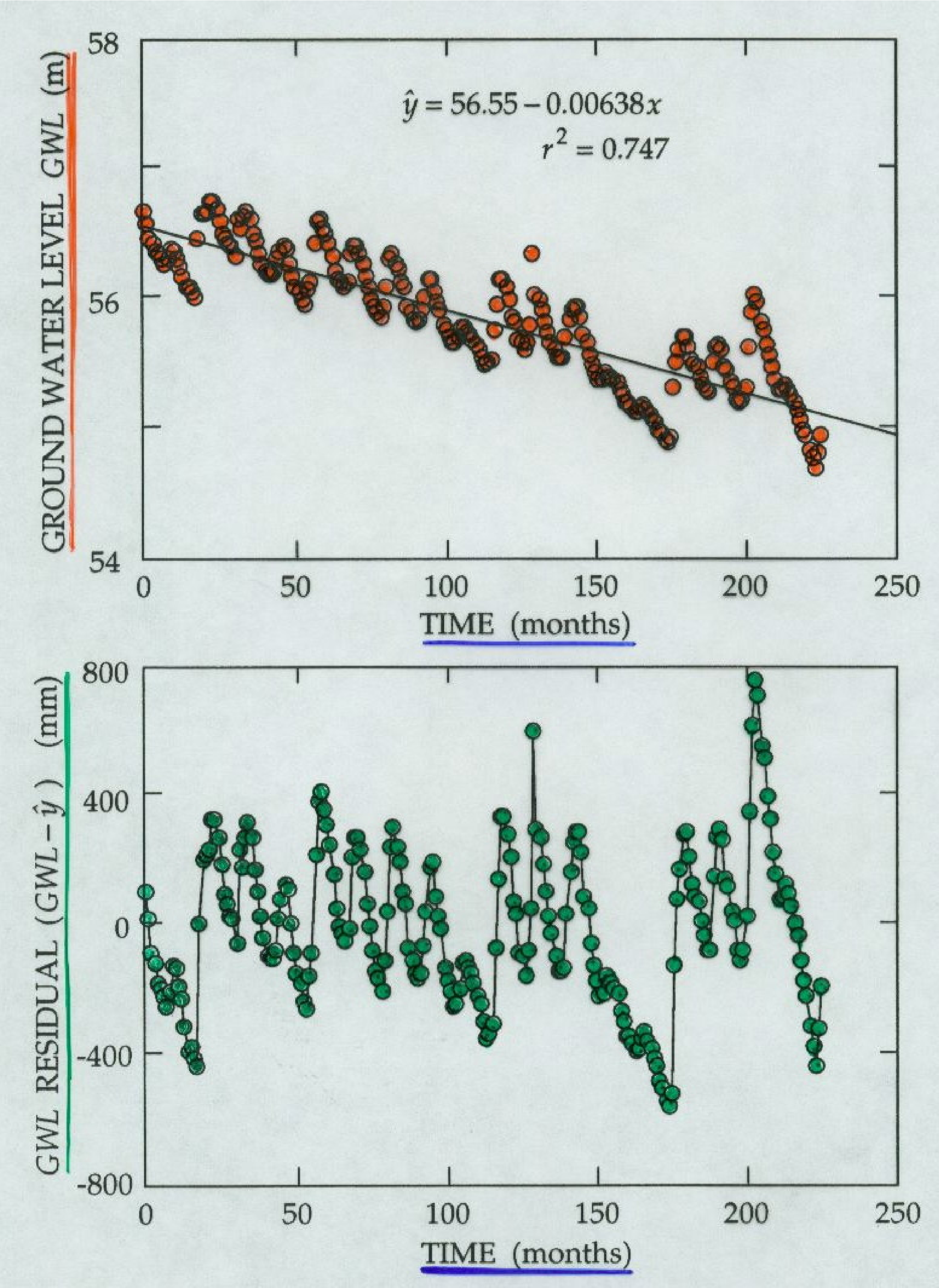


TRAVEL TIME
FOR WATER INFILTRATING THE SOIL SURFACE
TO REACH THE WATER TABLE

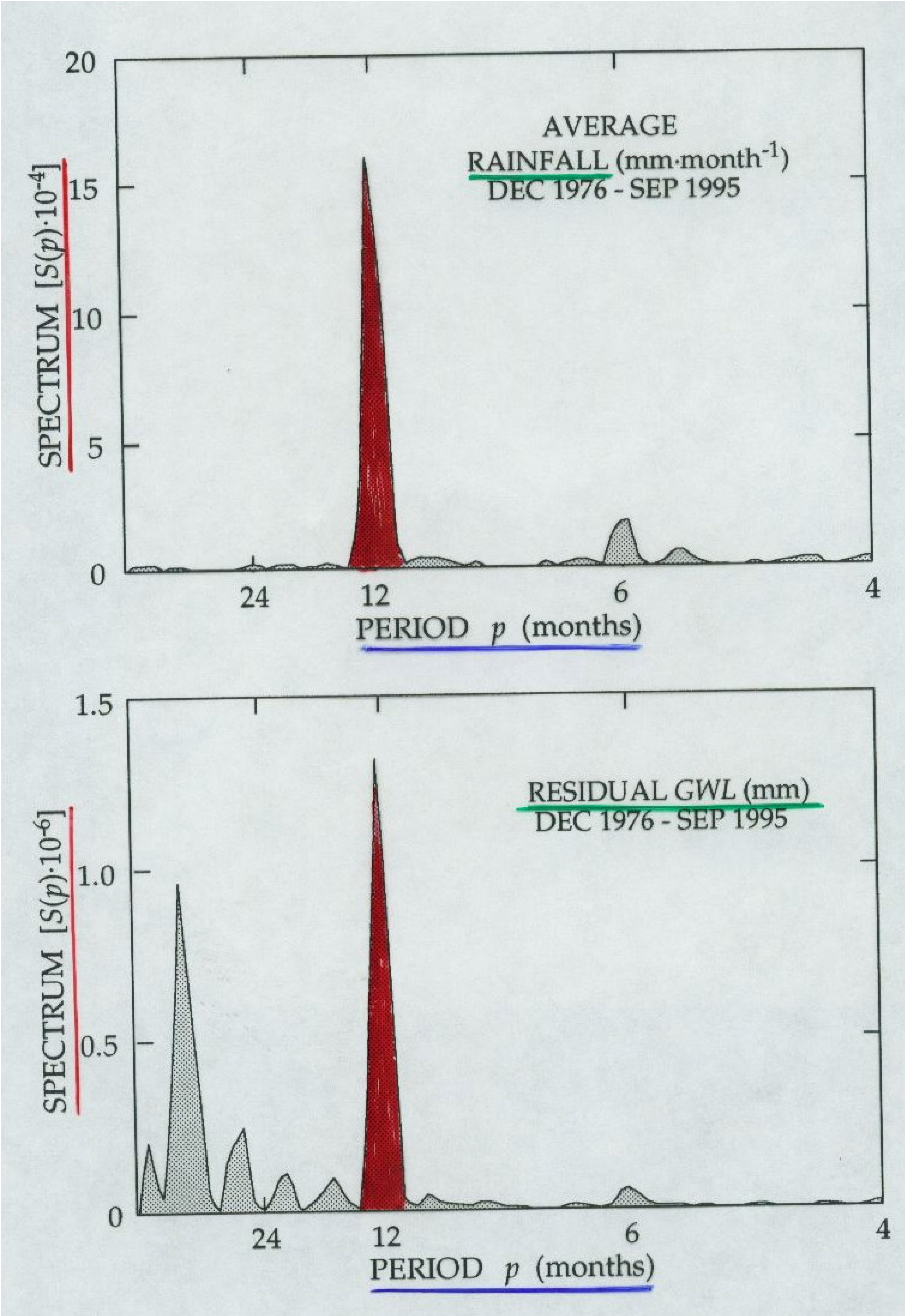
rainfall and GWL



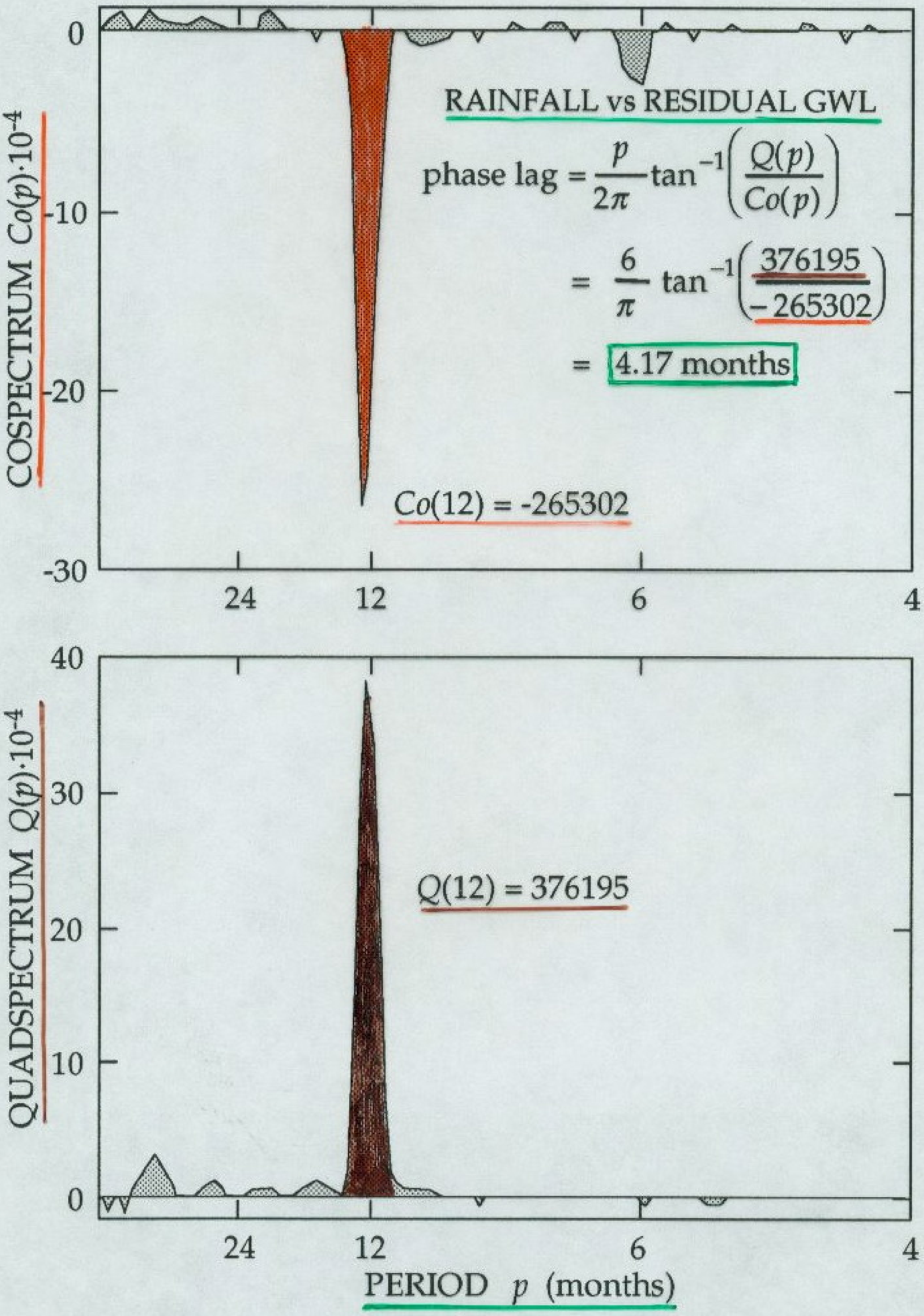
groundwater fluctuations



spectra rain & GWL



crospectra rain & GWL



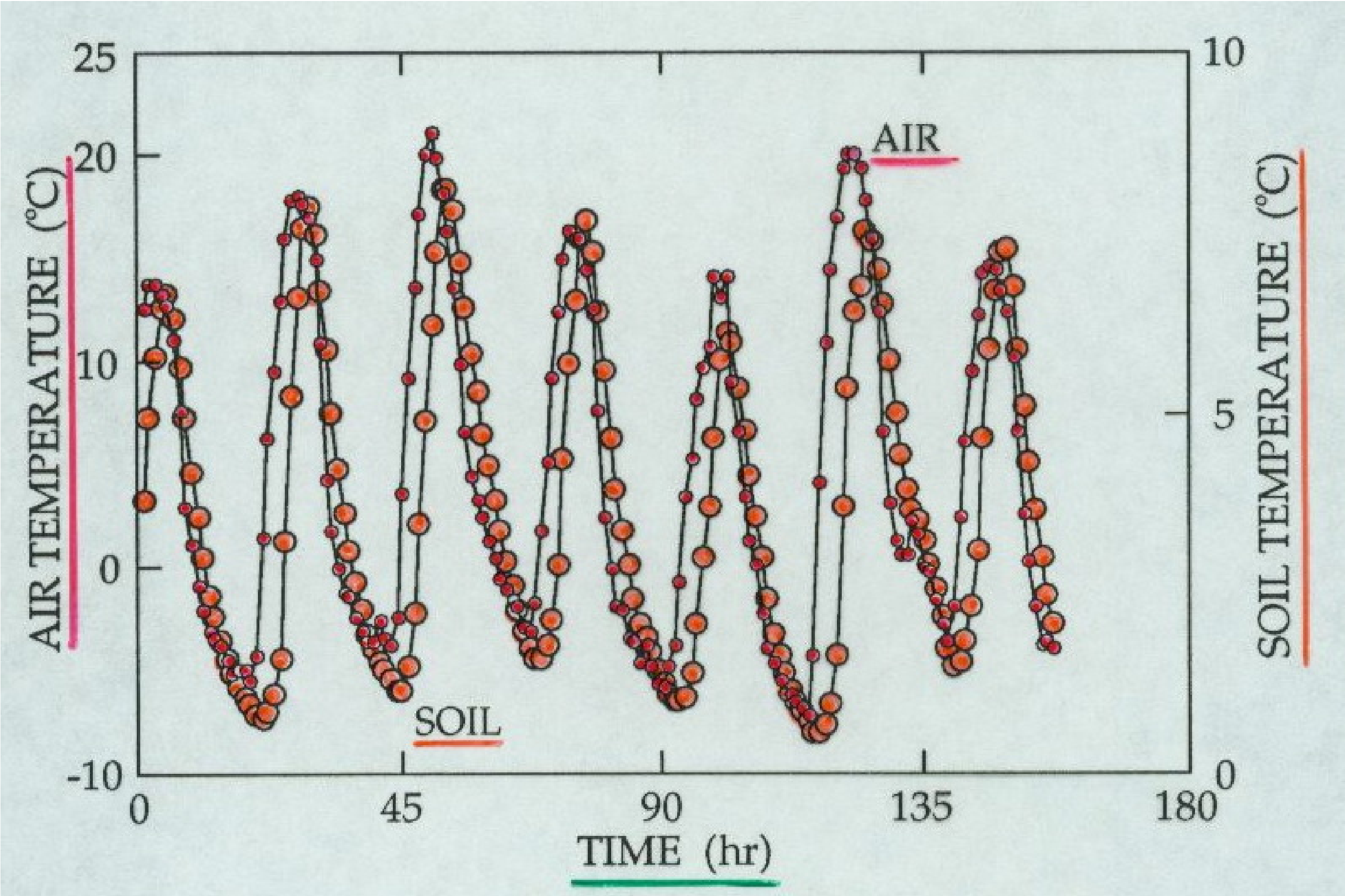
Cospectrum and quadrature spectrum of rainfall versus residual groundwater level. Assuming a period of 12 months, ground water lags rainfall by 4.17 months.

AIR TEMPERATURE

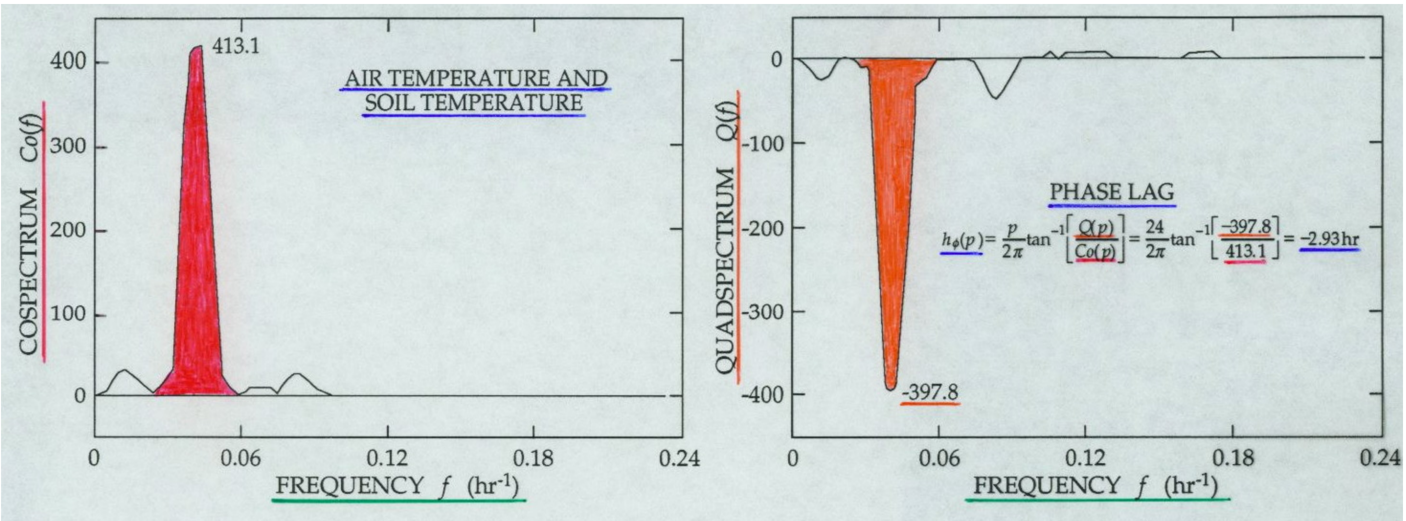
AND

SOIL TEMPERATURE

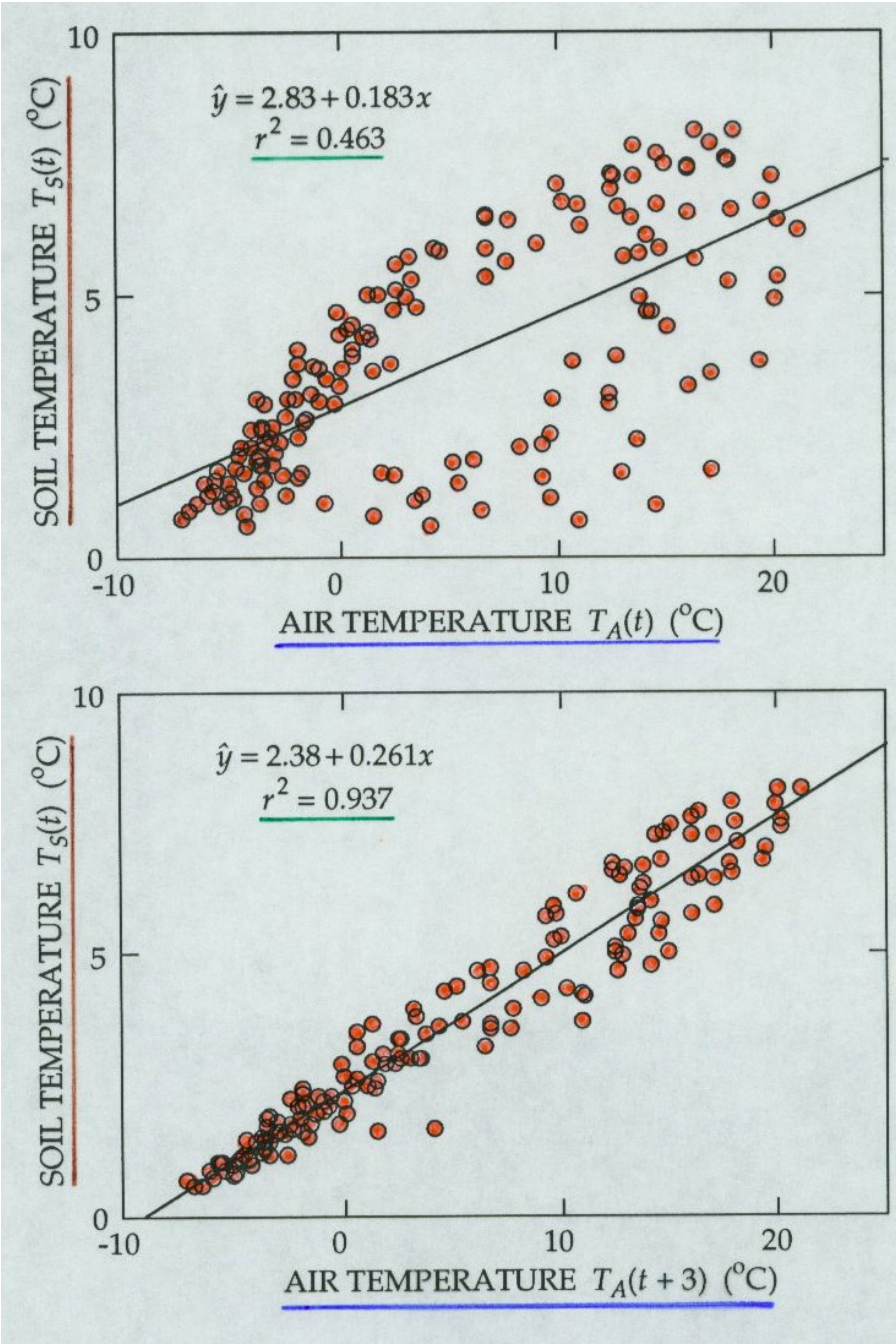
air&soilT versus time



Air & soil temperature cospect



regressions same time and lag of 3 hr

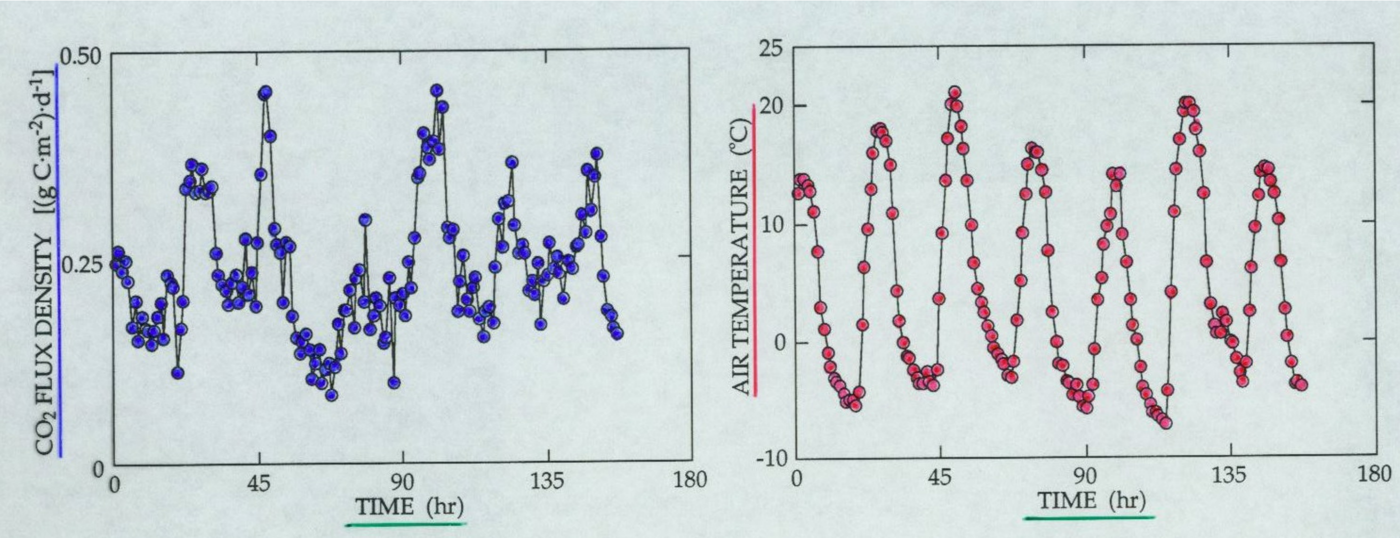


RESPIRATION

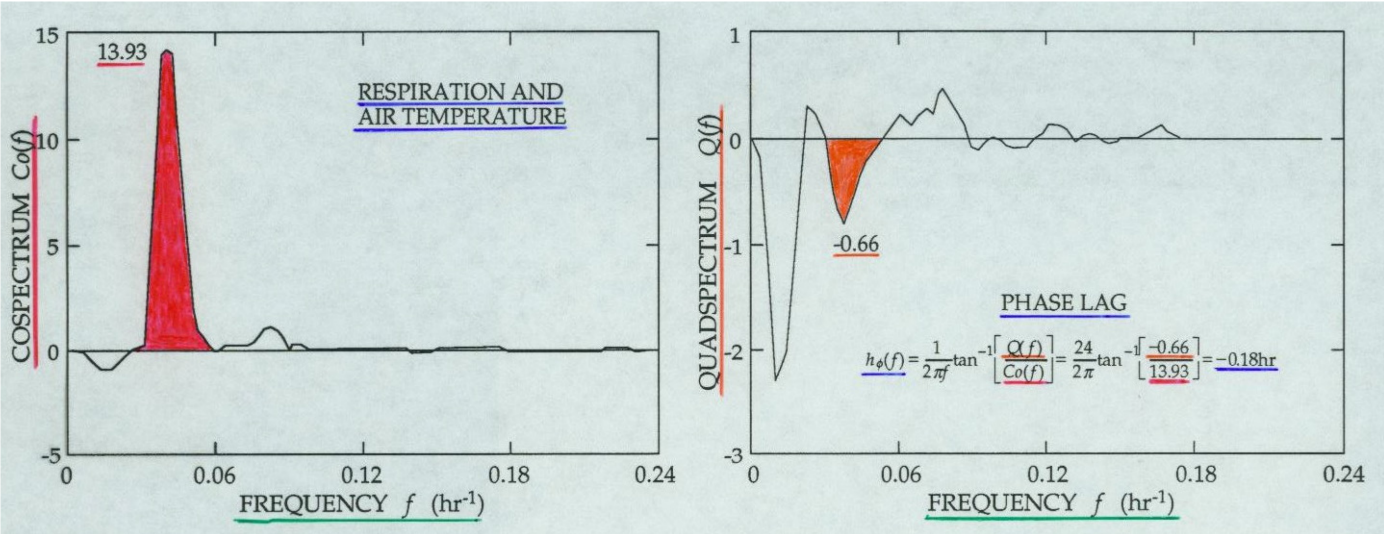
AND

AIR TEMPERATURE

resp & air T versus time



Resp & air T cospectrum

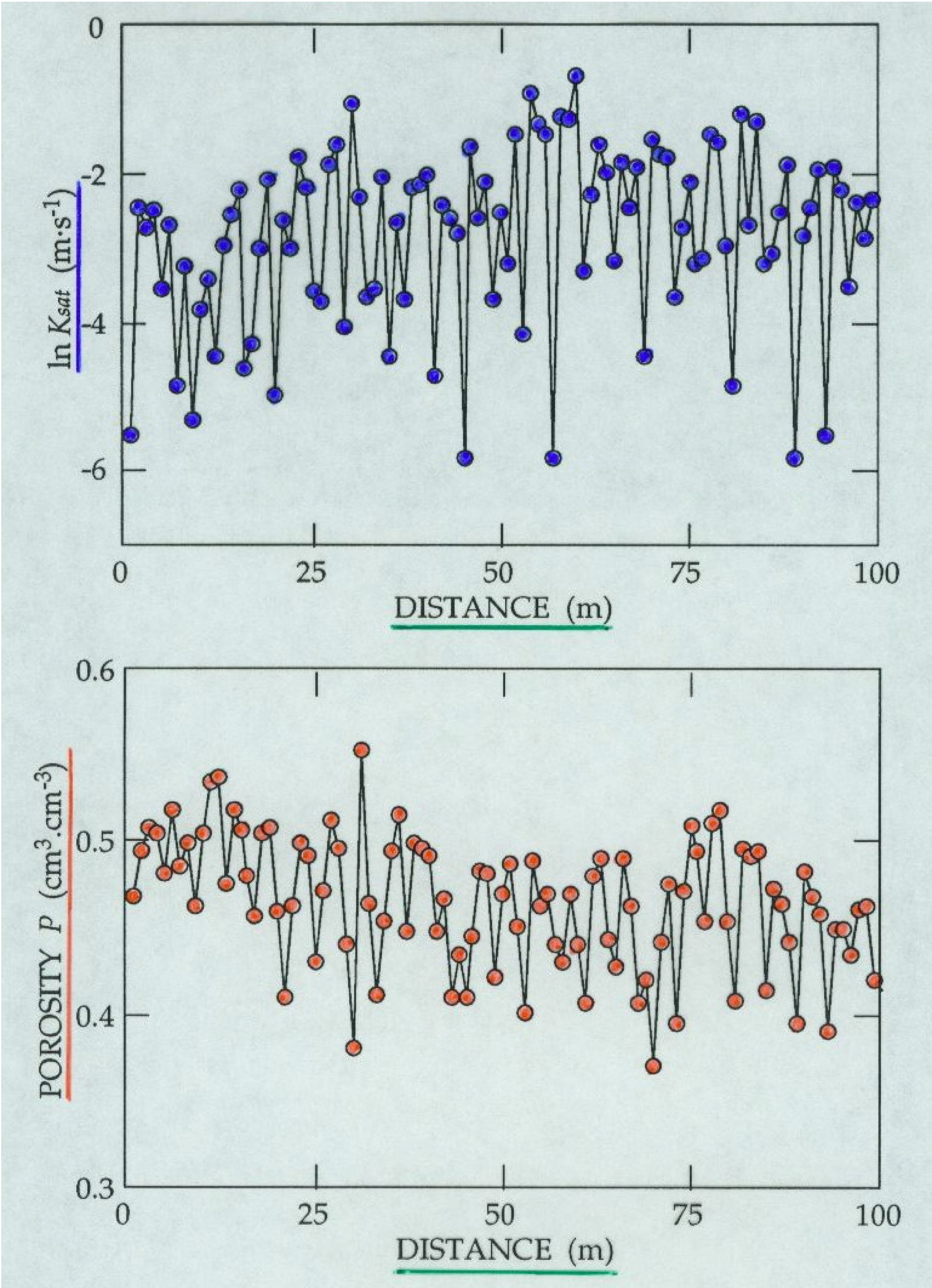


SOIL HYDRAULIC CONDUCTIVITY

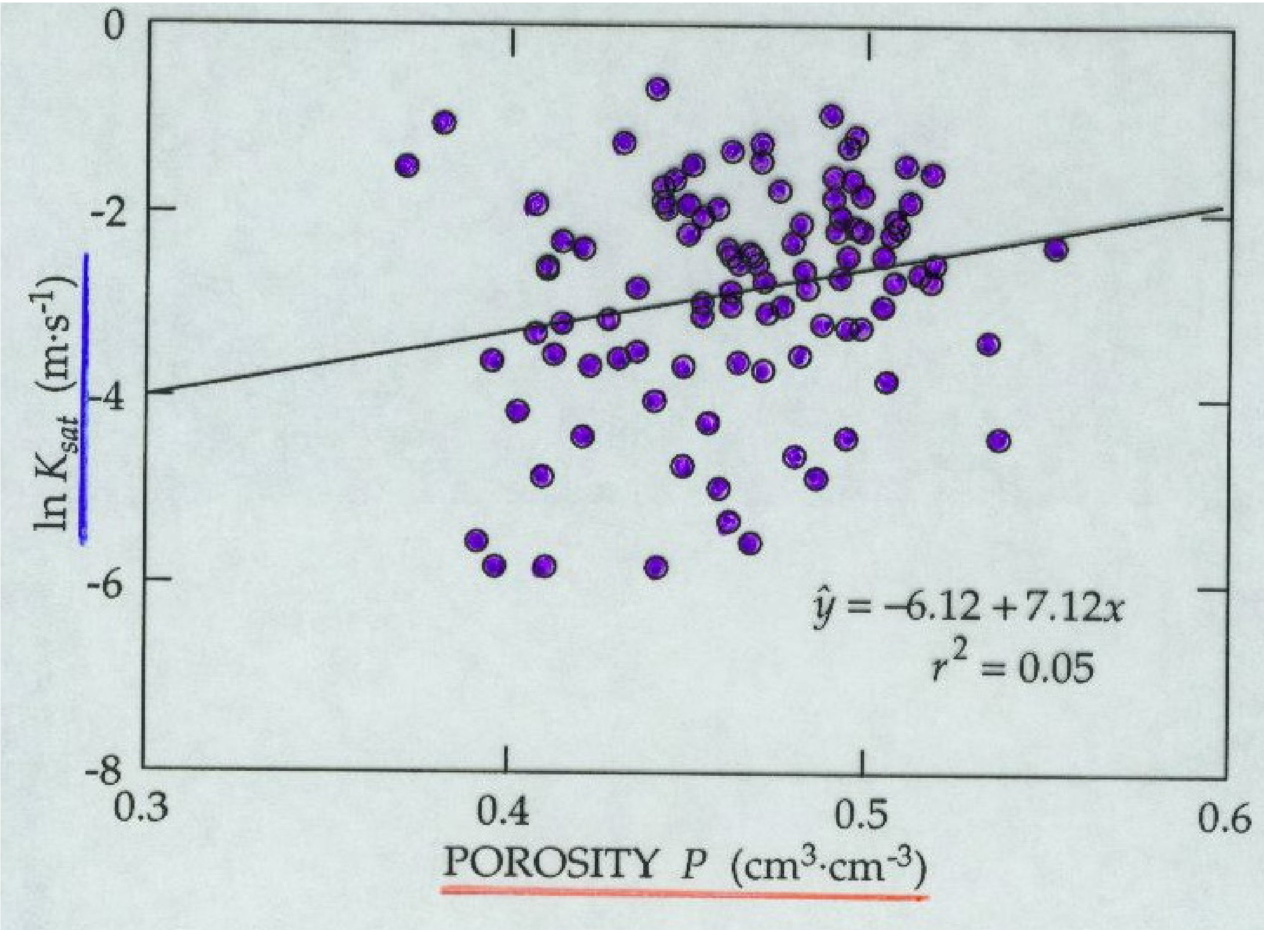
AND

SOIL POROSITY

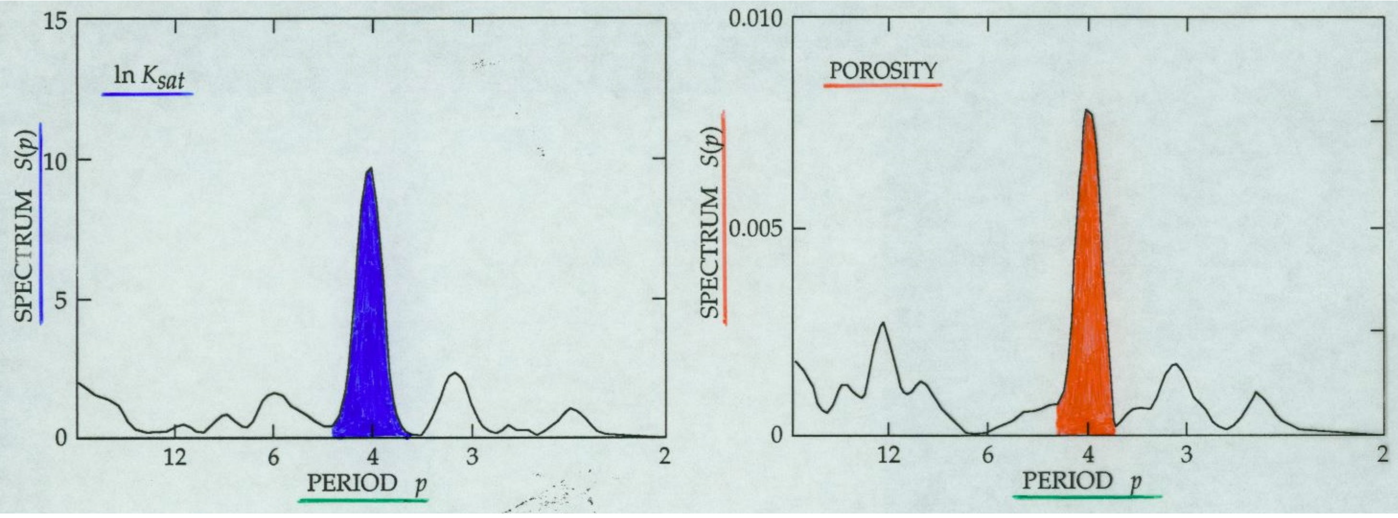
K & porosity versus distance



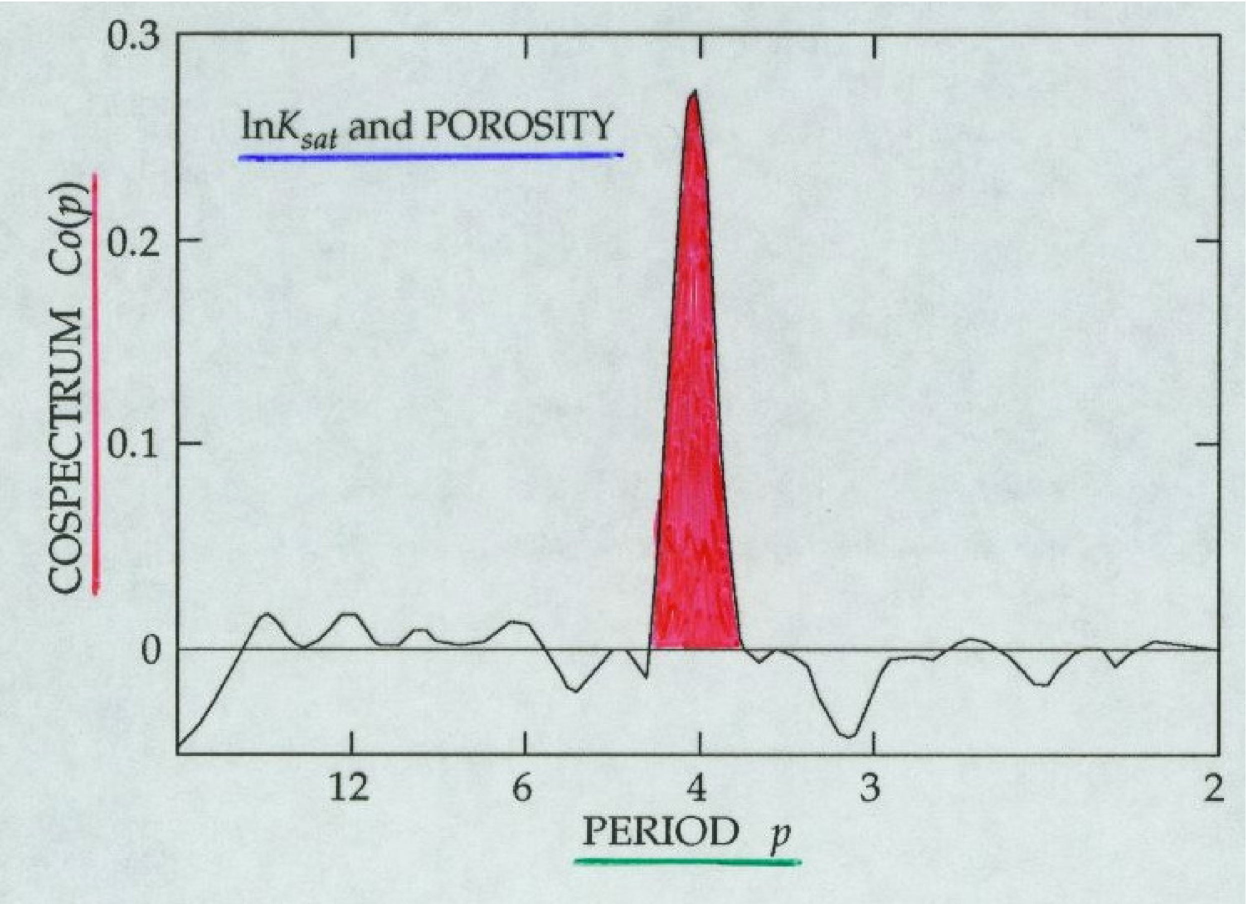
K versus porosity regres



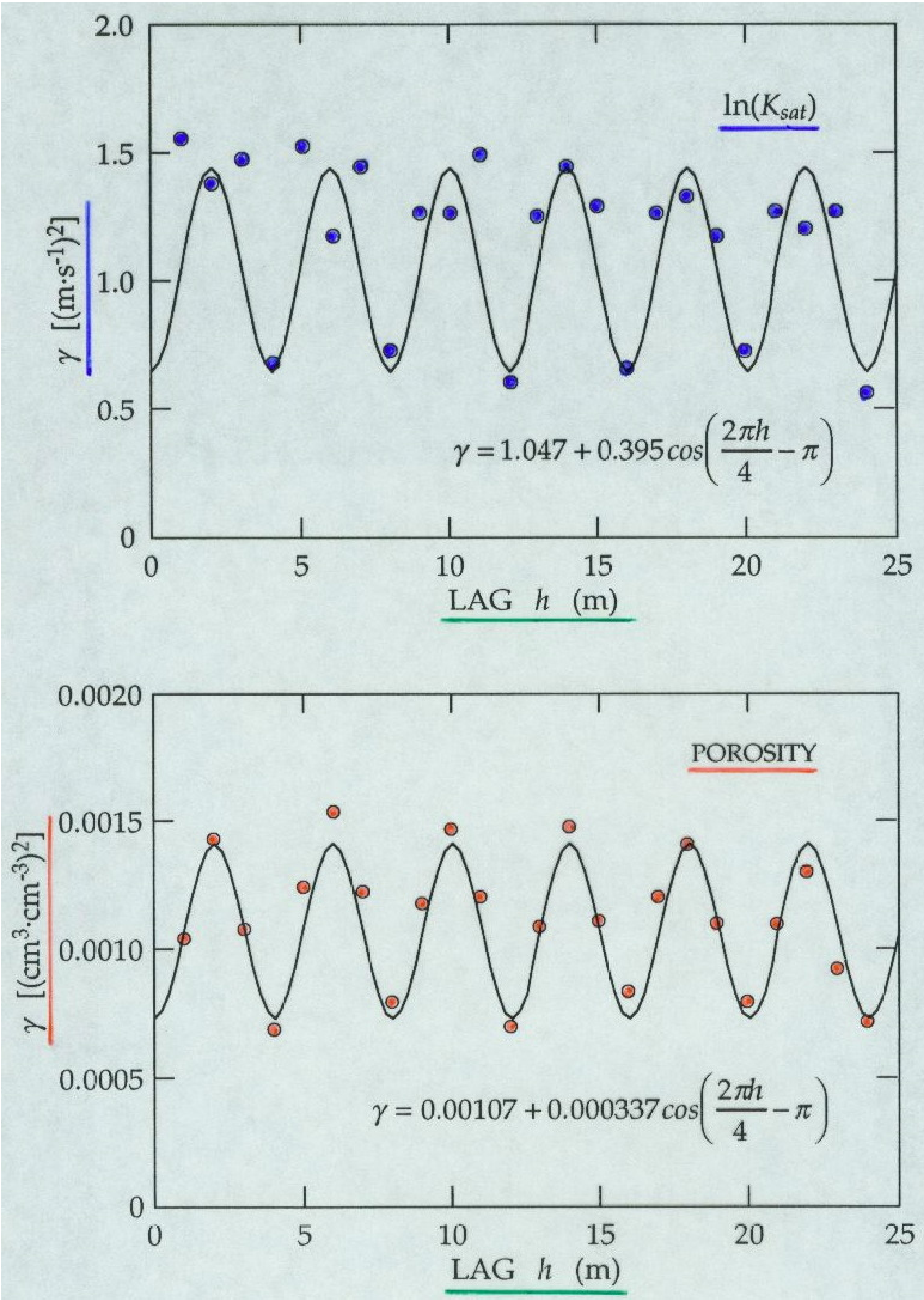
K versus porosity spectrum



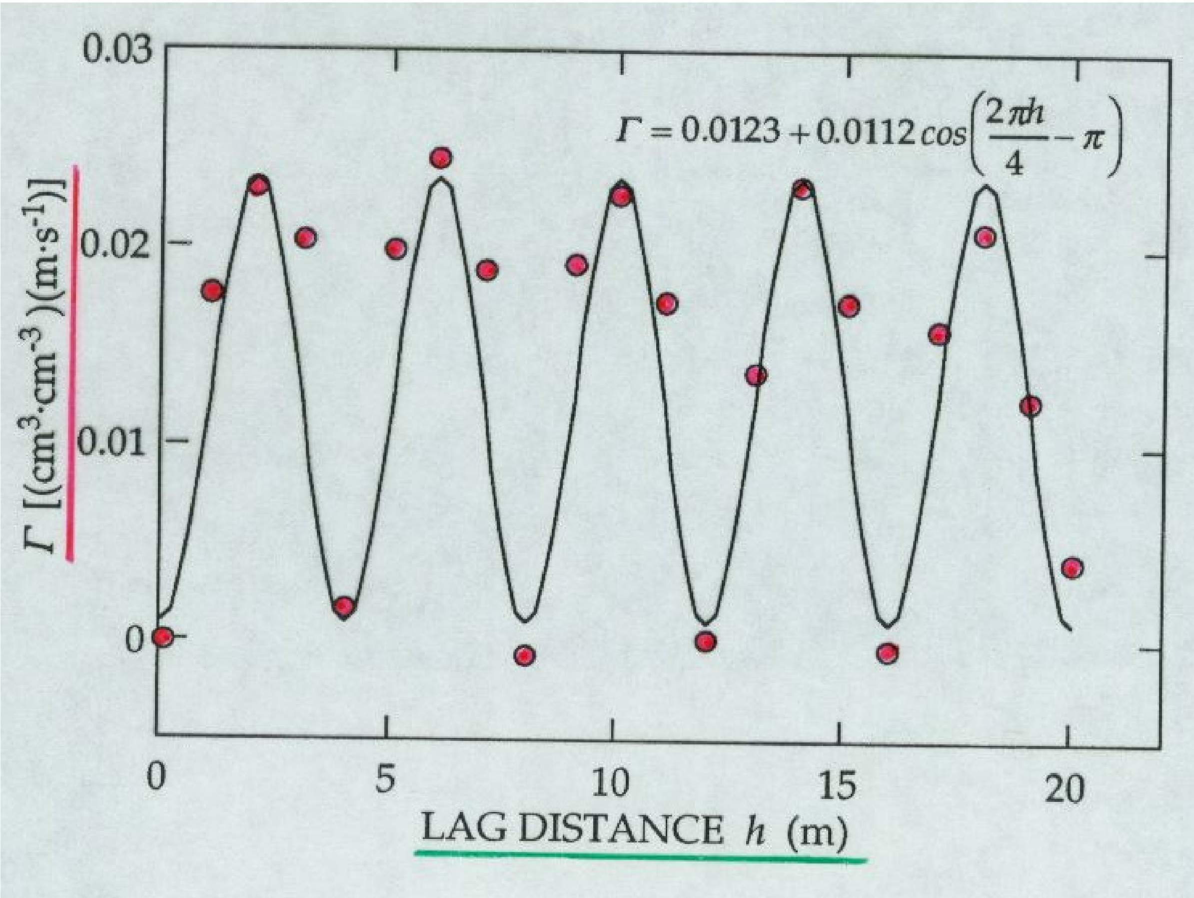
K versus porosity cospectrum



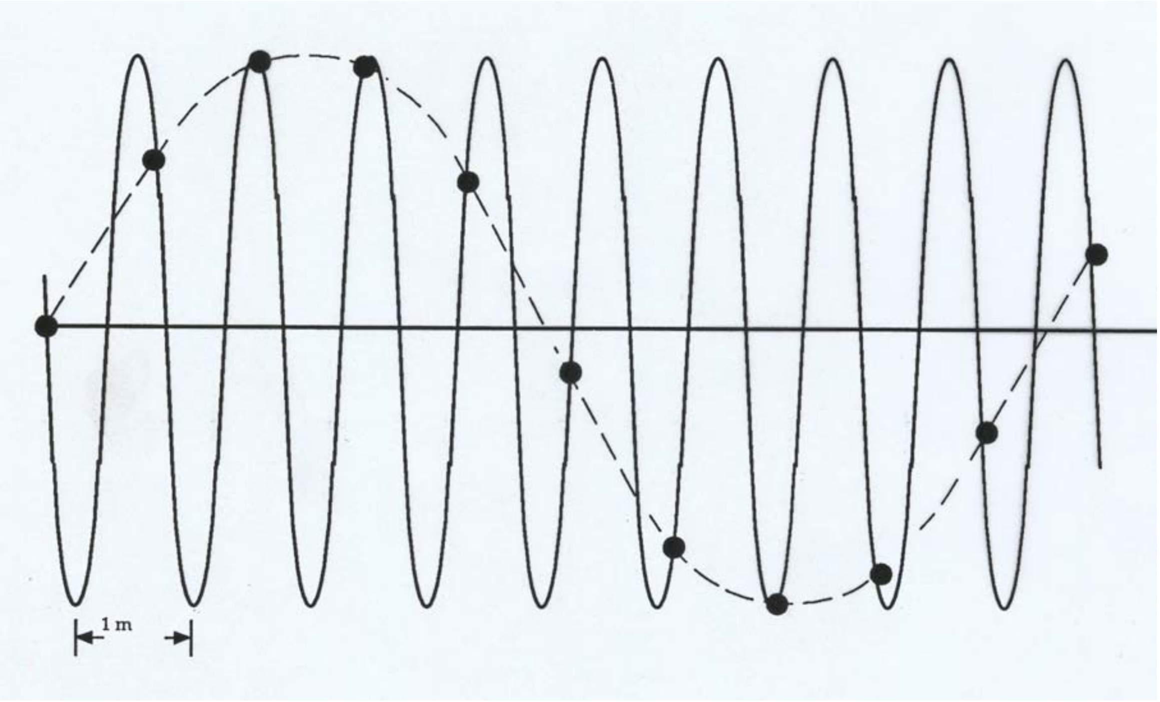
K and porosity variogram



K and porosity covariogram



minimal sampling spectral analysis



why spectral analysis?

¿WHY SPECTRAL ANALYSIS ?

Fields are traversed in cyclic patterns

Impact and persistence of cyclic patterns should be known

Link observations with different physical and chemical phenomena

Size of sensor should depend upon period of oscillation

Cyclic pattern may be more important than average behavior

Over what distances should observations be made to obtain a “meaningful average”?

Filter out trends across a field to look at local variations, or vice versa

Analyze entire field or group of fields rather than small plots

AUTOREGRESSIVE AND MOVING AVERAGE FUNCTIONS

AR and MA equations

Random Walk Model

$$A_i - A_{i-1} = \omega_i$$

$$A_i = A_{i-1} + \omega_i$$

Autoregressive Model $AR(p)$

$$A_i = \phi_1 A_{i-1} + \phi_2 A_{i-2} + \cdots + \phi_p A_{i-p} + \omega_i$$

Partial Autocorrelation Function

$$\phi_{i+1,i+1} = \frac{r(i+1) - \sum_{j=1}^{i} \phi_{p,j} \cdot r(i+1-j)}{1 - \sum_{j=1}^{i} \phi_{i,j} \cdot r(j)}$$

where

$$\phi_{i+1,j} = \phi_{i,j} - \phi_{i+1,i+1} \cdot \phi_{i,i-j+1}$$

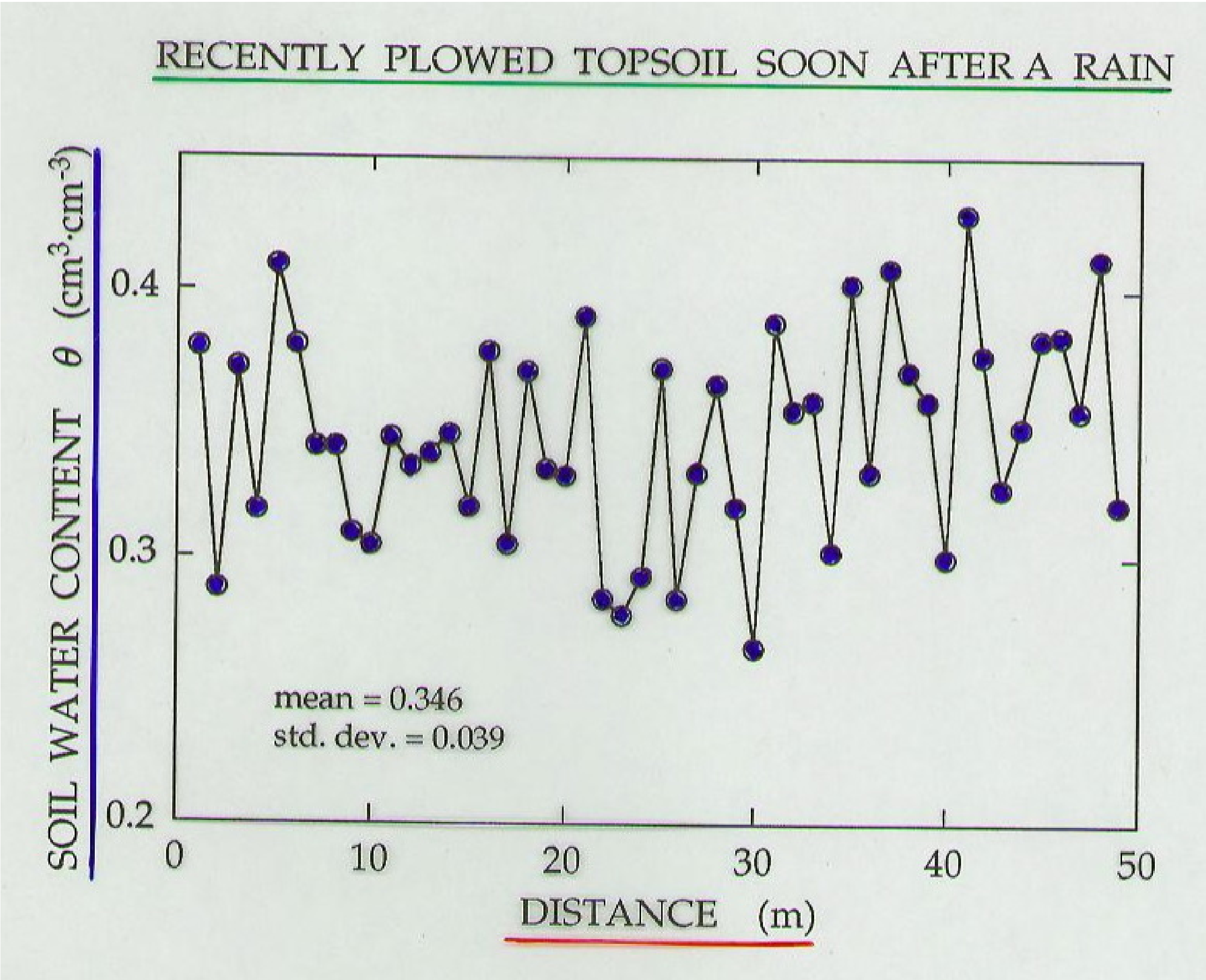
Moving Average Model $MA(q)$

$$A_i = \omega_i - \theta_1 \omega_{i-1} - \theta_2 \omega_{i-2} - \cdots - \theta_q \omega_{i-q}$$

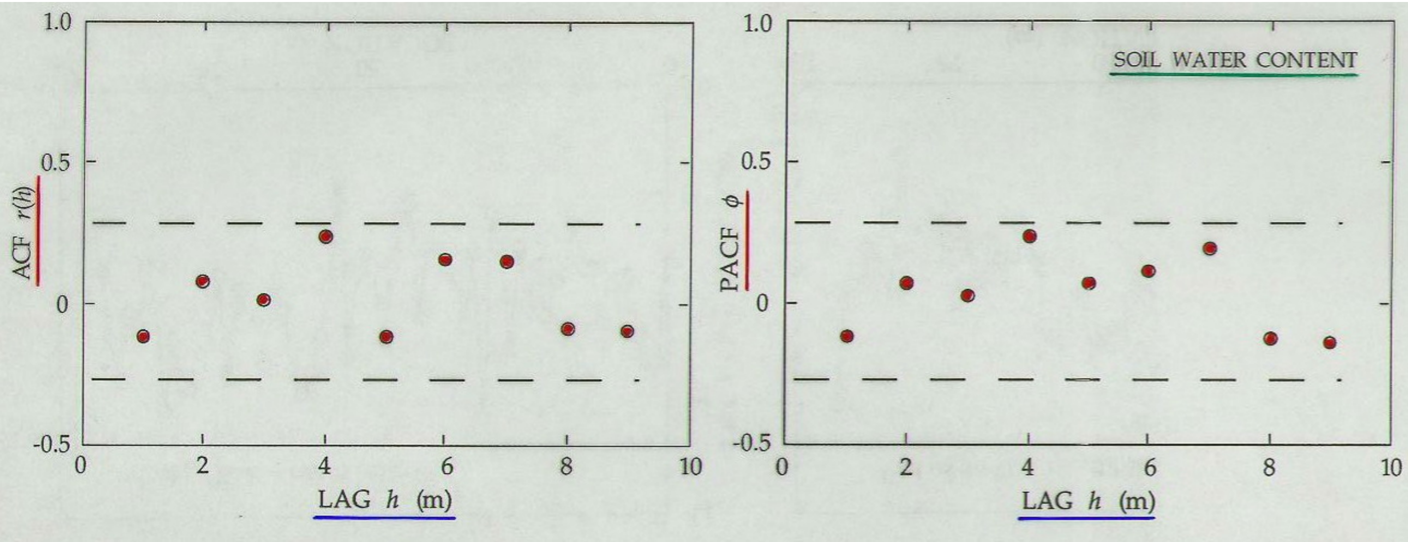
Autoregressive Moving Average Model $ARMA(p,q)$

$$A_i = \phi_1 A_{i-1} + \phi_2 A_{i-2} + \cdots + \phi_p A_{i-p} + \omega_i - \theta_1 \omega_{i-1} - \theta_2 \omega_{i-2} - \cdots - \theta_q \omega_{i-q}$$

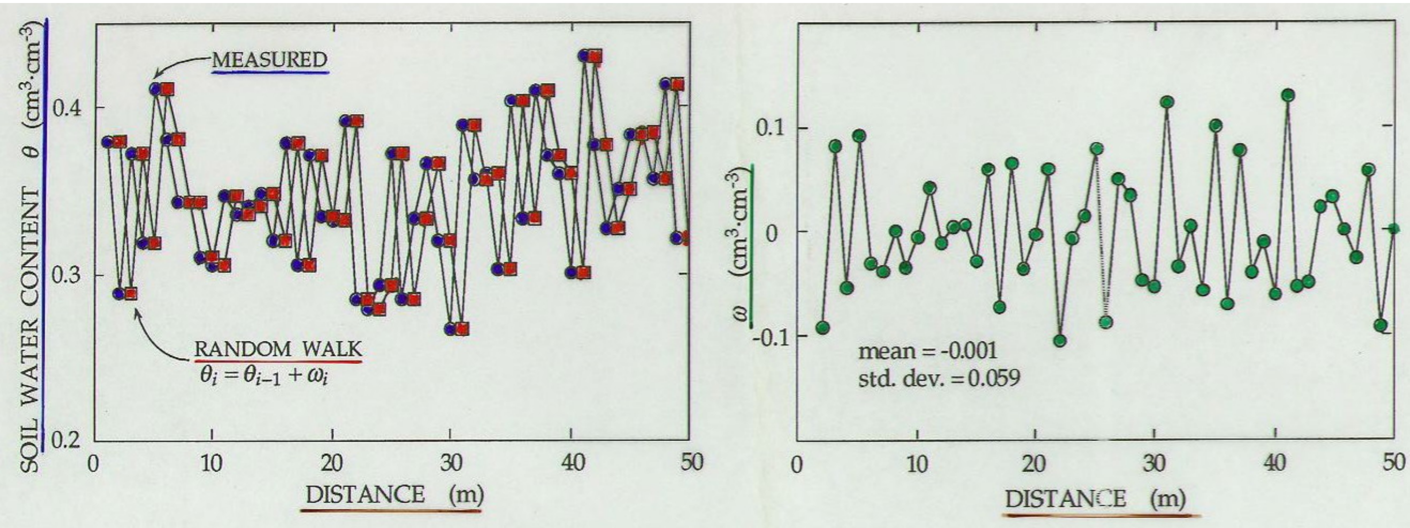
soil water after rain vs distance



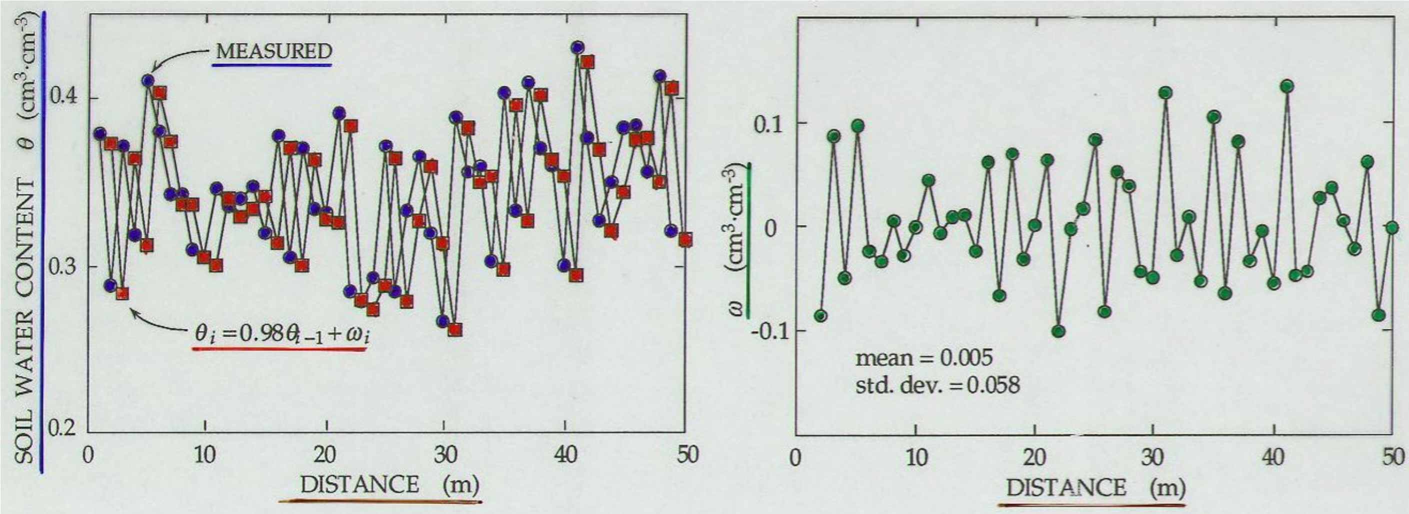
ACF & PACF of soil water



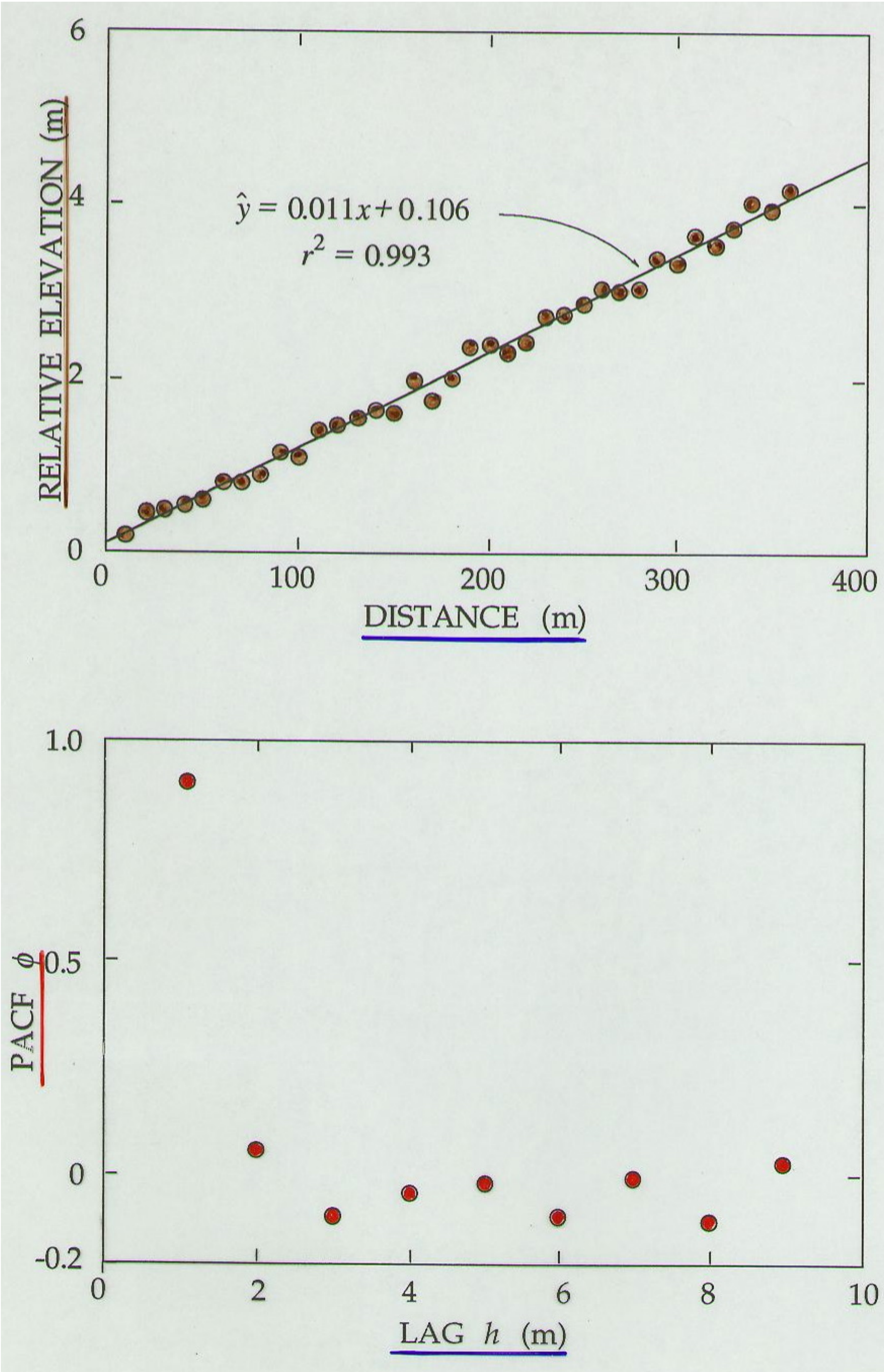
random walk soil water



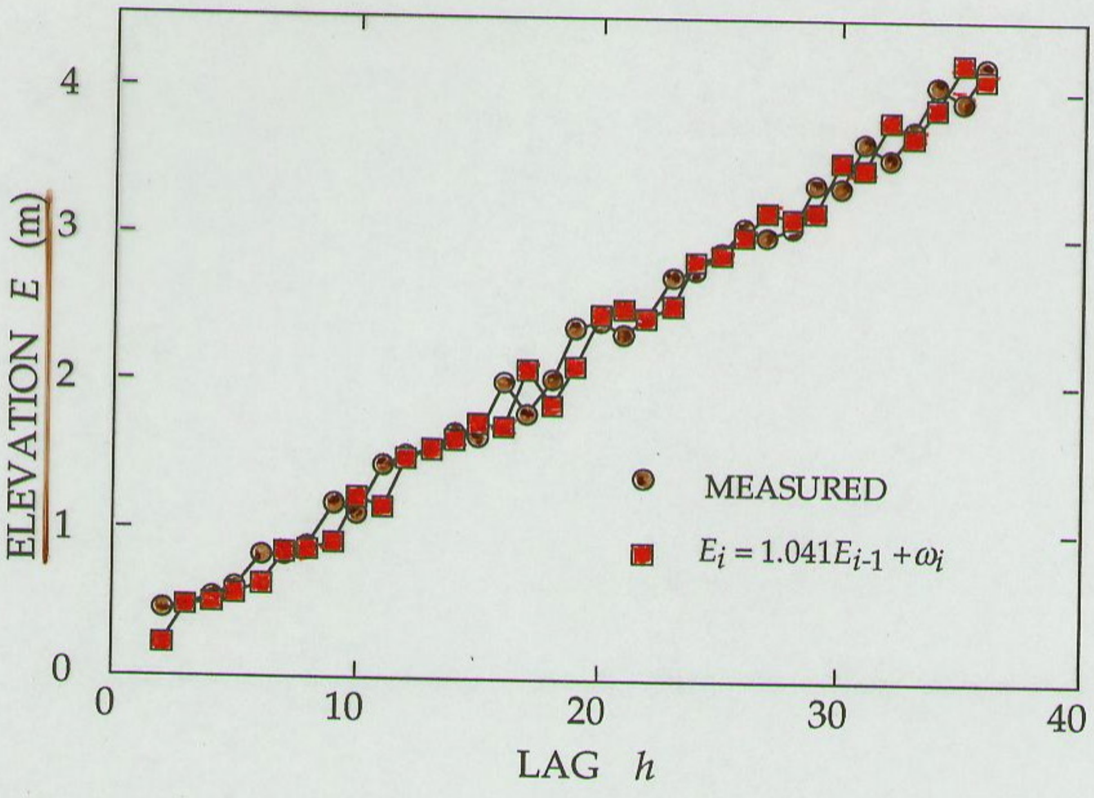
AR(1) soil water

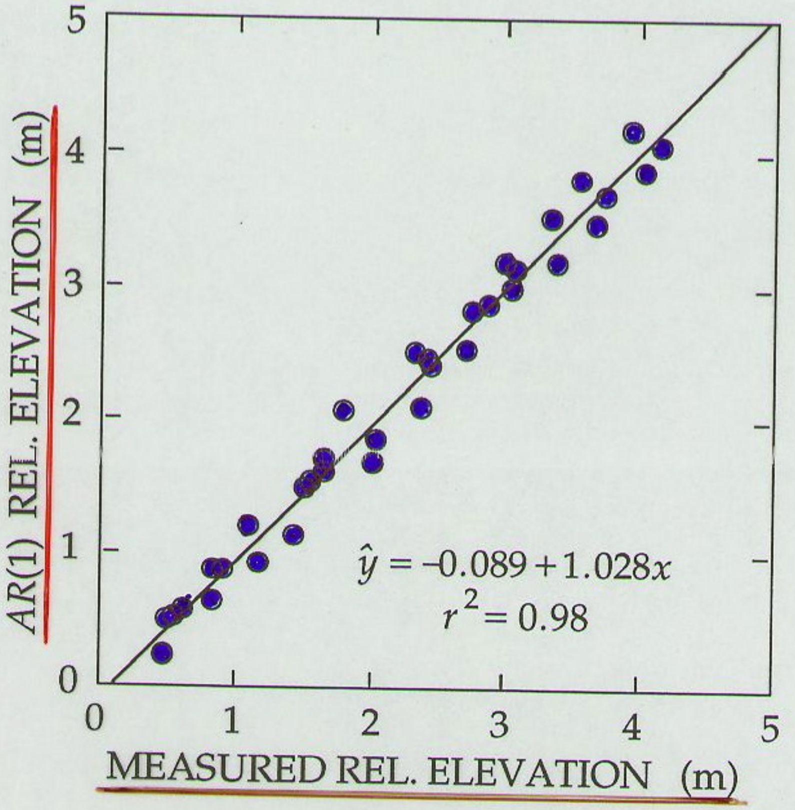


linear soil elevation and ACF

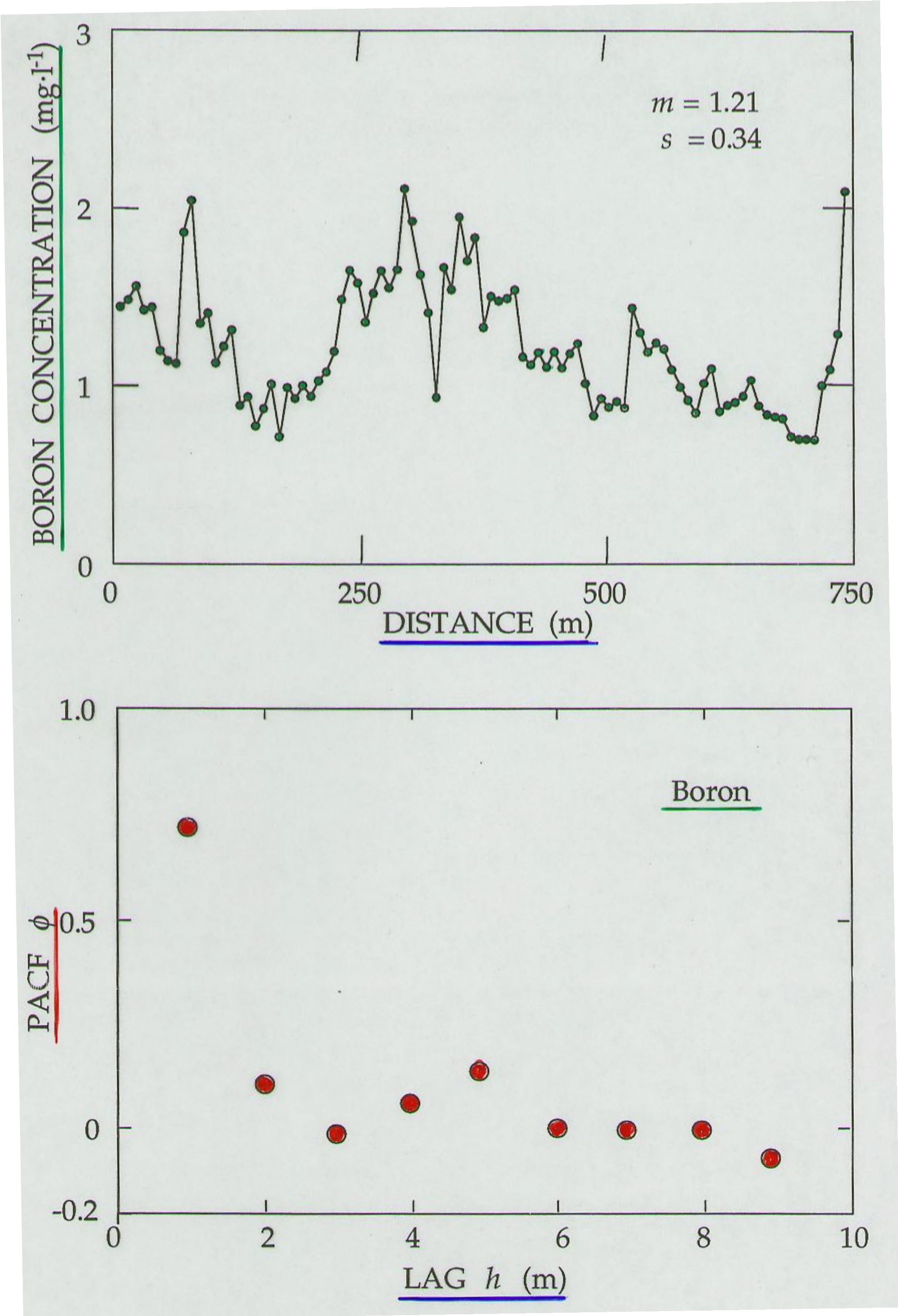


AR(1) of soil elevation

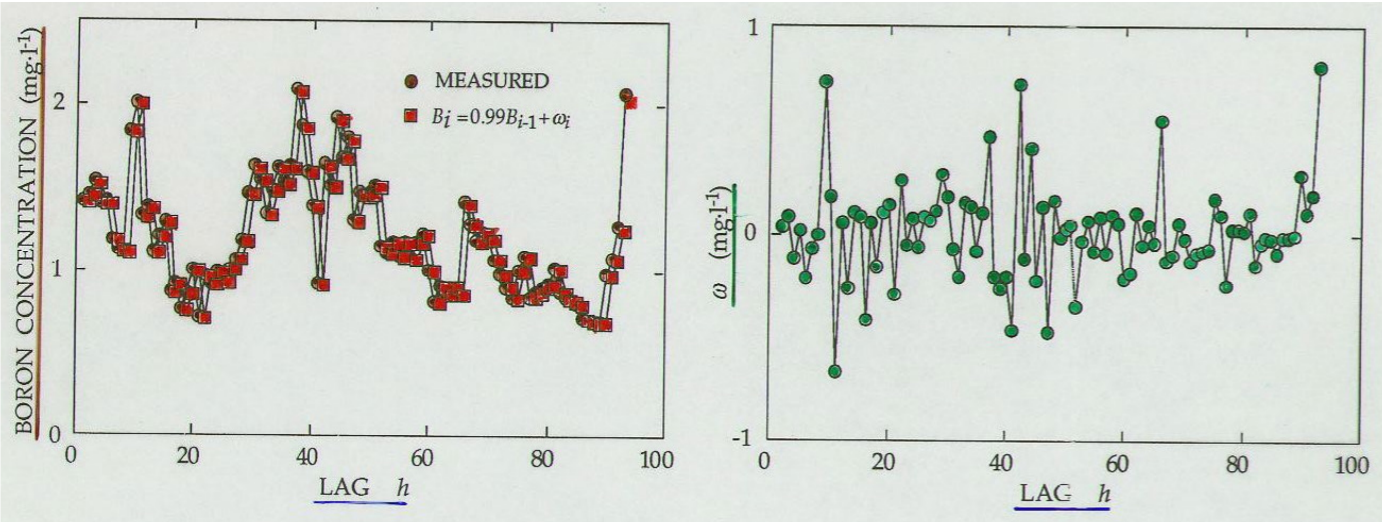




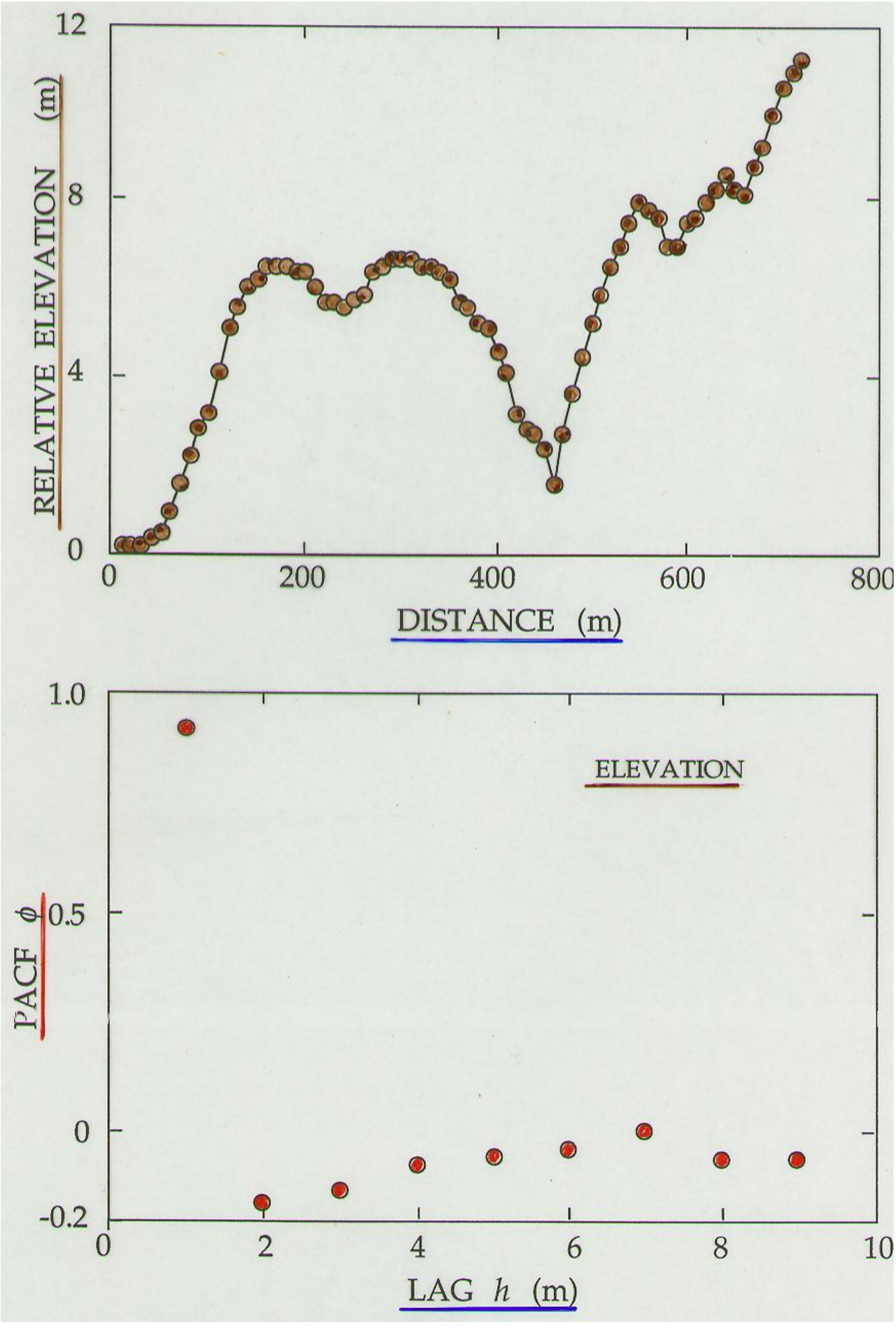
boron conc vs distance & PACF (NM)



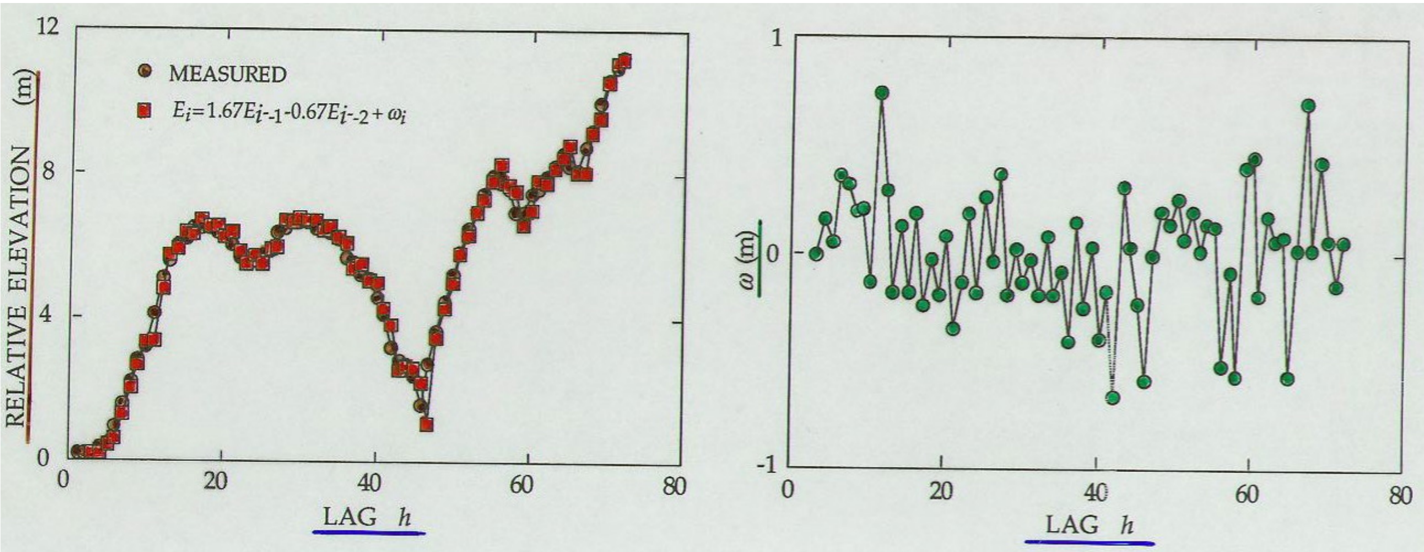
AR(1) of boron NM



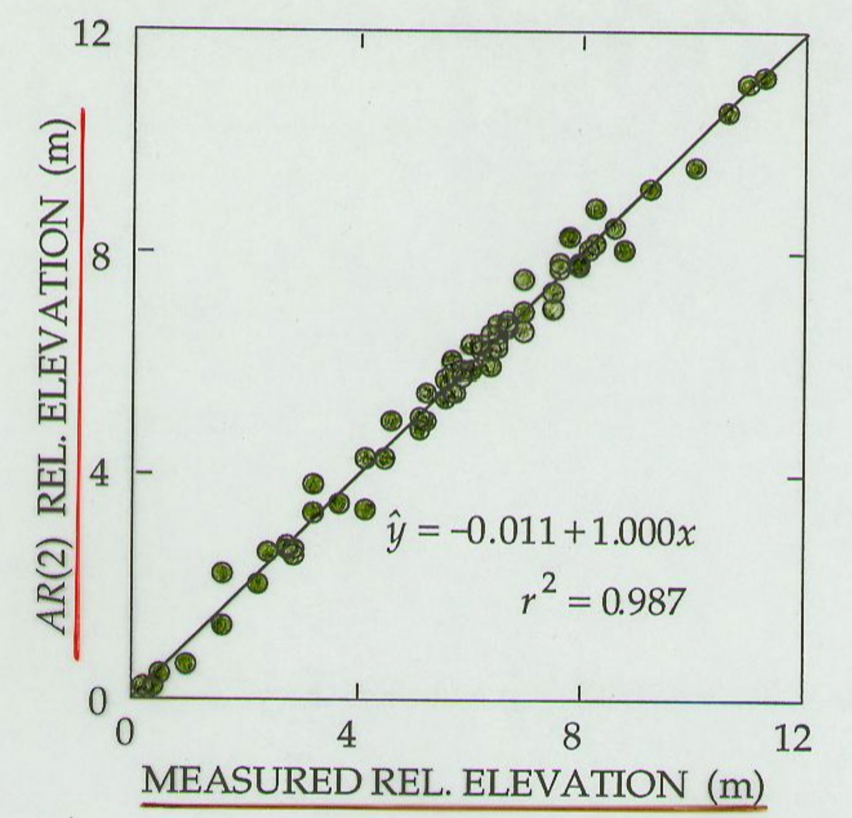
soil elevation vs distance

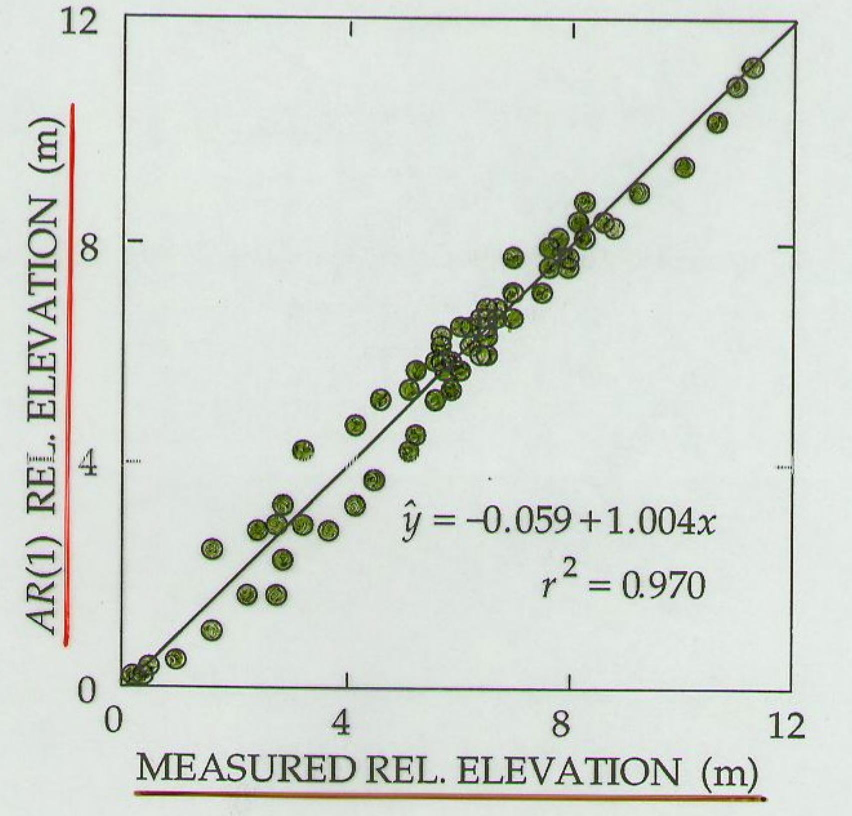


AR(1) and residual elevation

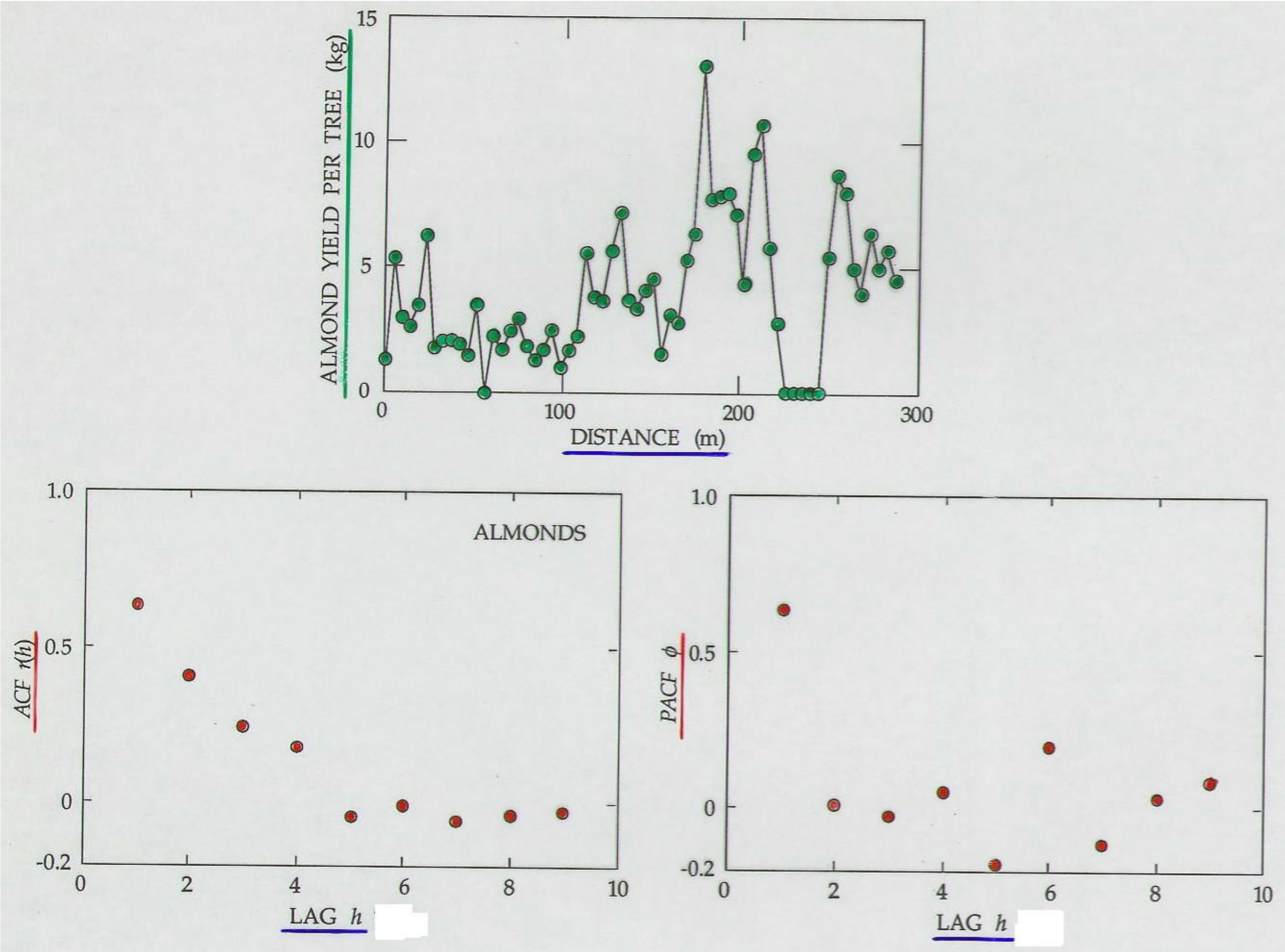


AR(1) & AR(2) elevation

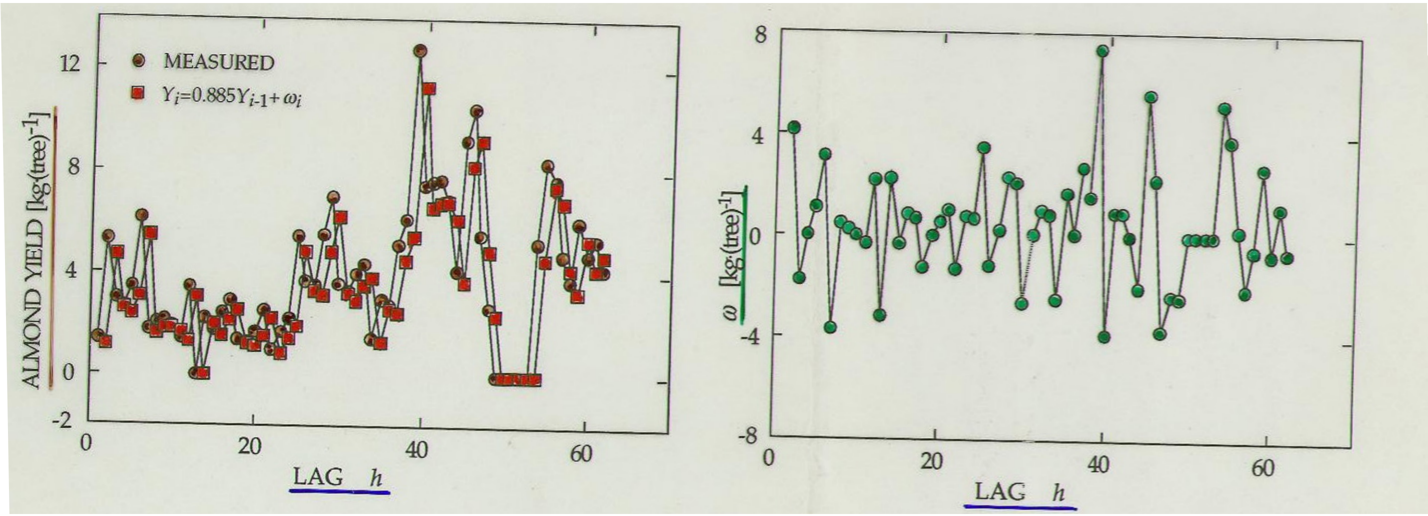




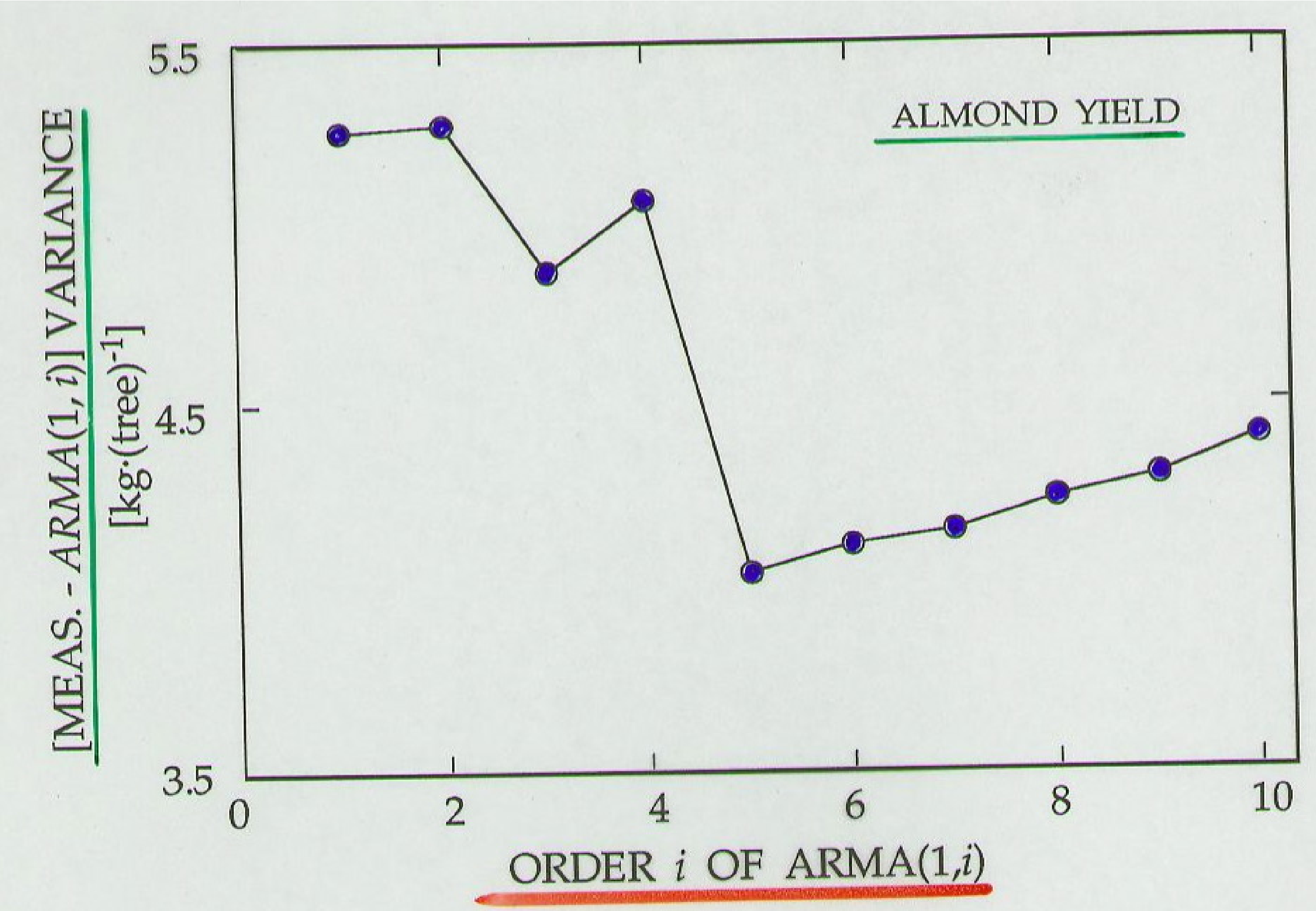
almond yield per tree vs distance



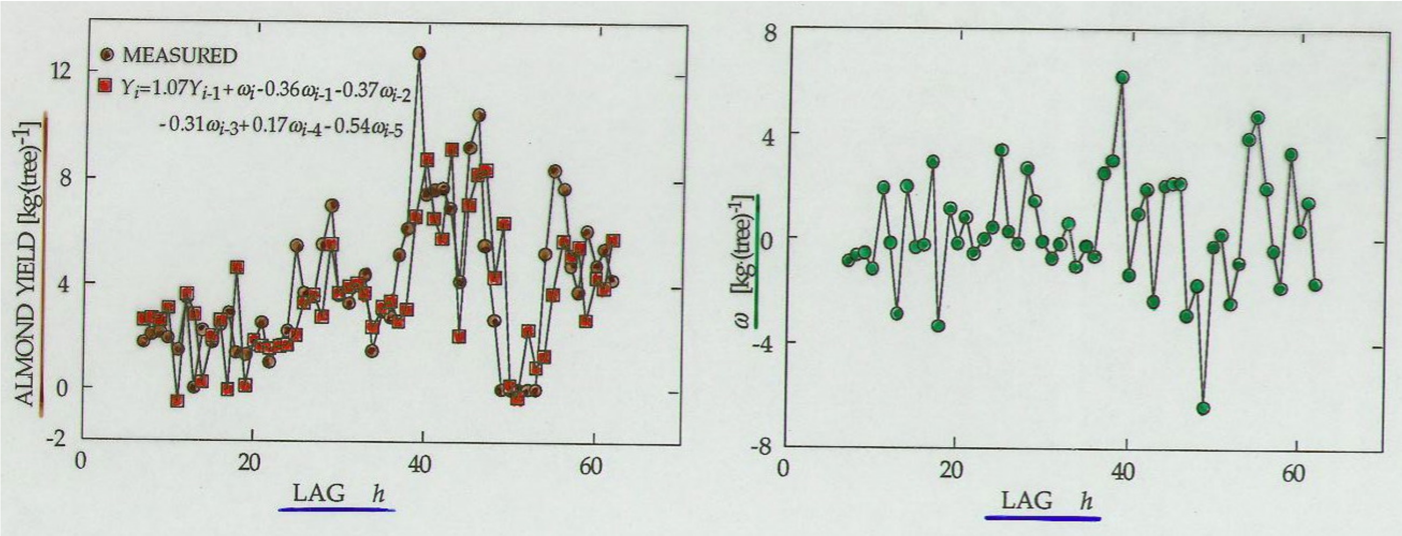
AR(1) of almond yield per tree



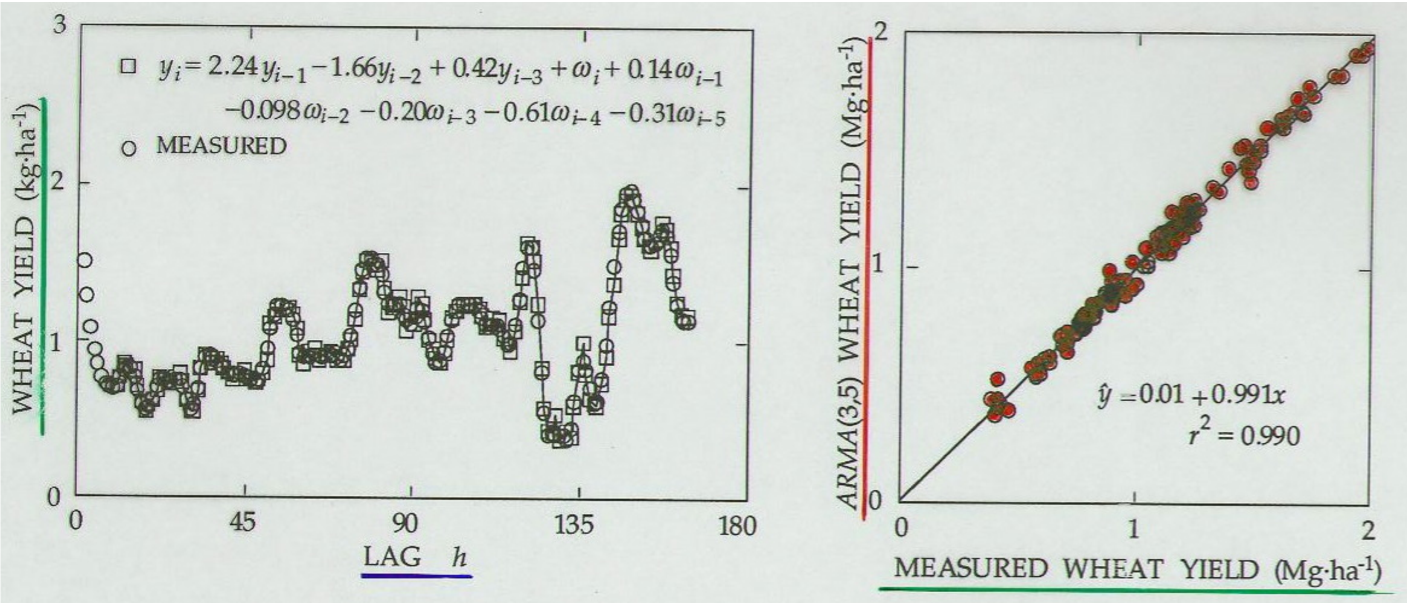
almond yield variance vs AR order



AR(1) and moving ave almond

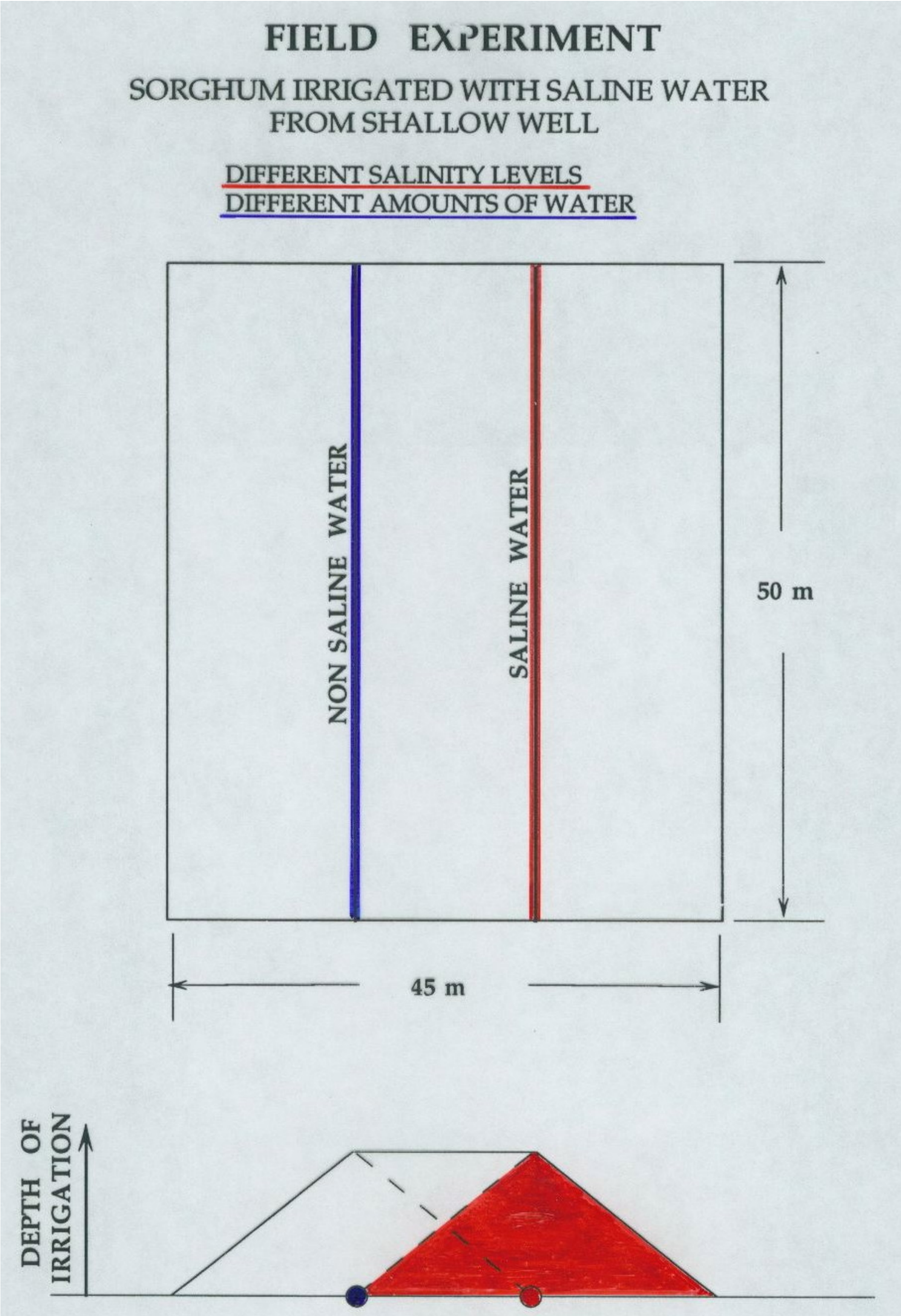


AR(3) and moving ave. wheat

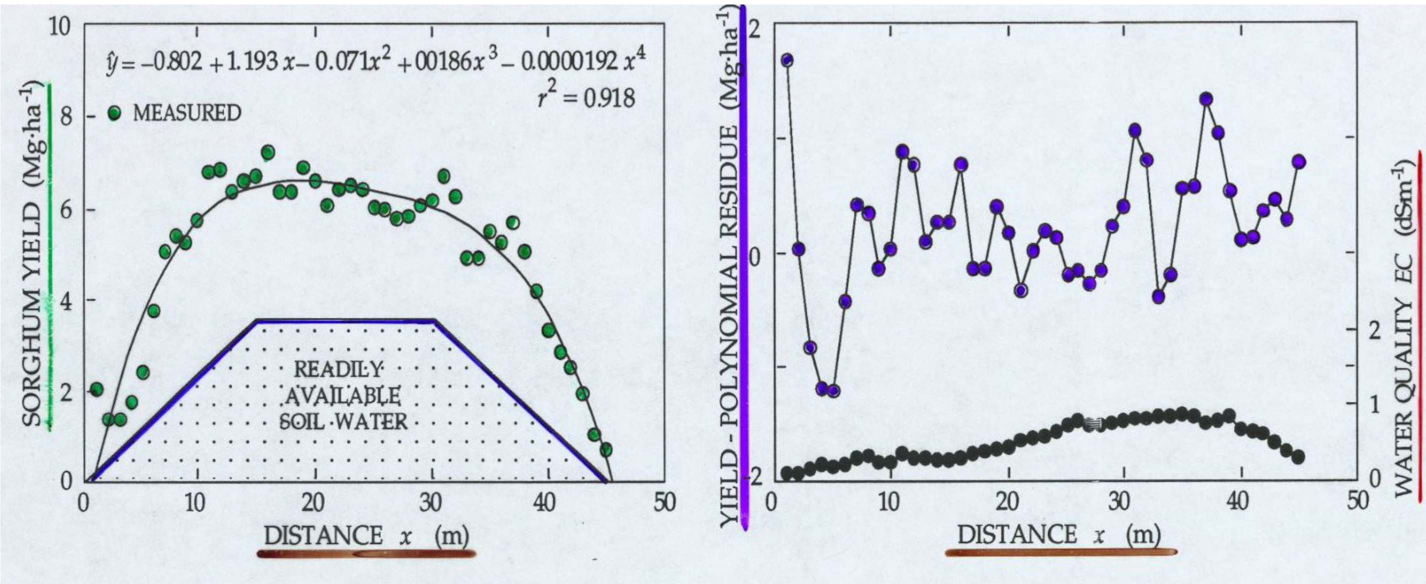


SORGHUM YIELD, SOIL WATER CONTENT AND SOIL SALINITY

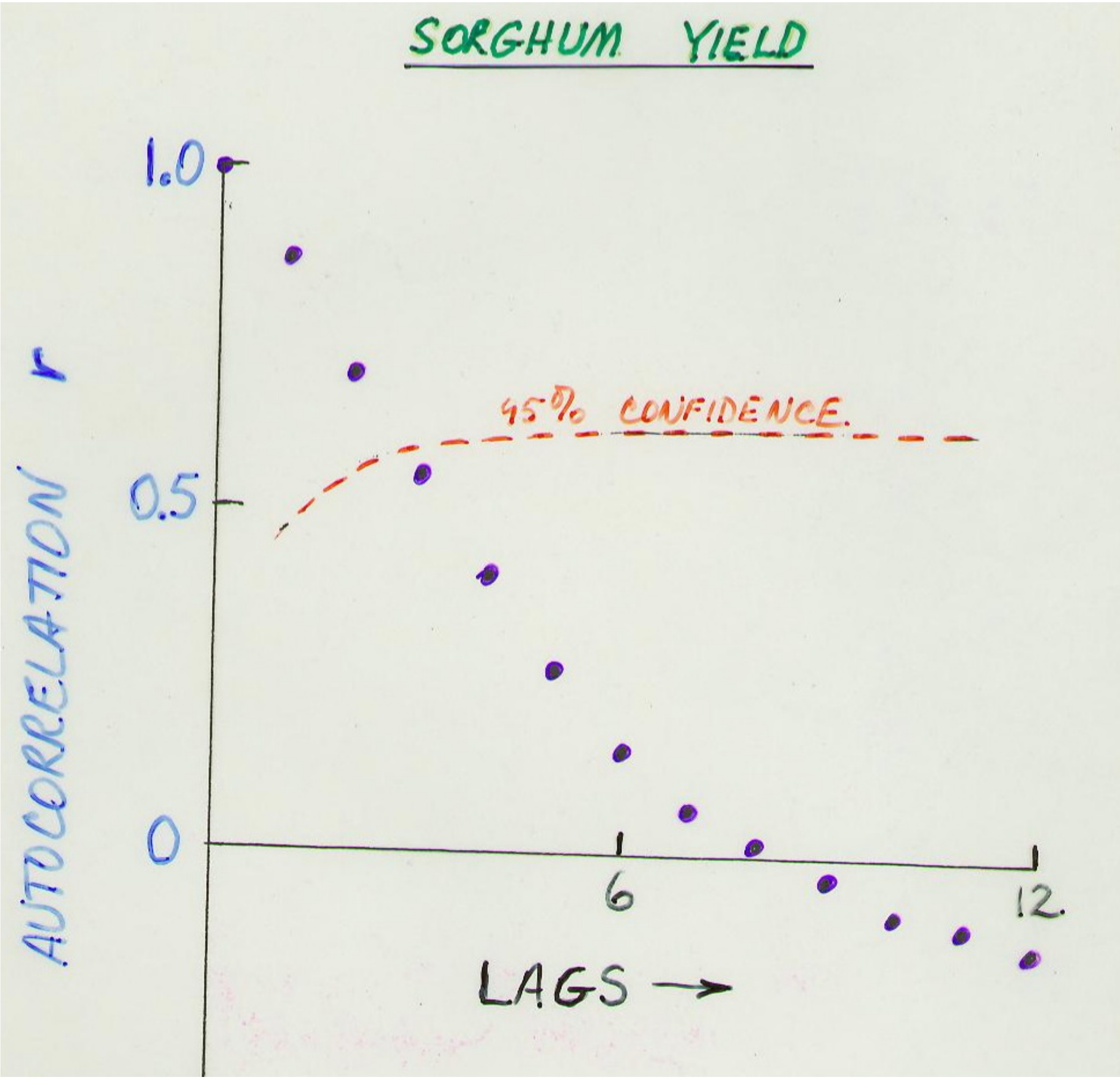
sorghum irrigation expt design



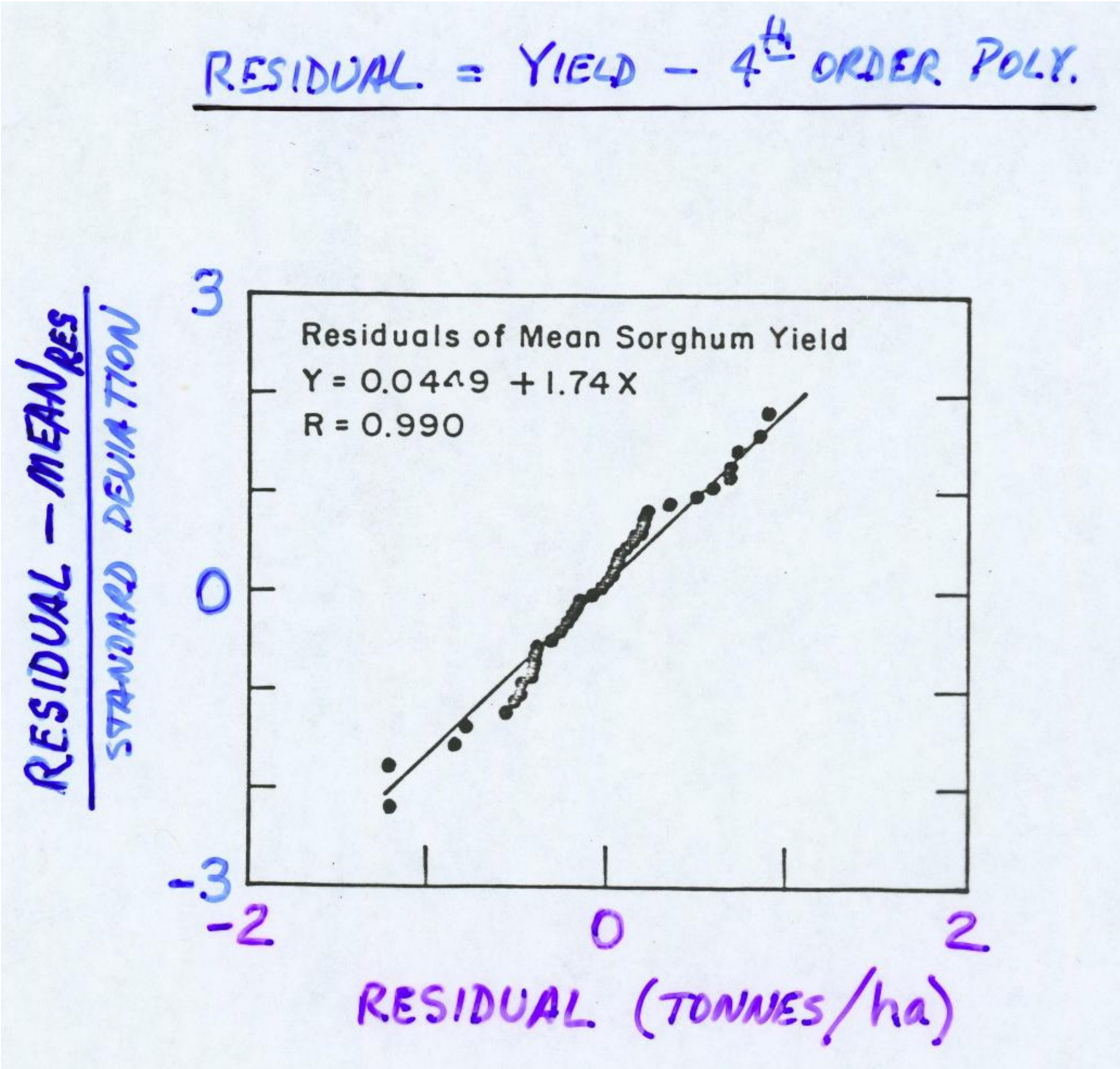
sorghum yld (4th order & residuals)



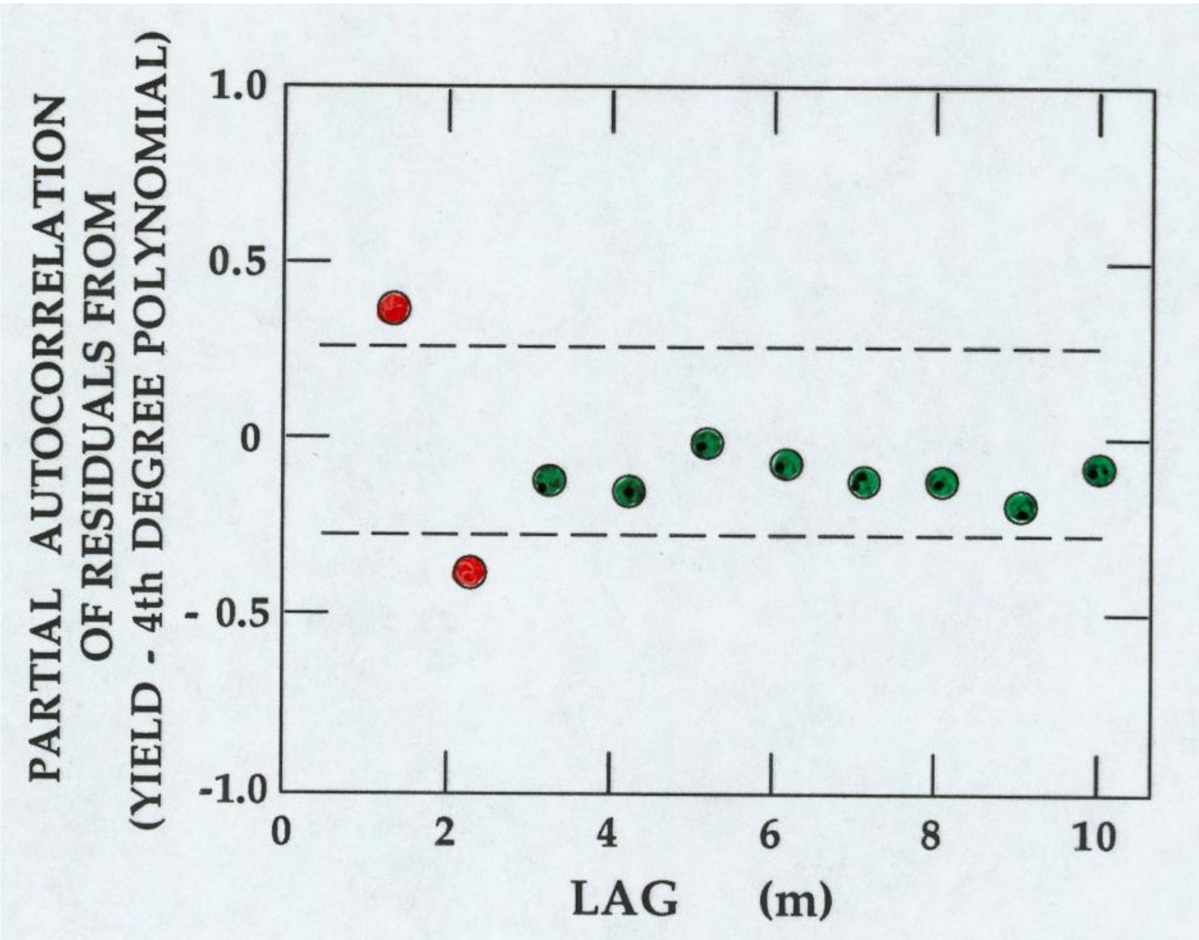
ACF sorghum yield



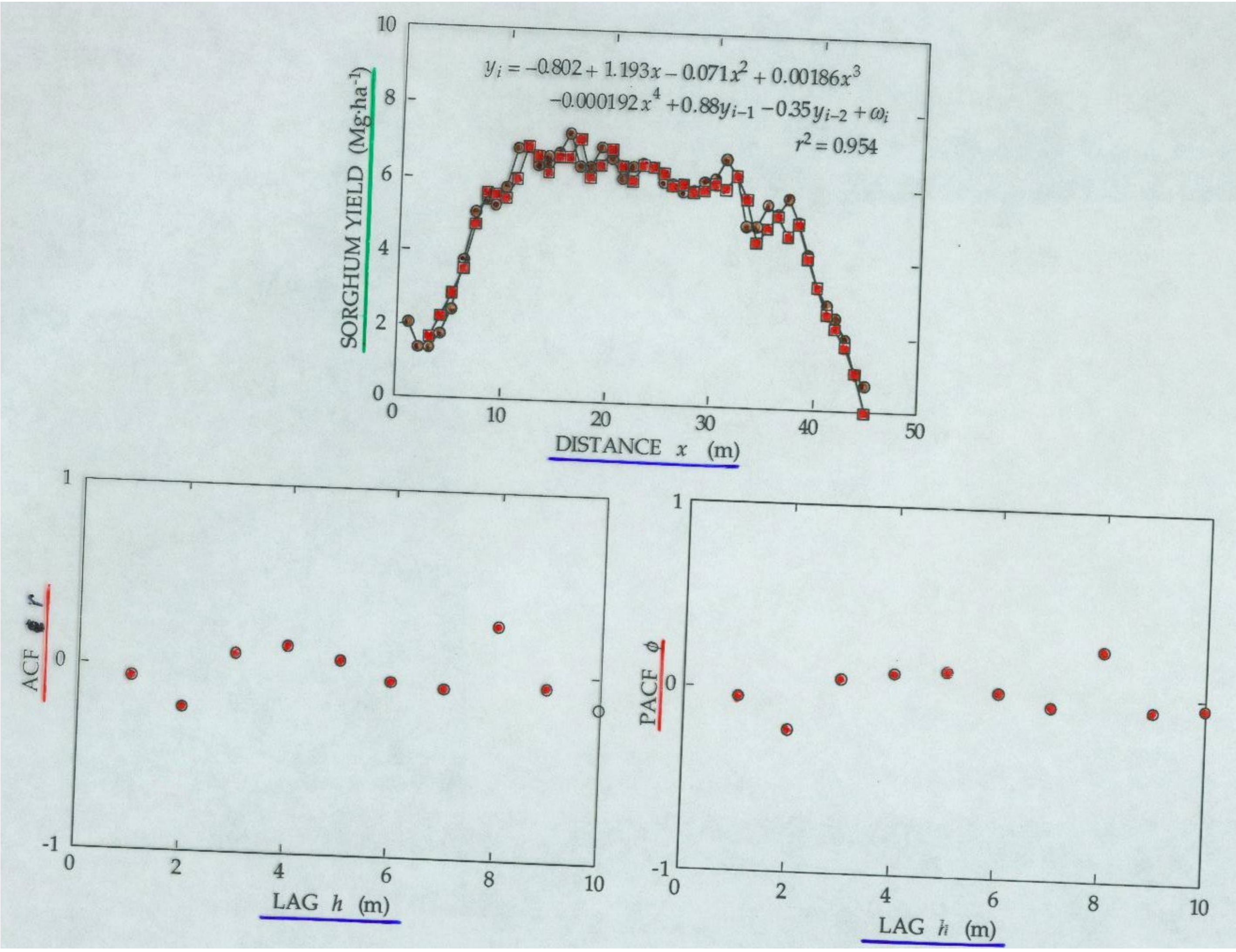
sorghum residuals fractile diagram



PACF (sorghum yield - 4th order)



4th order polynomial plus AR(2) sorghum



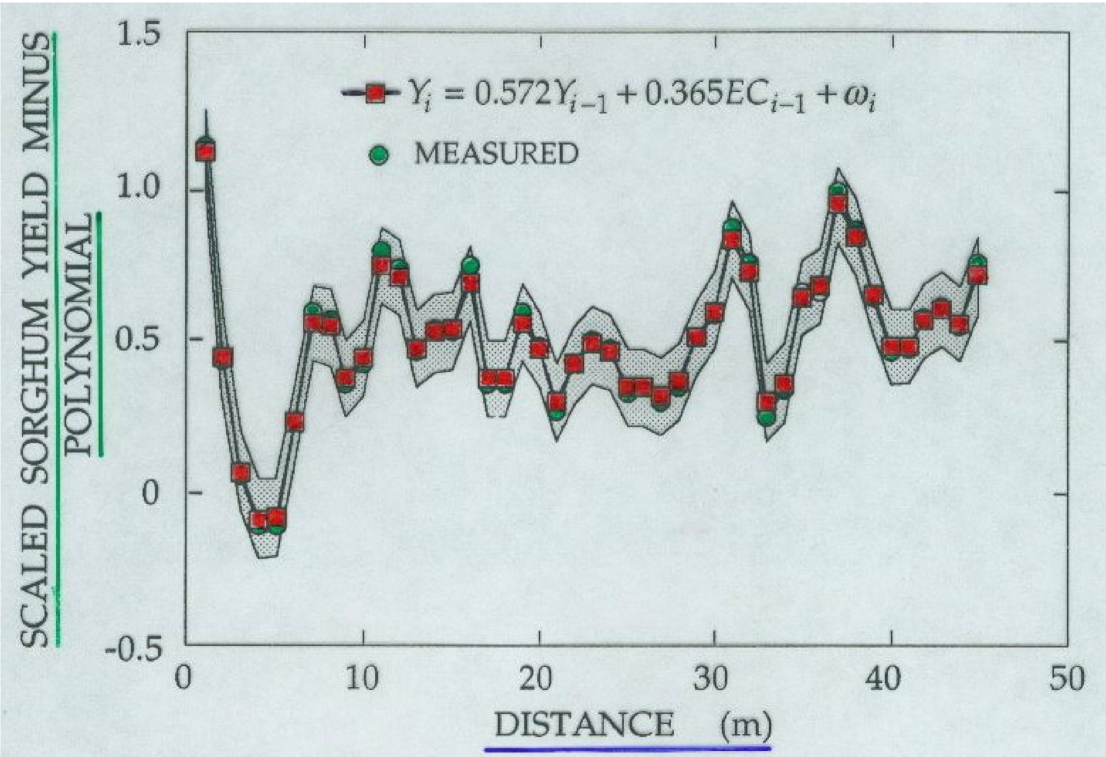
4th order polynomial plus AR(2) equation

$$\text{YIELD} = a_0 + a_1 X^1 + a_2 X^2 + a_3 X^3 + a_4 X^4 + AR(2)$$

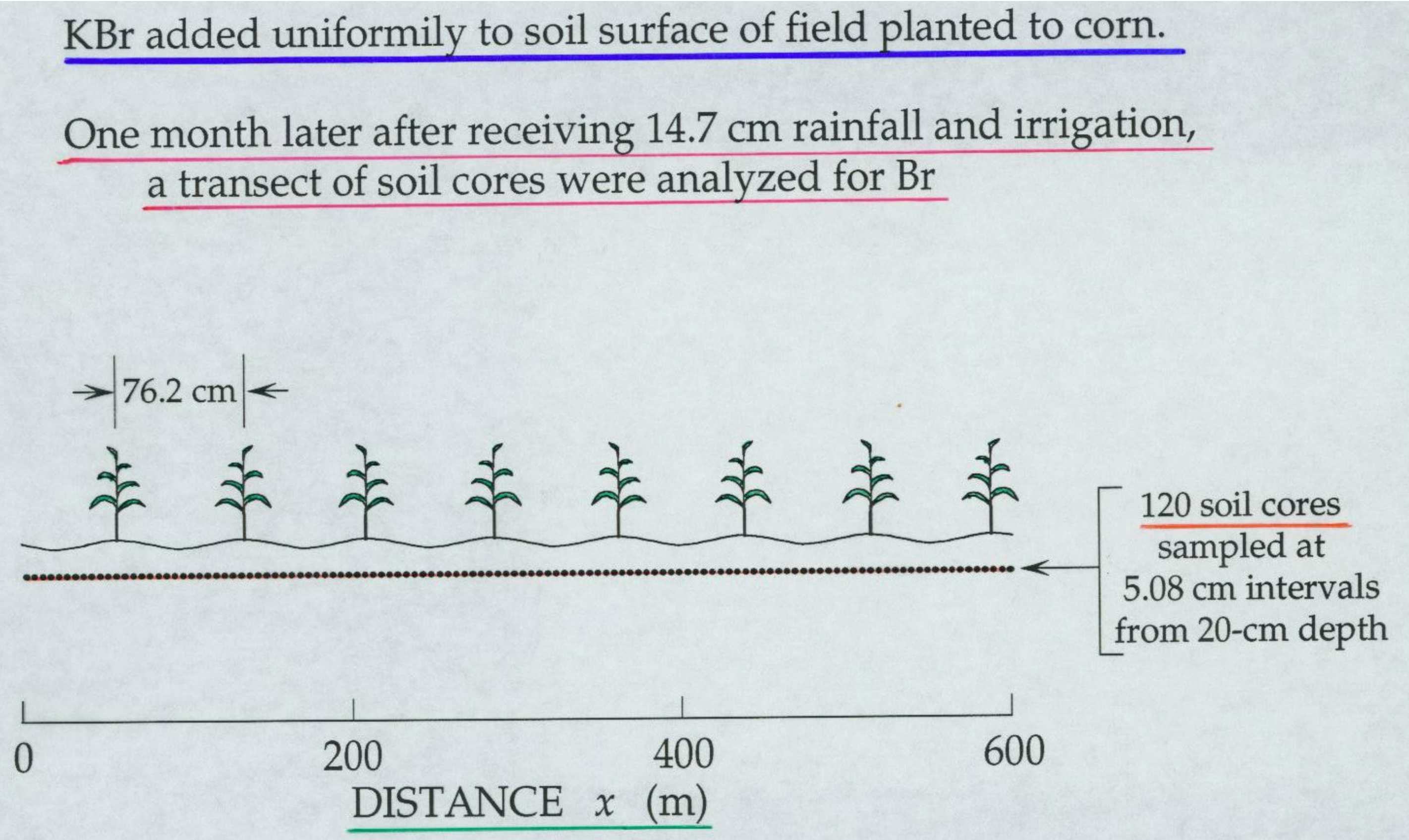
SOIL WATER

SALINITY

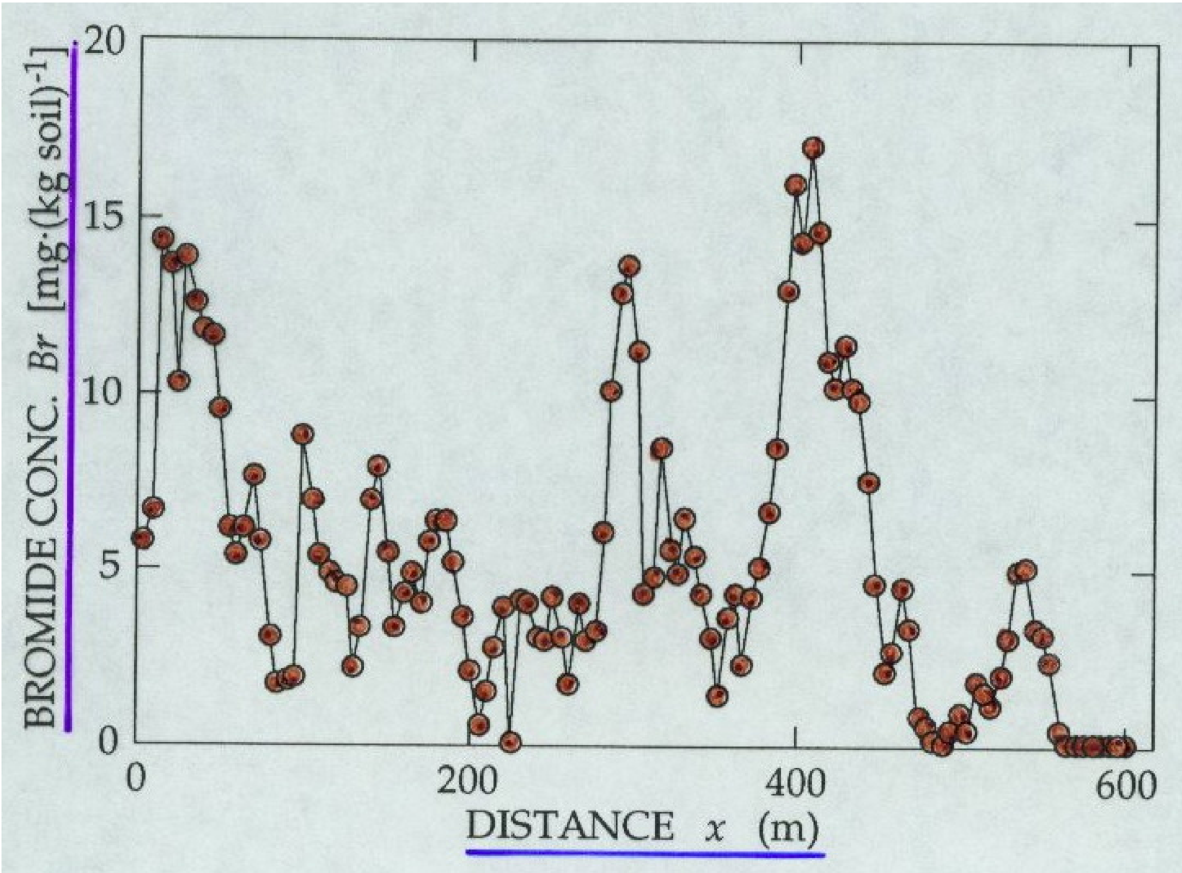
State-space sorghum minus 4th polynomial



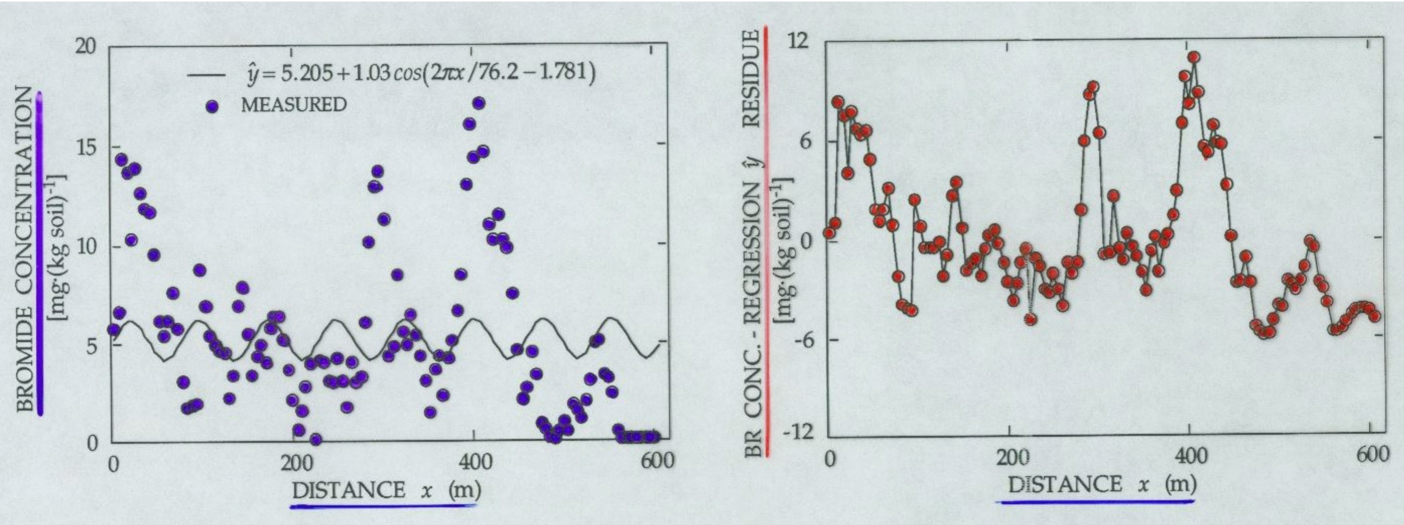
Bromideapplication expt design



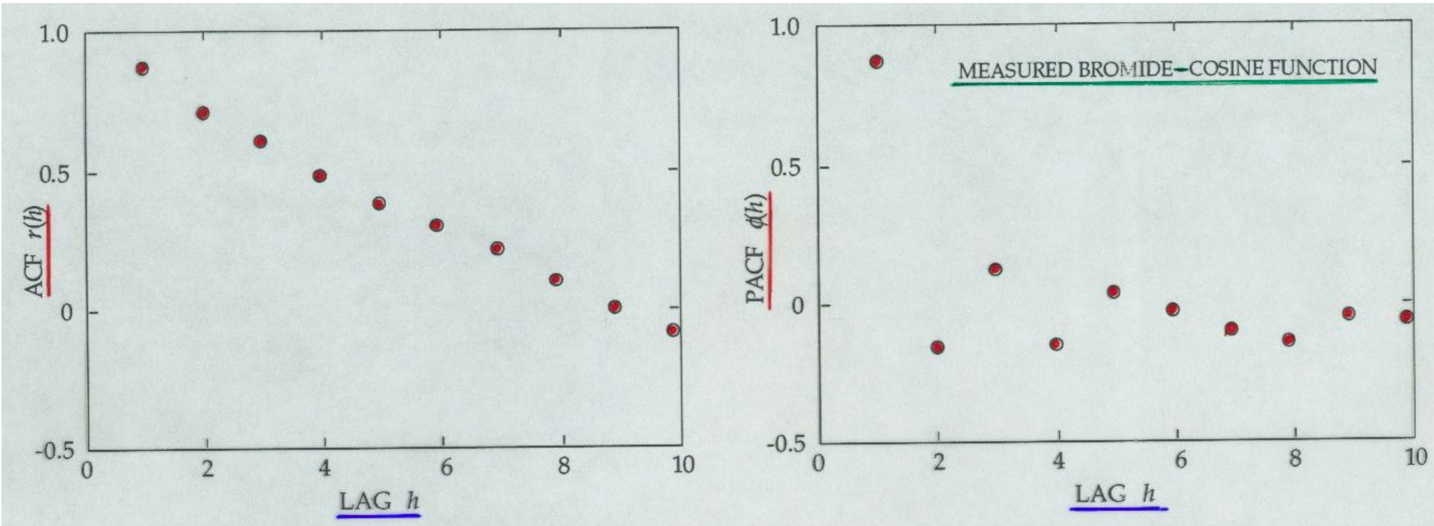
bromide measurements vs distance



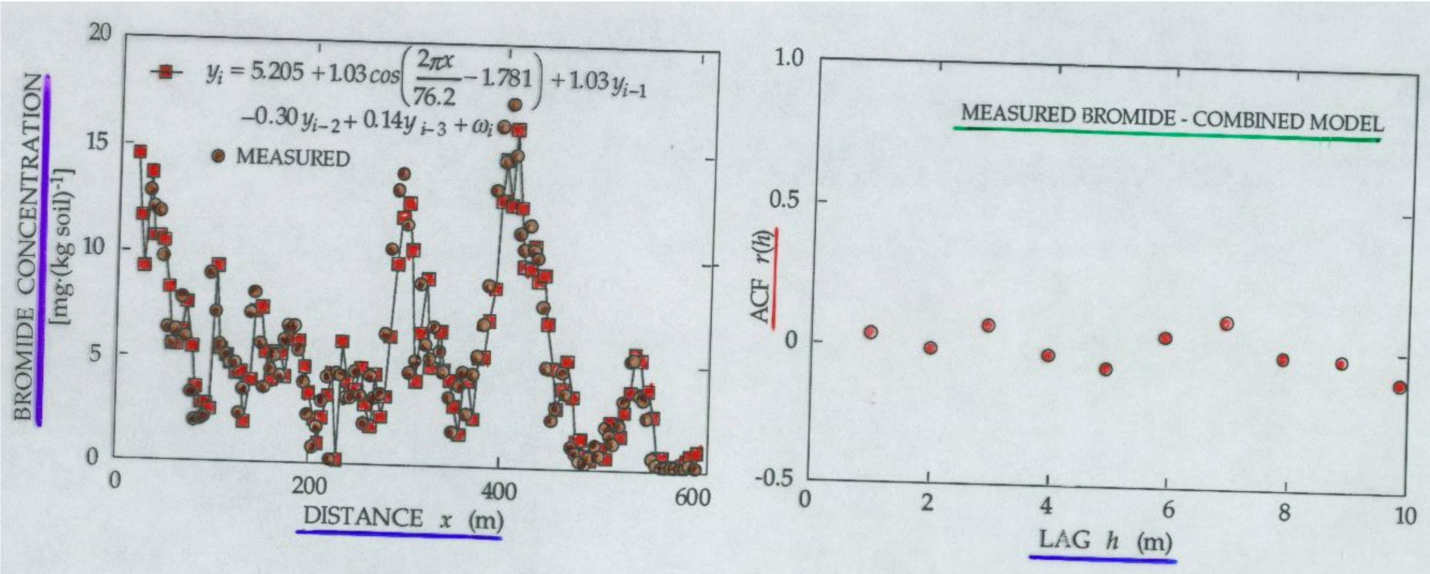
measured bromide & cosine



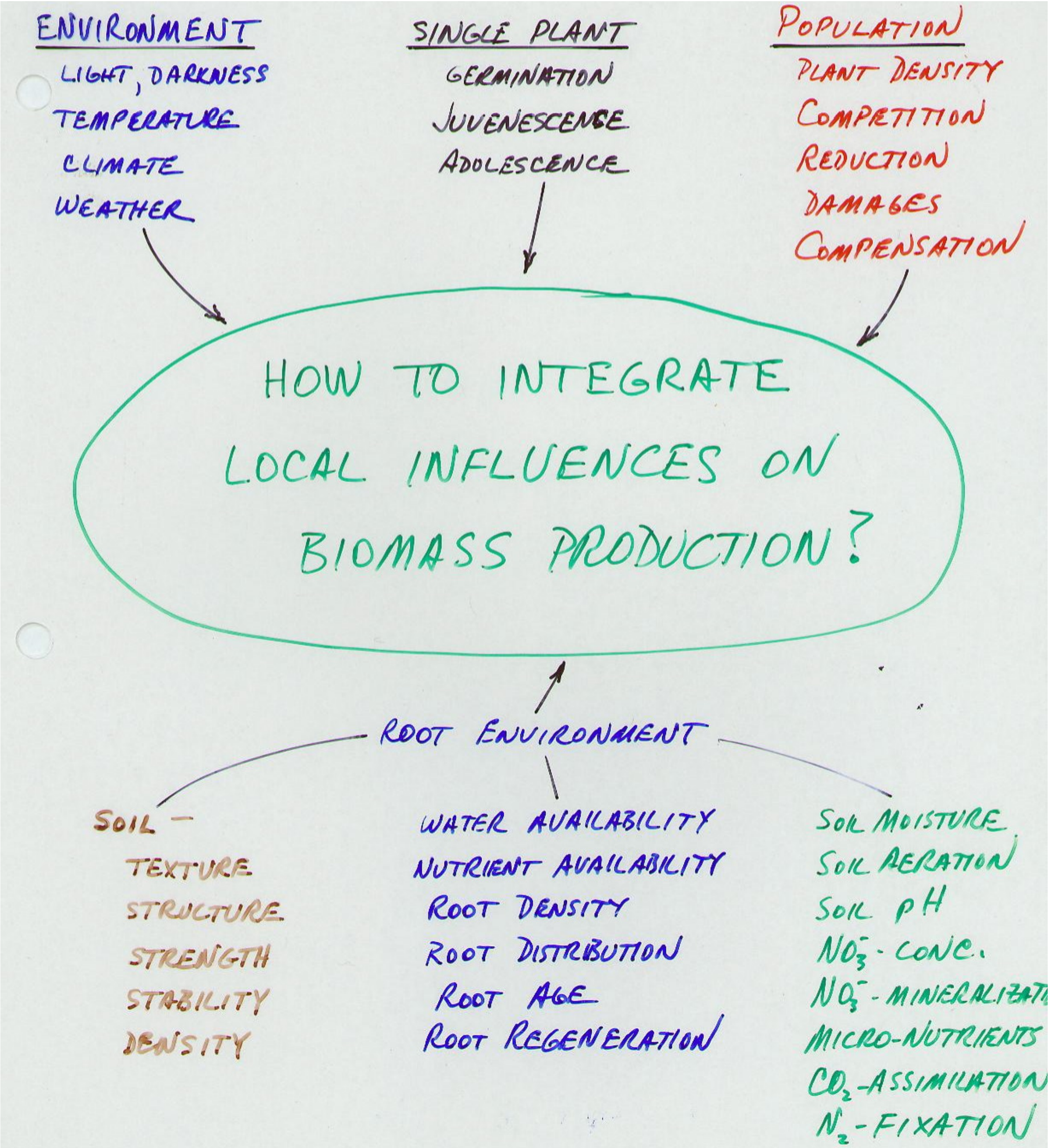
ACF & PACF (Br minus cos)



Cosine + AR(3) br



how to integrate local influence



STATE-SPACE ANALYSIS

state space analysis logic

STATE-SPACE ANALYSIS

- THE LOGIC BEHIND STATE-SPACE ANALYSIS IS SIMILAR TO THAT OF A FARMER WALKING ACROSS A CULTIVATED FIELD COMPARING THE HEALTH AND STATE OF A CROP AND ITS UNDERLYING SOIL CONDITION AT FIRST ONE LOCATION, THEN AT A SECOND LOCATION IN CLOSE PROXIMITY TO THE FIRST, AND THEN AT A THIRD LOCATION AND SO ON UNTIL THE FARMER HAS TRAVERSED THE ENTIRE FIELD.

- THE FARMER DOES NOT HAVE THE KNOWLEDGE TO INTEGRATE THE COUNTLESS REACTIONS AND PROCESSES OCCURRING WITHIN THE FIELD TO PREDICT THE EXACT HEALTH AND STATE OF A CROP AT ANY LOCATION.

- BUT THE FARMER CAN READILY OBSERVE DIFFERENCES IN CROP BEHAVIOR AT DIFFERENT LOCATIONS WITHIN THE FIELD AT ANY ONE TIME OR DURING A SERIES OF TIMES.

- THE FARMER ALSO INTUITIVELY KNOWS THAT CROP DIFFERENCES OCCURRING OVER RELATIVELY SHORT DISTANCES IN ONE REGION ARE NOT NECESSARILY CAUSED BY THE SAME REACTIONS AND PROCESSES OCCURRING IN OTHER REGIONS OF THE FIELD.

- THE FARMER'S OBJECTIVE AND THAT OF STATE-SPACE ANALYSIS ARE IDENTICAL – TO UNDERSTAND OR DIAGNOSE WHAT ARE THE CAUSES OF THE DIFFERENT CROP BEHAVIOR IN ORDER TO IMPROVE CONDITIONS AT ALL LOCATIONS FOR BETTER CROP PRODUCTION.

state space questions

RELEVANT QUESTIONS

- WHAT PROCESSES AND CONDITIONS ARE RESPONSIBLE OR RELATED TO SPATIAL VARIATIONS OF CROP OR SOIL ATTRIBUTES ACROSS THE LANDSCAPE?

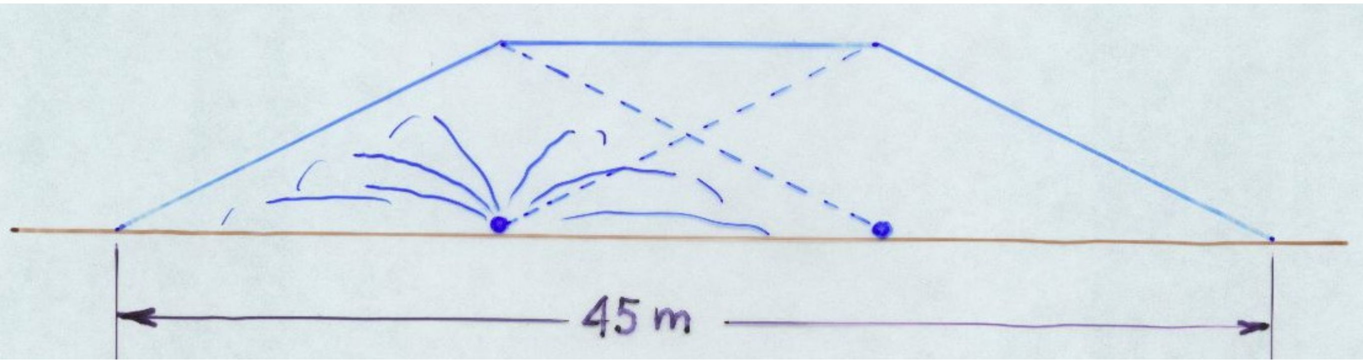
- WHAT STATE VARIABLES SHOULD BE OBSERVED TO IDENTIFY IMPORTANT PHYSICAL, CHEMICAL AND BIOLOGICAL PROCESSES?

- WHAT SHOULD BE THE SAMPLE SPACING FOR OBSERVING STATE VARIABLES?

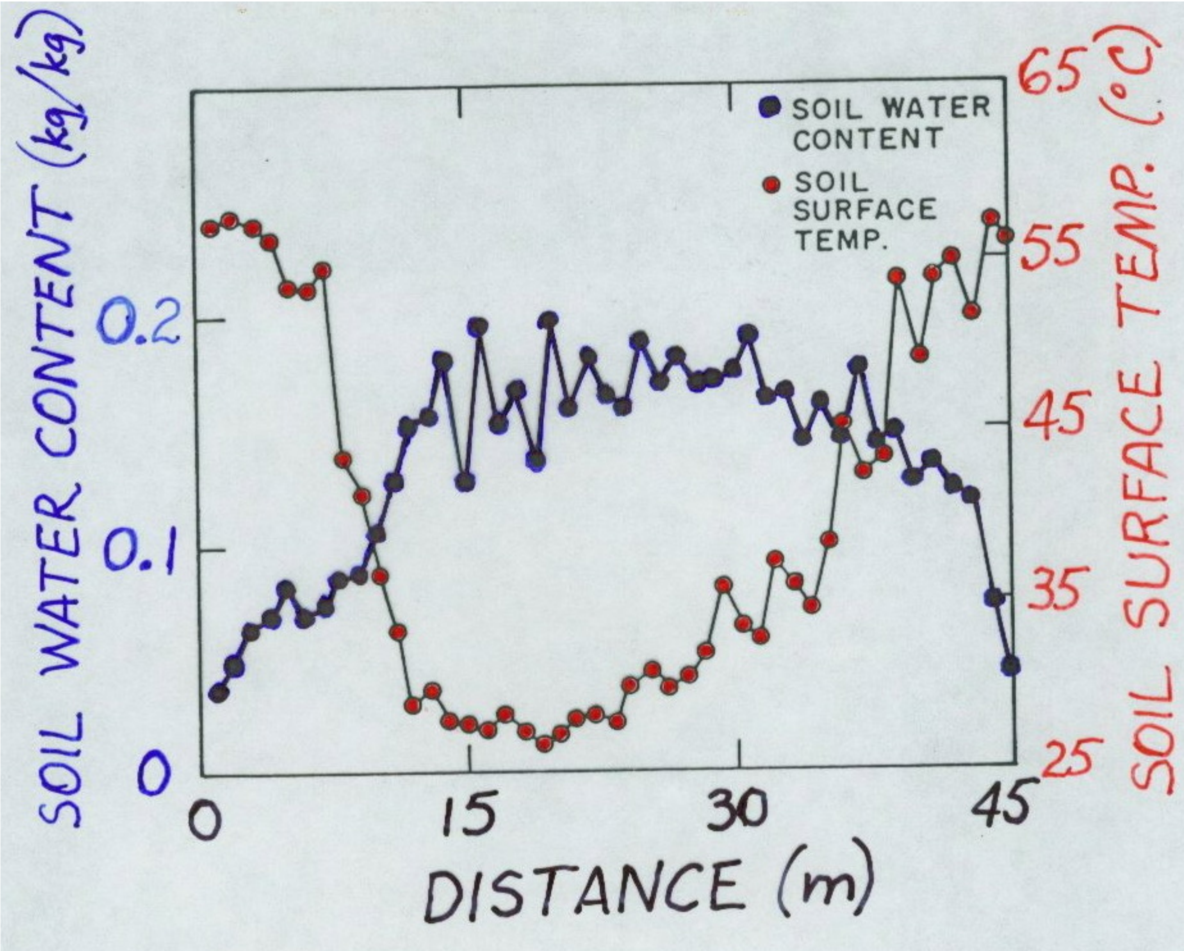
- WHICH OBSERVATIONS REVEAL THE GREATEST INFORMATION ABOUT THE STATE OF A SOIL OR CROP?

SURFACE SOIL TEMPERATURE AND SOIL WATER CONTENT

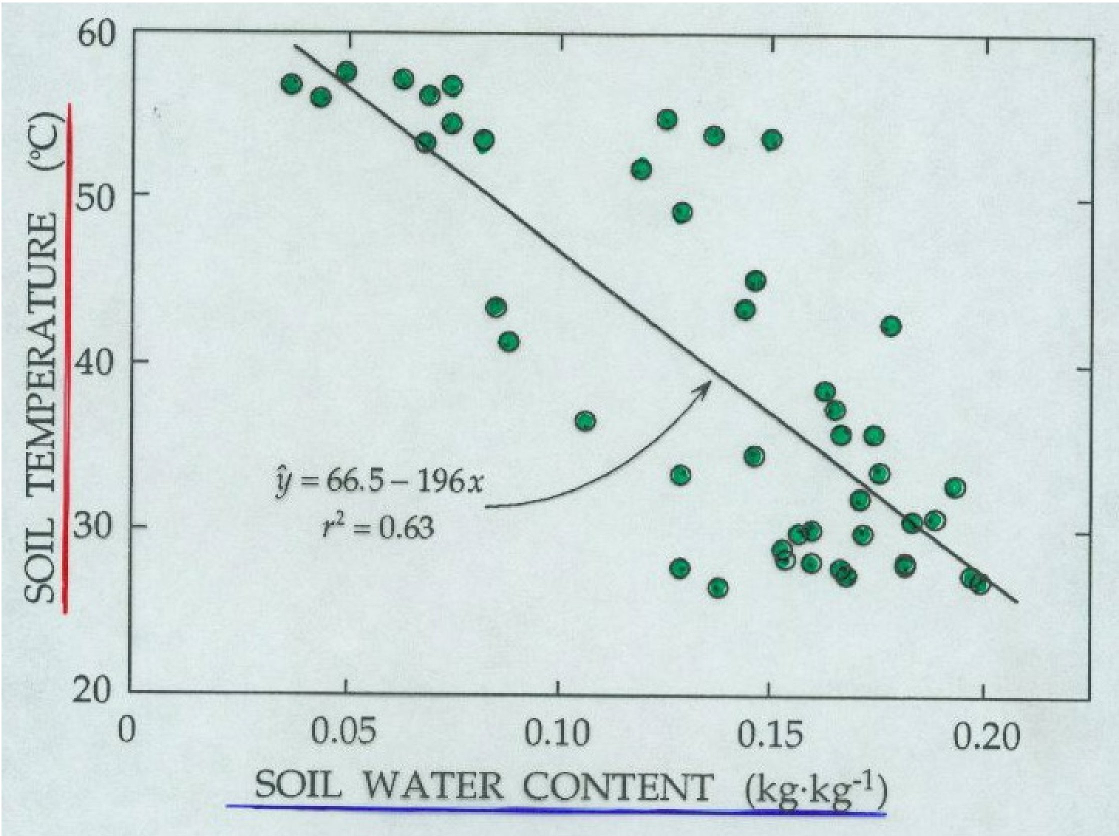
Sorghum irrigation line source



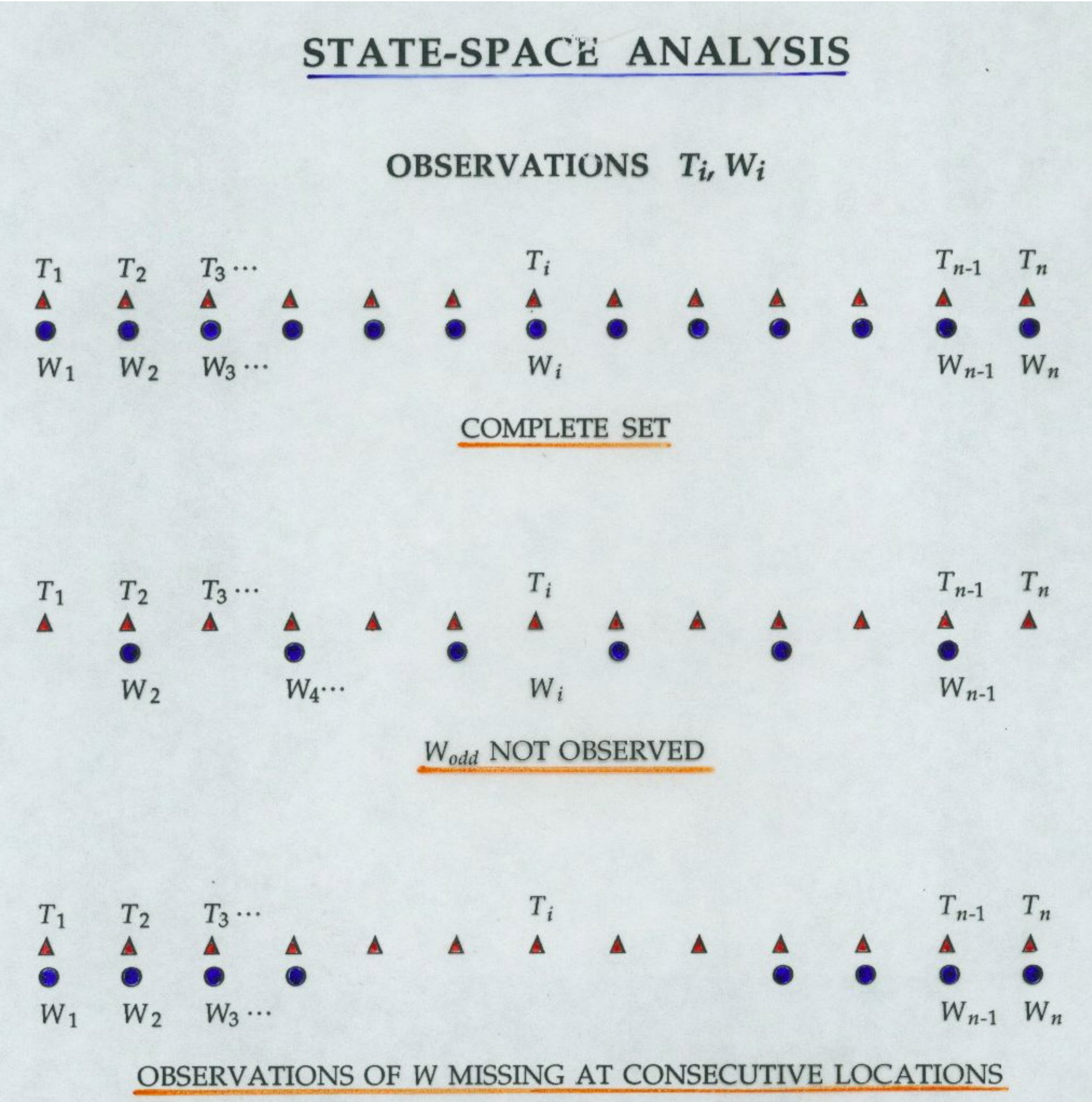
measured T and theta



T vs theta regression



st space equation illustration



st space equations

STATE-SPACE ANALYSIS

$$Z_i = \Phi Z_{i-1} + \omega_i$$

Z_i state vector (a set of p variables at location i)

Φ $p*p$ matrix of state coefficients ϕ indicating spatial regression

ω_i uncorrelated zero mean model error

$$Y_i = M_i Z_i + \upsilon_i$$

Y_i observed vector

M_i observation matrix

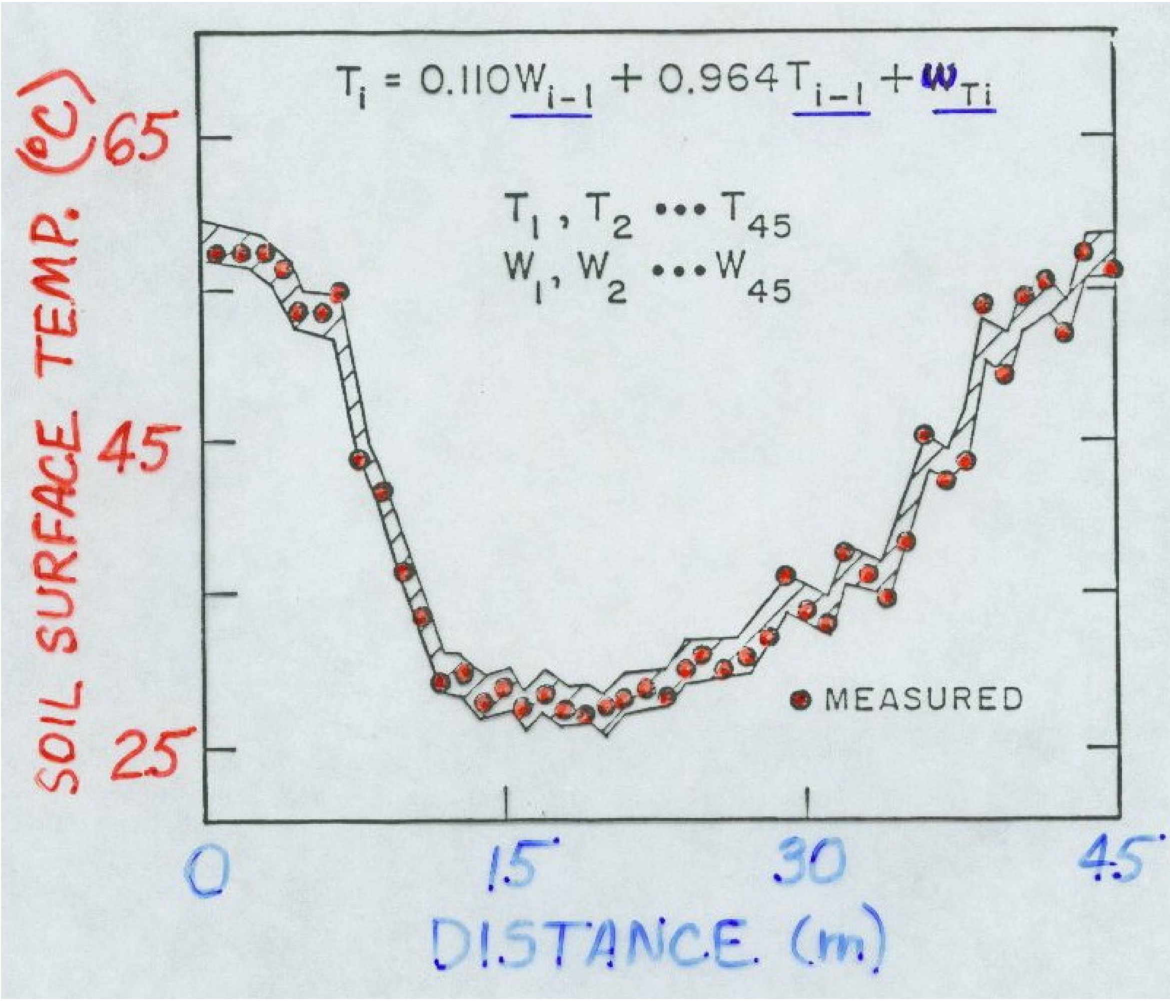
Z_i state vector

υ_i uncorrelated, zero mean observation error

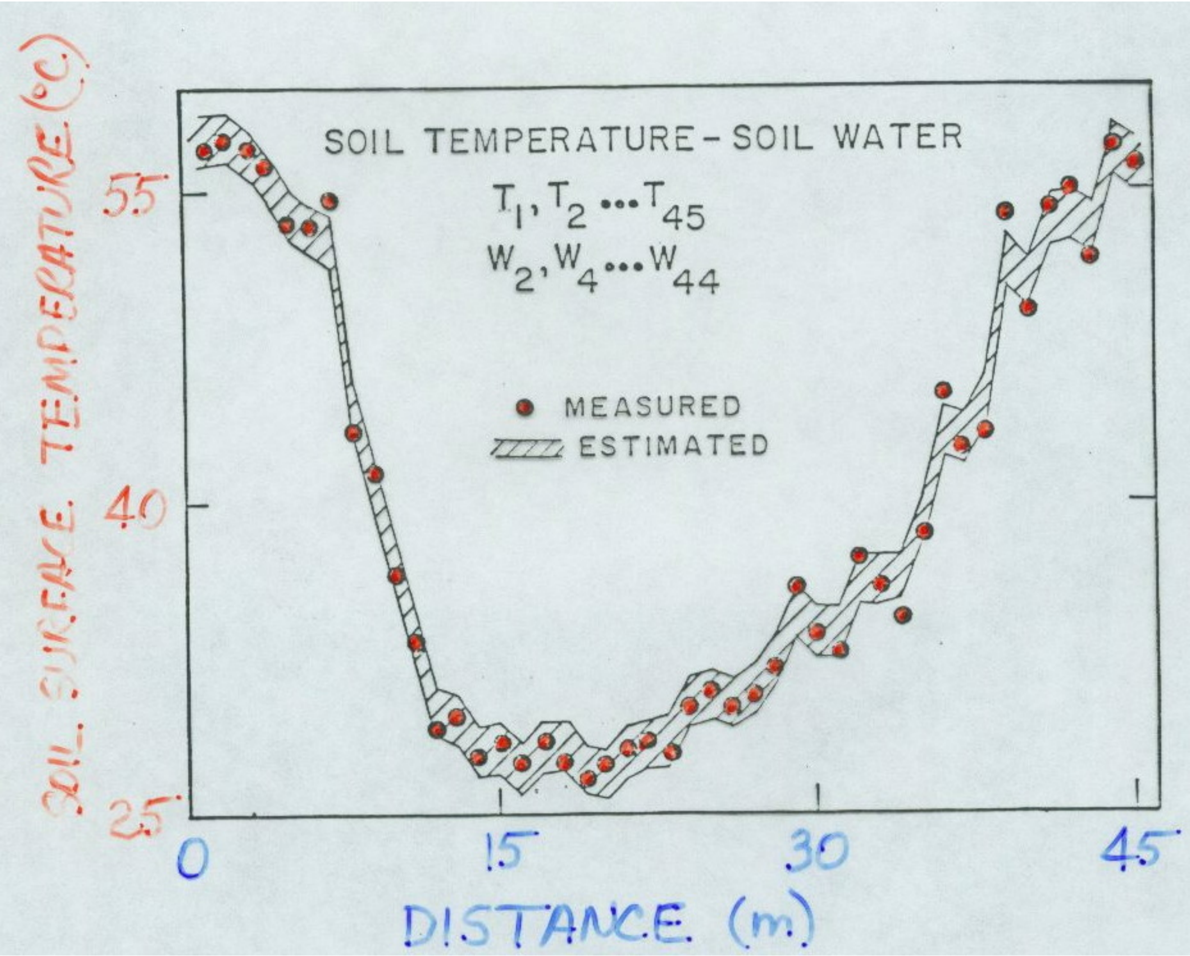
— Observations contain measurement and calibration errors.

— The state coefficient and covariance matrices are optimized with Kalman filtering.

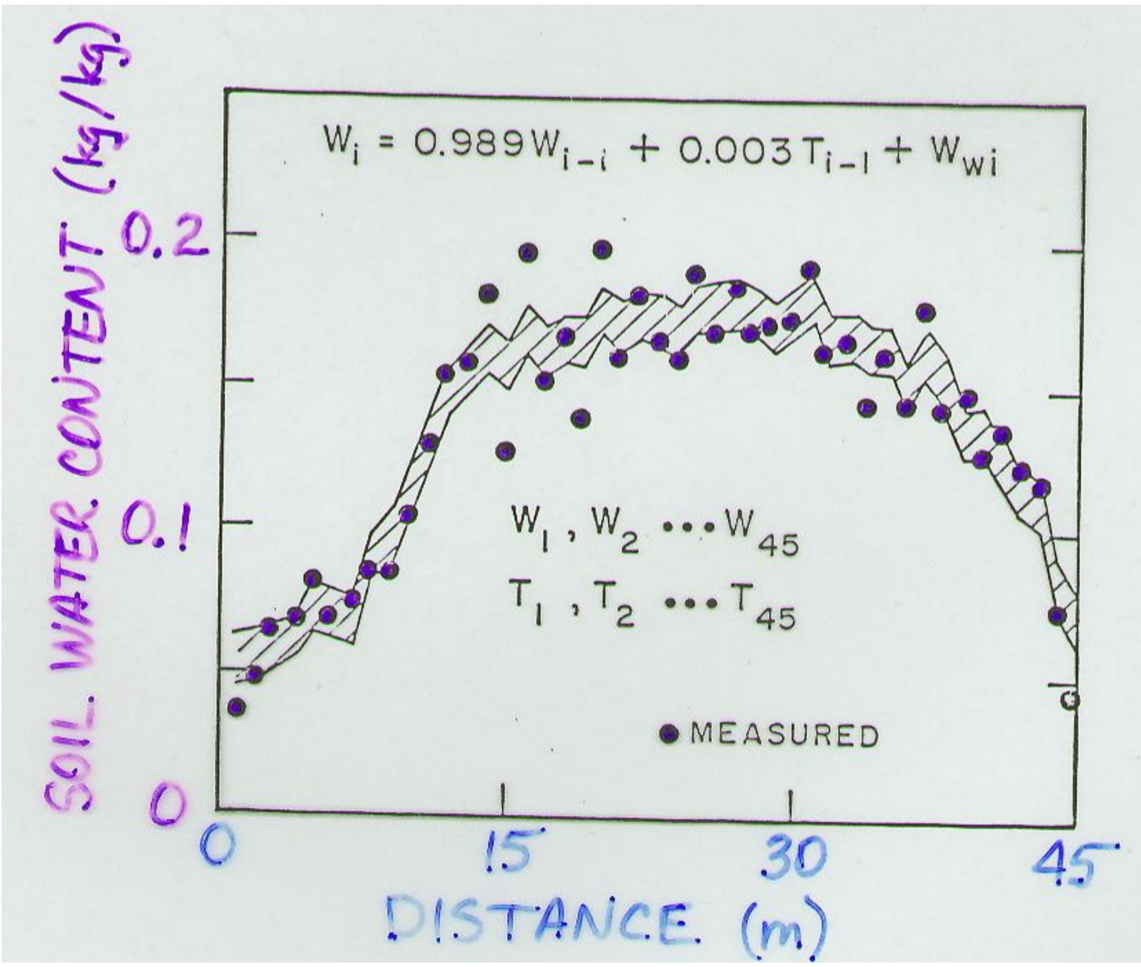
st space estimation T



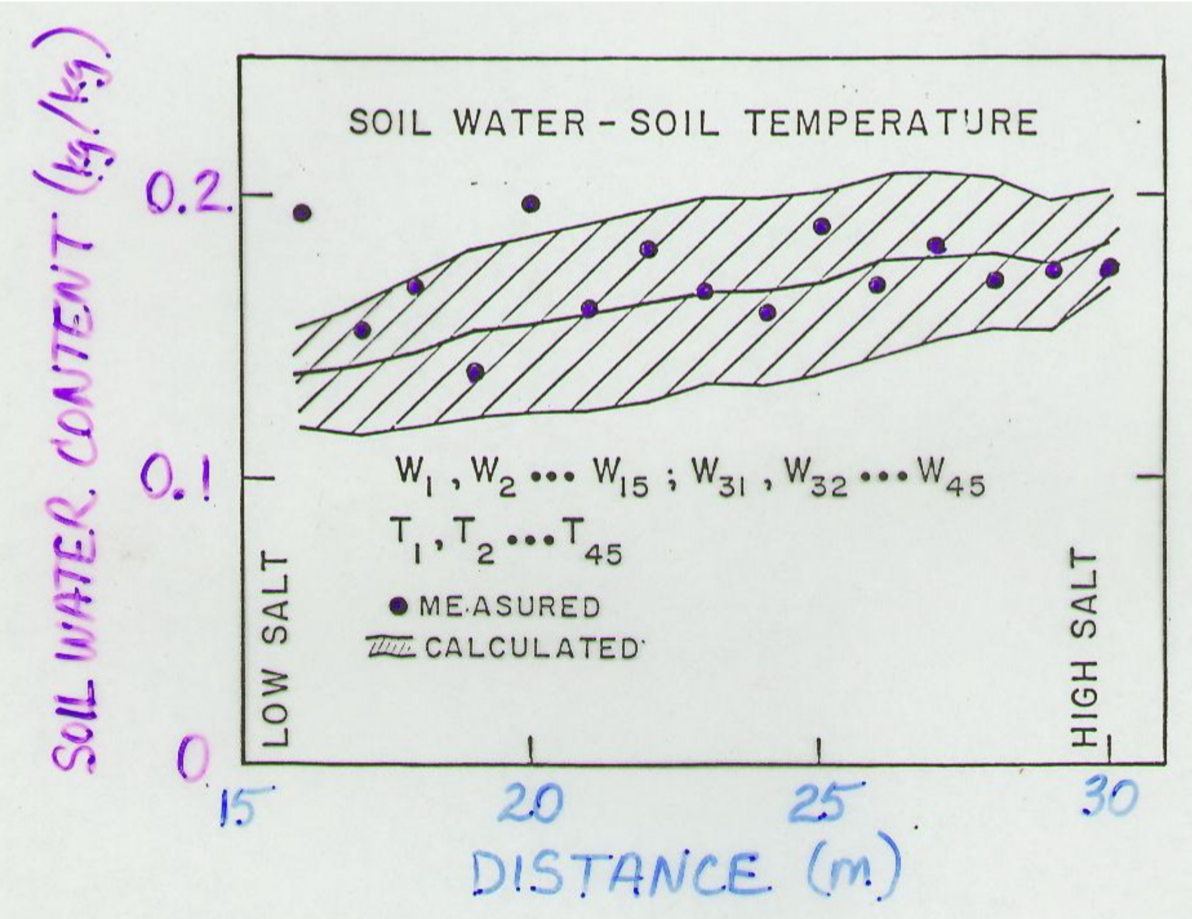
st space estimation T (even q)



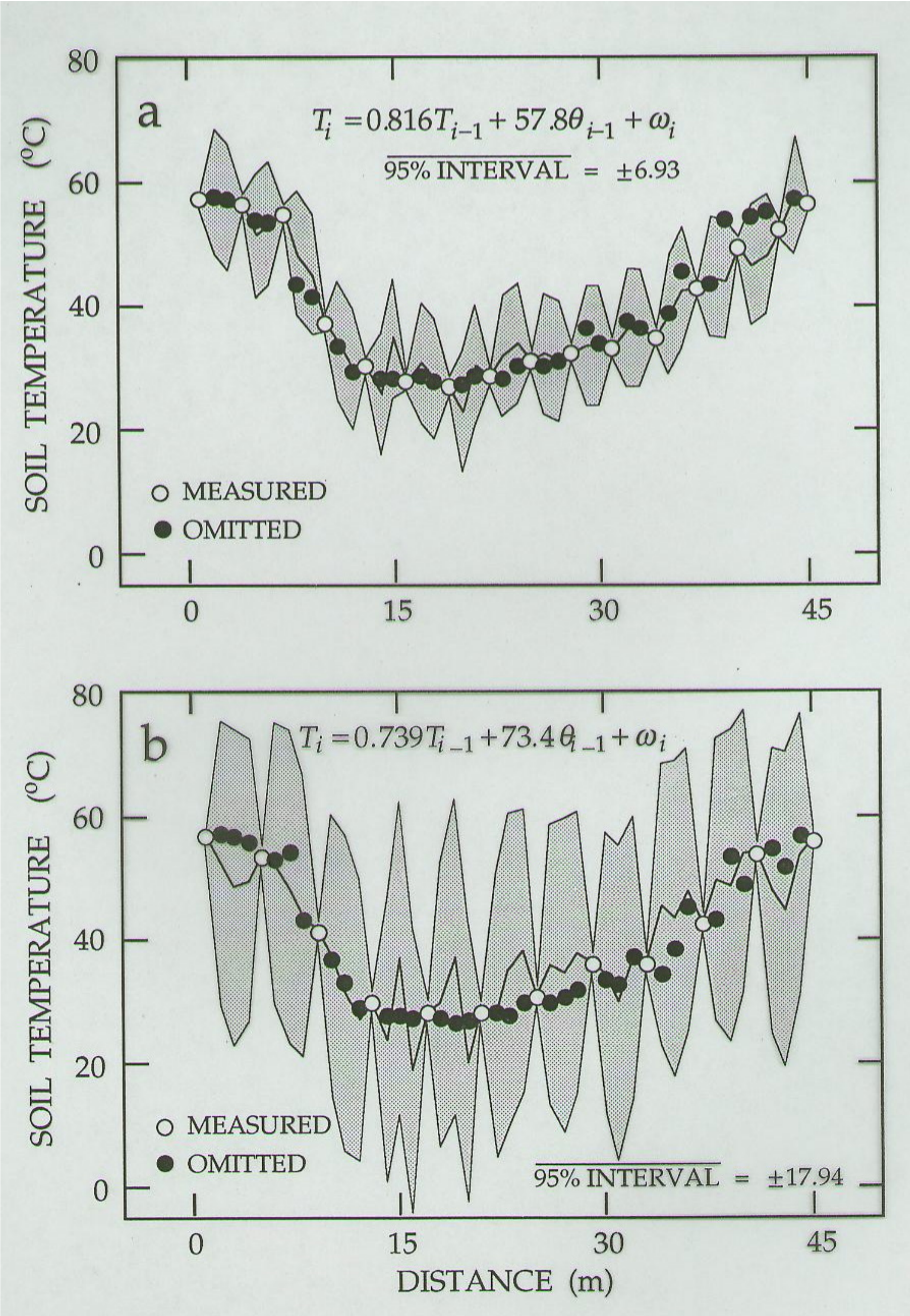
st sp soil water content (temp)



st sp soil water calculated (15-30m)



kriged soil temp (omitting 2&4 values)

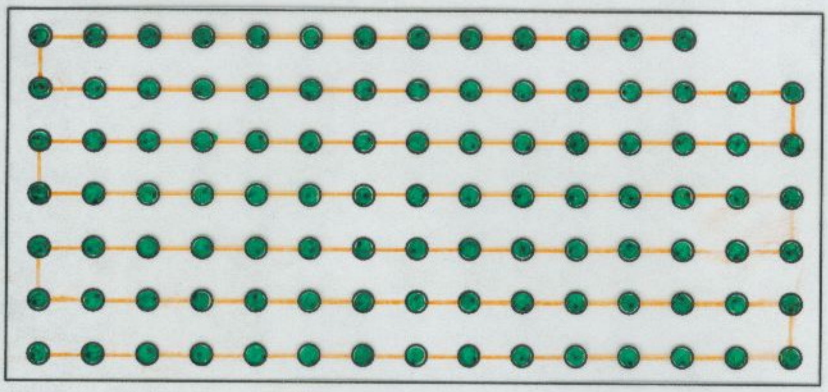


CORN YIELD AND SOIL NUTRIENTS

Michigan corn field samples

MICHIGAN FARM

Sampled 103 locations
on a 30.5-m (100-ft) grid



AT EACH LOCATION

- Corn yield
- Plant population
- Ca (0-5 and 5-15 cm)
- Mg (0-5 and 5-15 cm)
- K (0-5 and 5-15 cm)

⋮

st space eqns corn

STATE-SPACE EQUATIONS OF CORN YIELD, Ca, Mg, K AND PLANT POPULATION FOR A MICHIGAN FARM

$$X_{i,1} = \phi_{11} X_{i-1,1} + \phi_{12} X_{i-1,2} + \phi_{13} X_{i-1,3} + \phi_{14} X_{i-1,4} + \omega_{i1}$$
$$X_{i,2} = \phi_{21} X_{i-1,1} + \phi_{22} X_{i-1,2} + \phi_{23} X_{i-1,3} + \phi_{24} X_{i-1,4} + \omega_{i2}$$
$$X_{i,3} = \phi_{31} X_{i-1,1} + \phi_{32} X_{i-1,2} + \phi_{33} X_{i-1,3} + \phi_{34} X_{i-1,4} + \omega_{i3}$$
$$X_{i,4} = \phi_{41} X_{i-1,1} + \phi_{42} X_{i-1,2} + \phi_{43} X_{i-1,3} + \phi_{44} X_{i-1,4} + \omega_{i4}$$

where $X_{i,1} = \frac{Y_i}{Y_{max}}$ $\quad X_{i,2} = \frac{\ell n Mg_i}{\ell n Mg_{max}}$ $\quad X_{i,3} = \frac{\ell n Ca/K_i}{\ell n Ca/K_{max}}$ $\quad X_{i,4} = \frac{Pl_i}{Pl_{max}}$

with Y_i = Corn Yield

$$\ell n Mg_i = \left[\ell n \left(\frac{5 Mg_{(0\text{-}5cm)} + 15 Mg_{(5\text{-}20cm)}}{20} \right) \right]_i$$

$$\ell n Ca/K_i = \left[\ell n \left(\frac{5 Ca_{(0\text{-}5cm)} + 15 Ca_{(5\text{-}20cm)}}{5 K_{(0\text{-}5cm)} + 15 K_{(5\text{-}20cm)}} \right) \right]_i$$

Pl_i = *Plant Population*

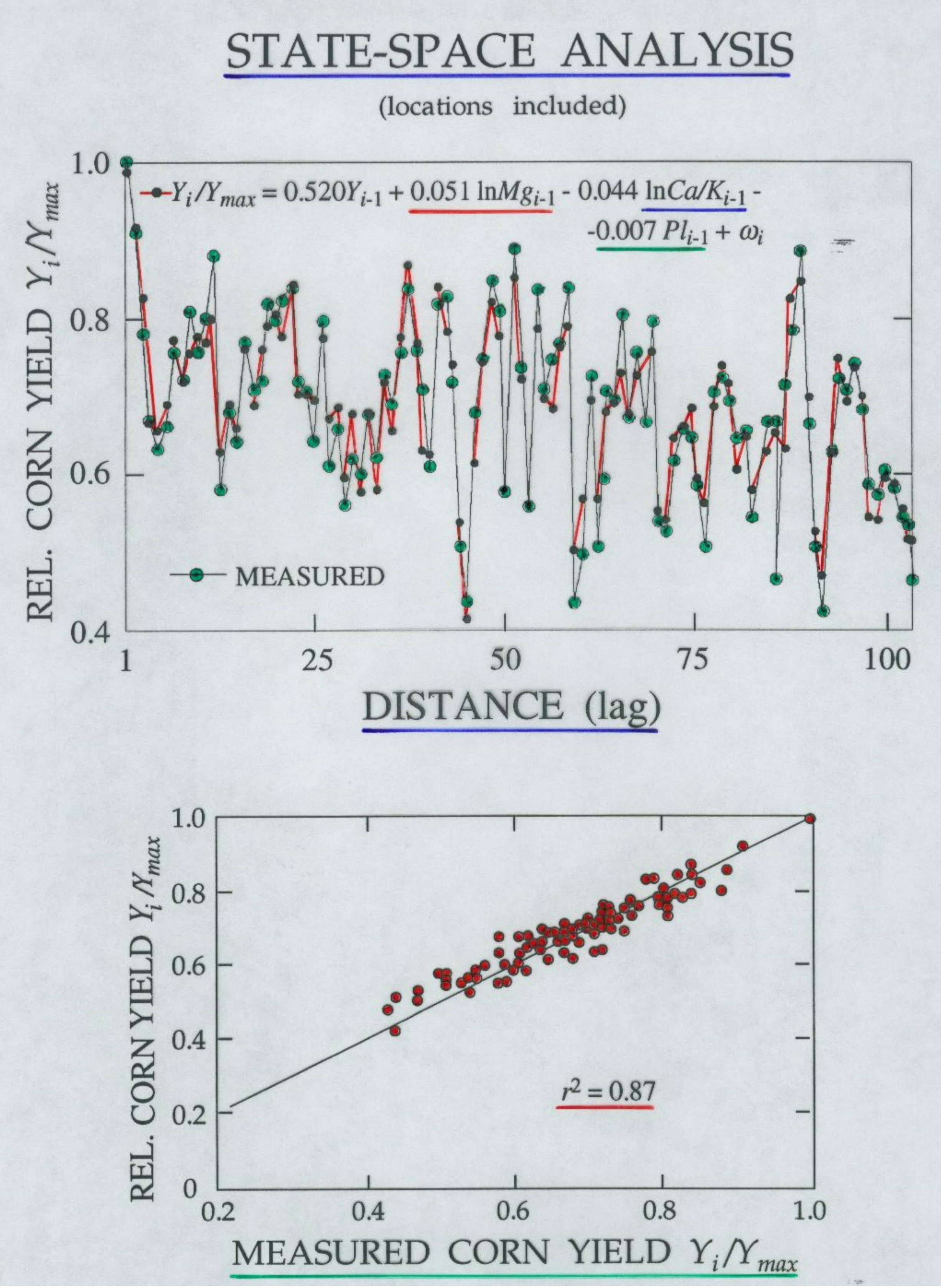
Subscripts *i* and *max* indicate sampling location and maximum value observed in the field, respectively.

$$\frac{Y_i}{Y_{max}} = 0.520 X_{i-1,1} + 0.051 X_{i-1,2} - 0.044 X_{i-1,3} \_ 0.007 X_{i-1,4} + \omega_i$$

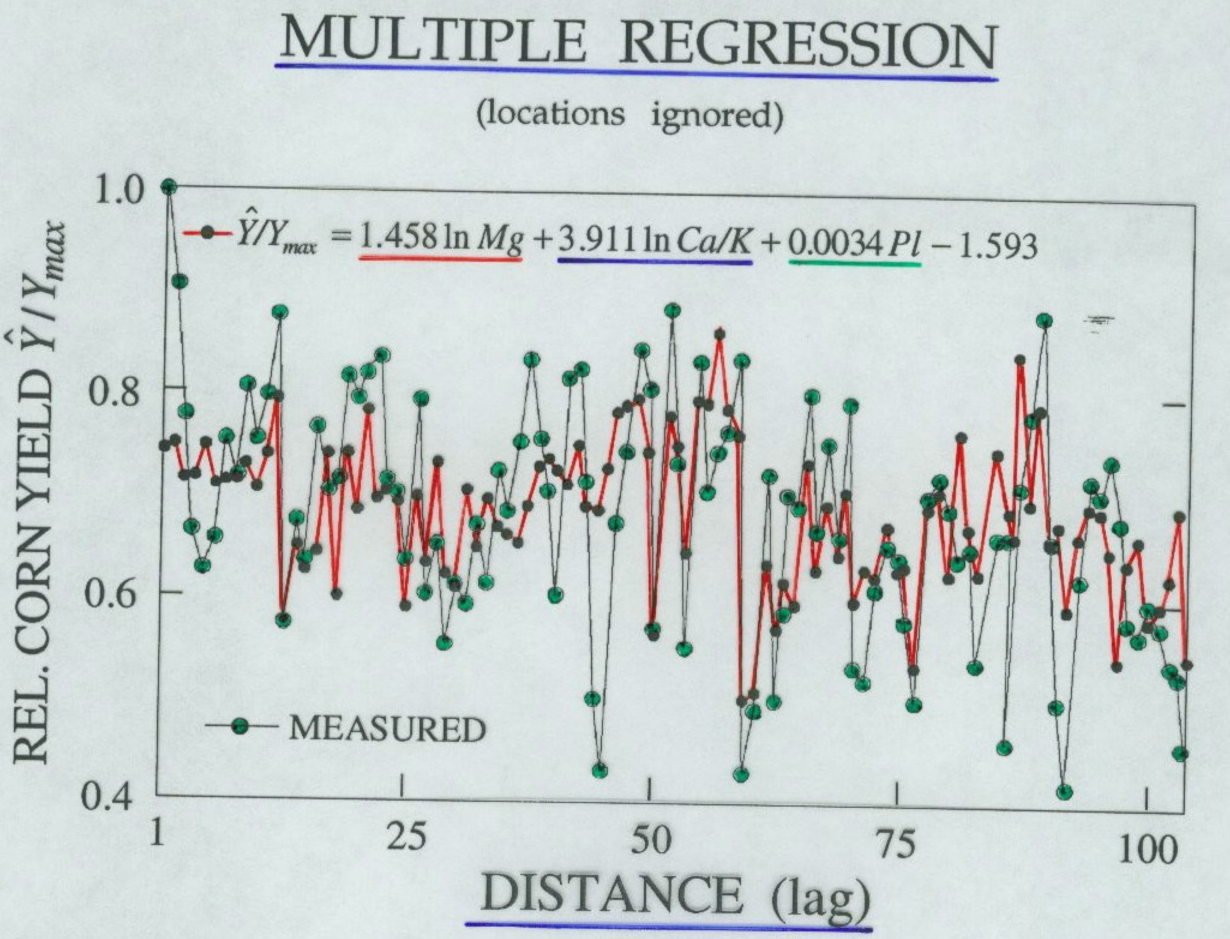
MULTIPLE REGRESSION EQUATION FOR CORN YIELD

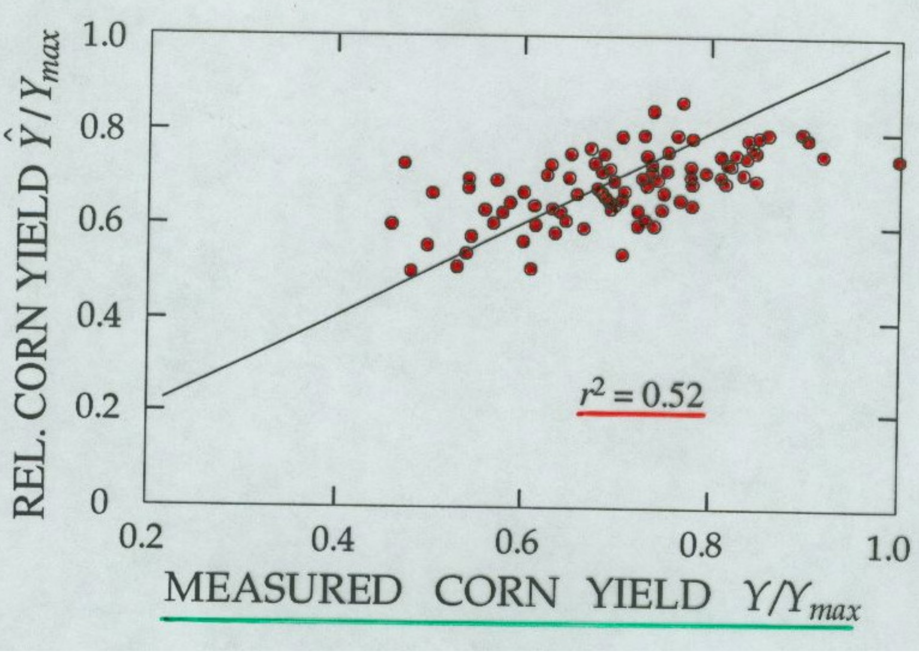
$$\frac{\hat{Y}_i}{Y_{max}} = 1.458 X_{i,2} + 3.911 X_{i,3} + 0.0034 X_{i,4} - 1.593$$

st space est. corn



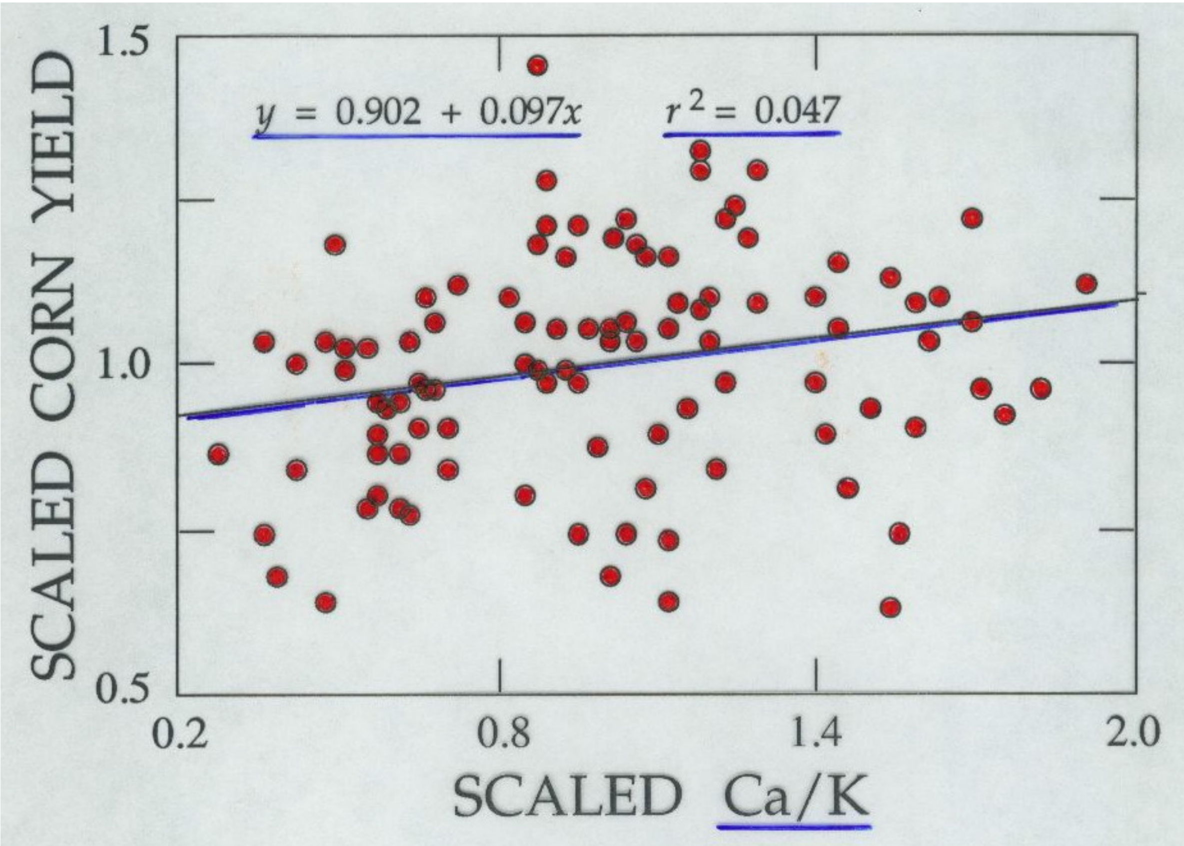
mult. regr est. corn



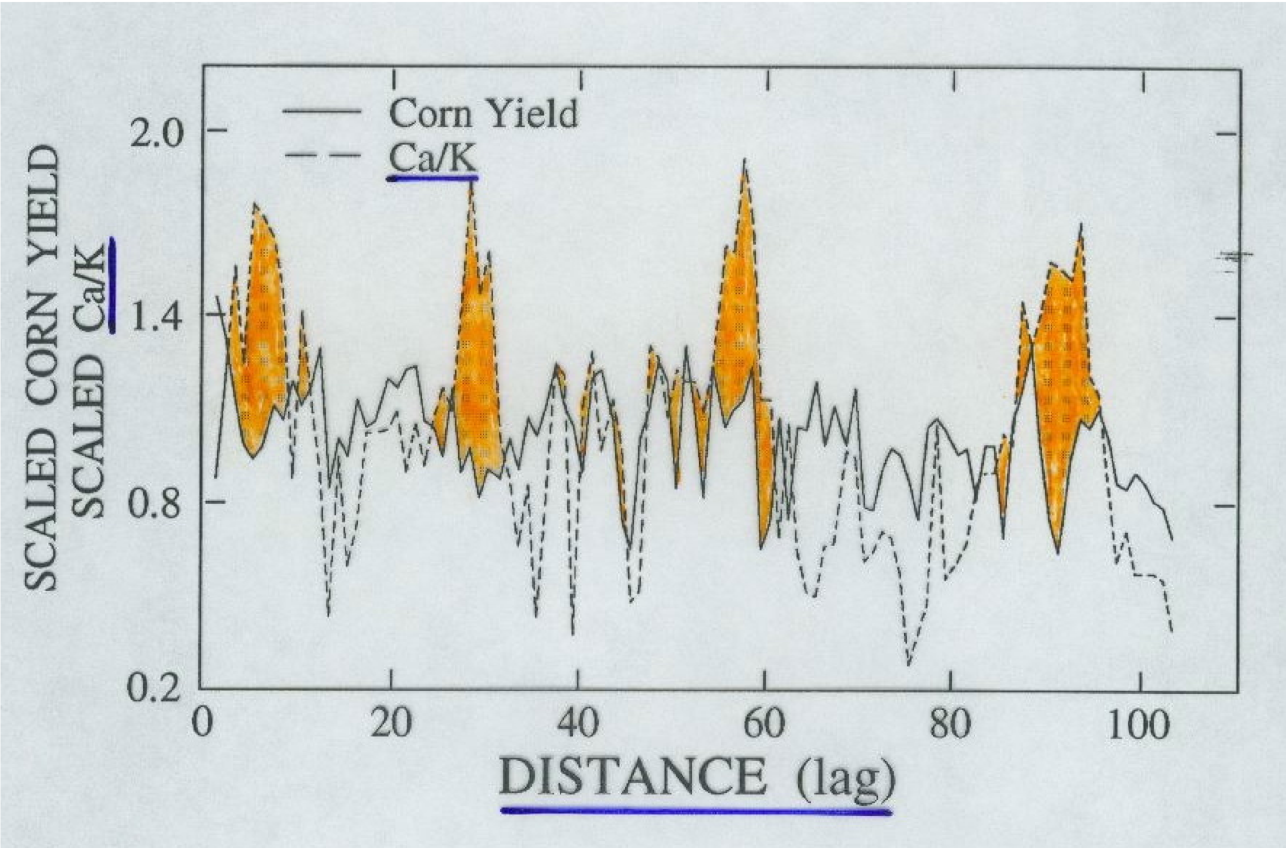


LOCAL, FUNCTIONALLY SIMILAR DOMAINS WITHIN A FARMER'S FIELD

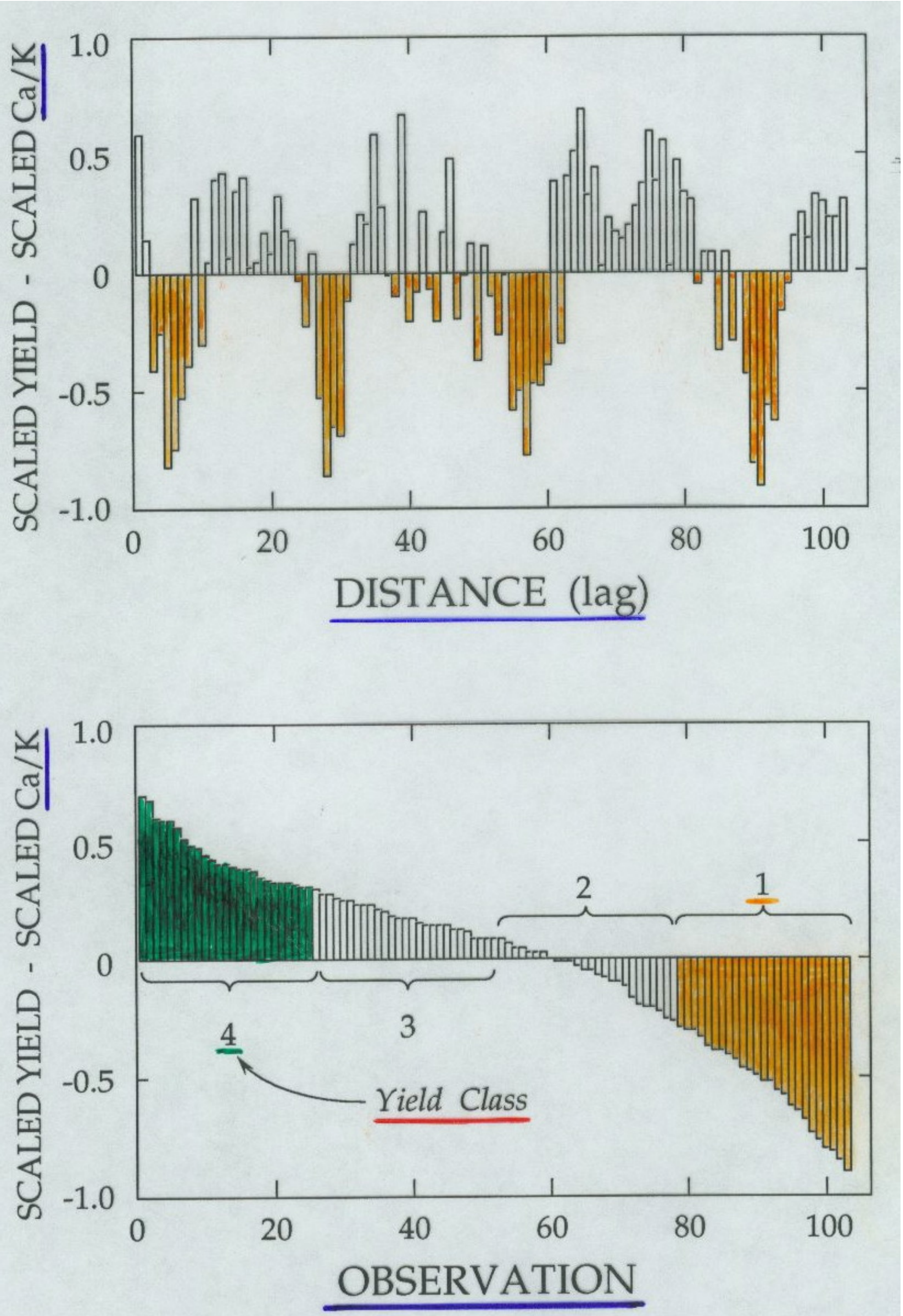
corn yld vs Ca/K



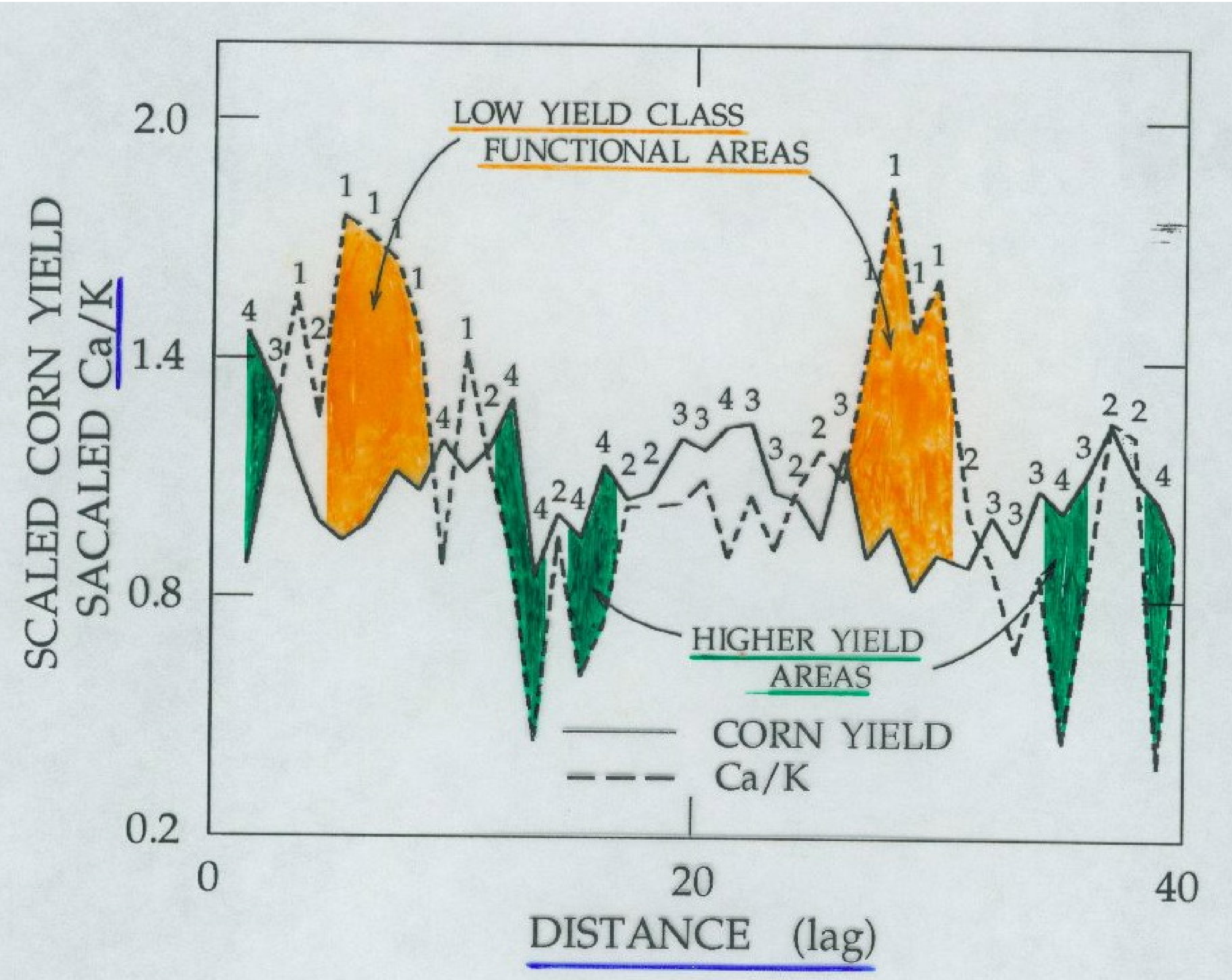
corn yld&Ca/K vs distanc



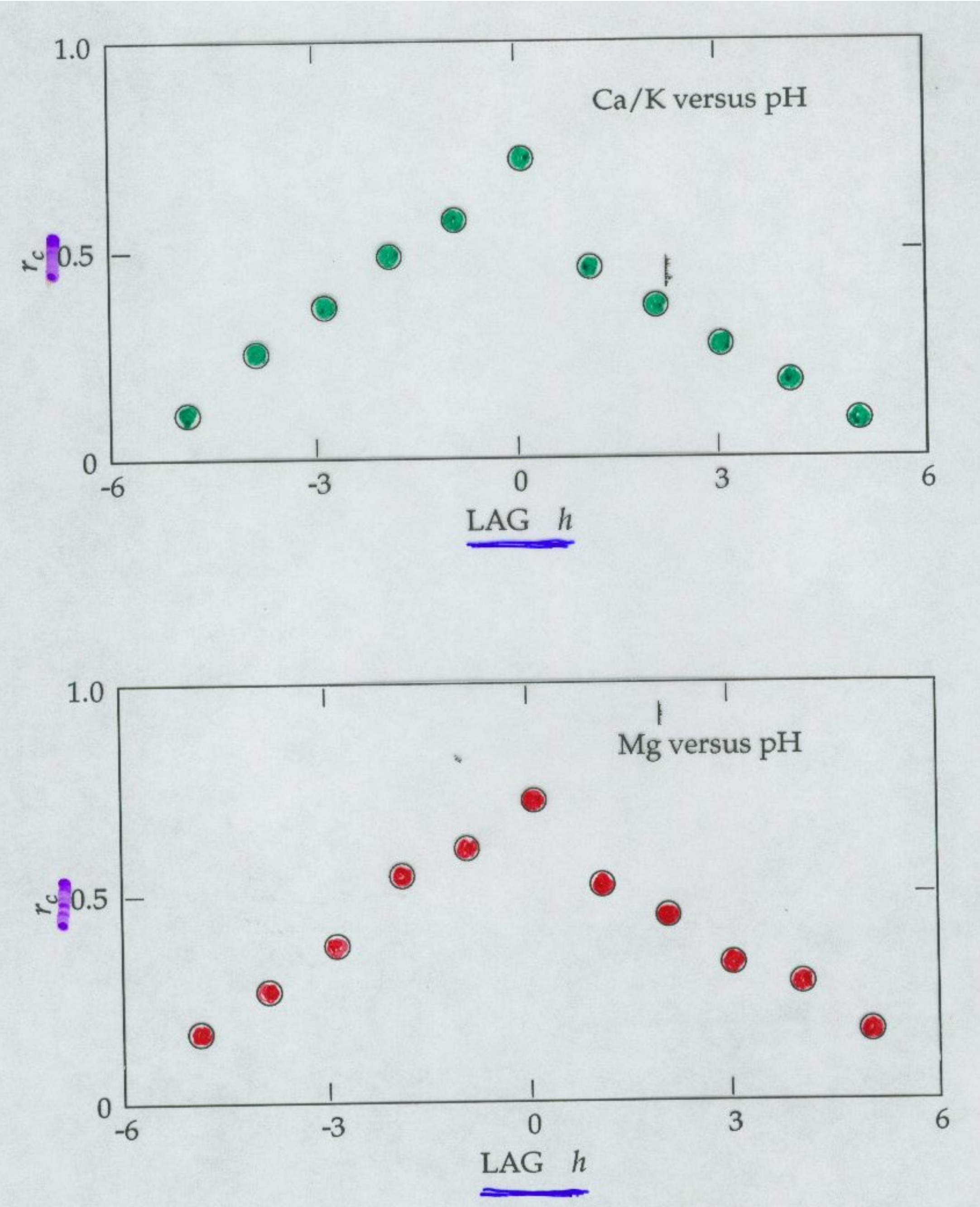
corn yield classes



corn yield class vs distance

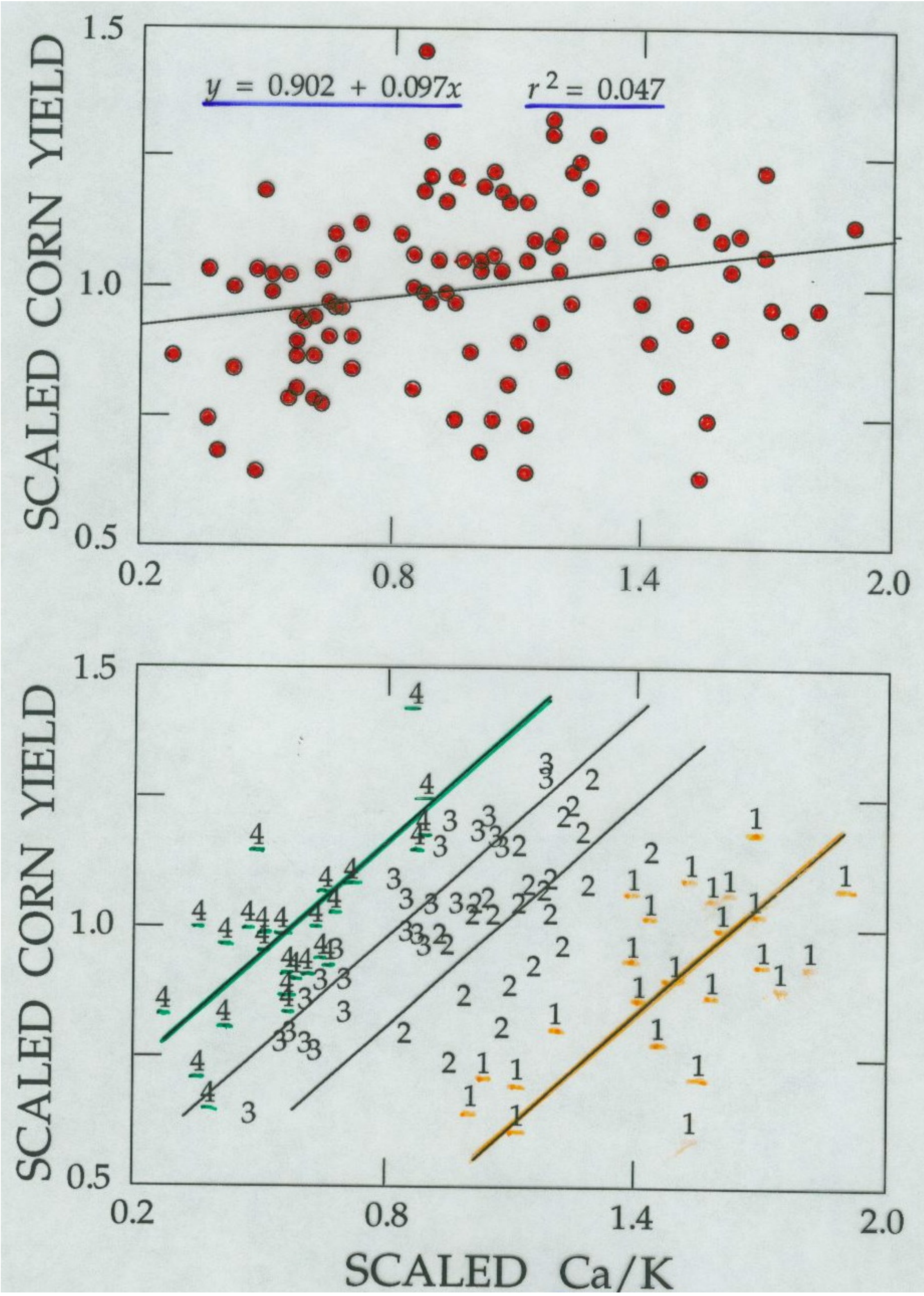


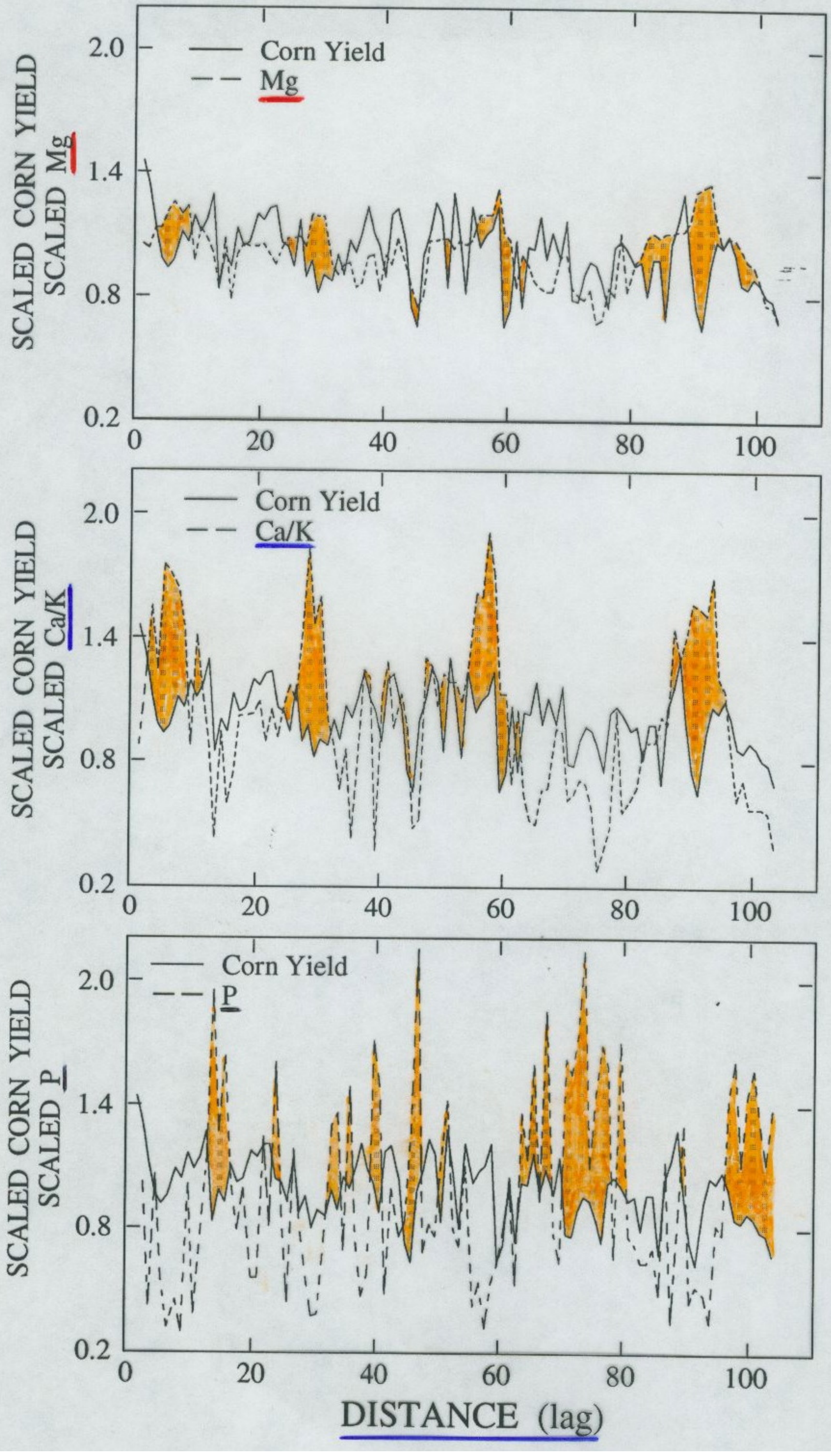
CCF Ca vs pH



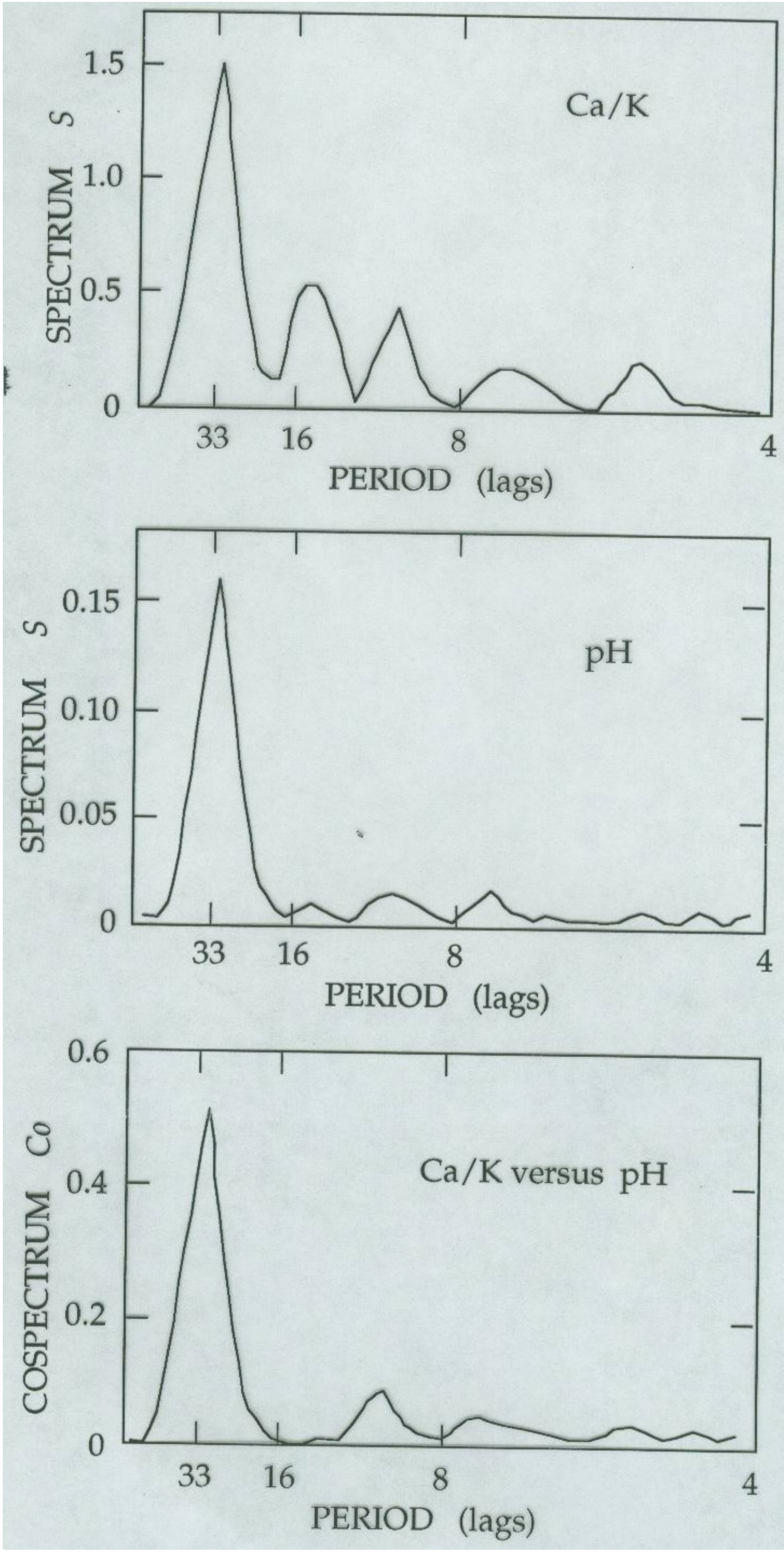
1.0
Ca/K versus pH
r_c 0.5
0
-6
-3
0
3
6
LAG h
1.0
Mg versus pH
r_c 0.5
0
-6
-3
0
3
6
LAG h

corn yield vs Ca by class

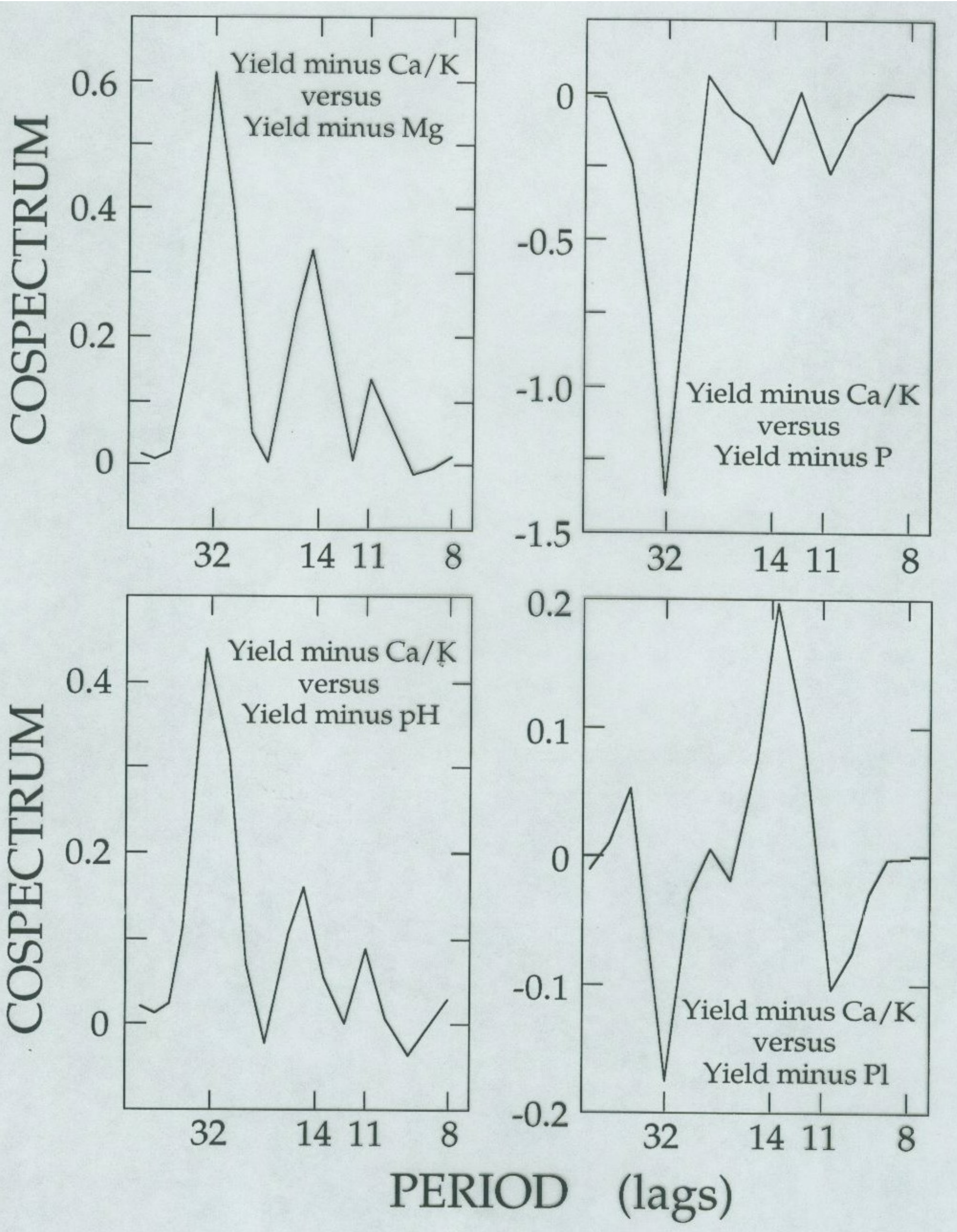



Corn Yield
Mg
SCALED CORN YIELD
SCALED Mg
Corn Yield
Ca/K
SCALED CORN YIELD
SCALED Ca/K
Corn Yield
P
SCALED CORN YIELD
SCALED P
DISTANCE (lag)

spectra Ca, Mg,K



Cospectra Ca vs pH



Conclusions & future

CONCLUSION

State-space analysis provides an alternative for exploring on-farm crop yield processes.

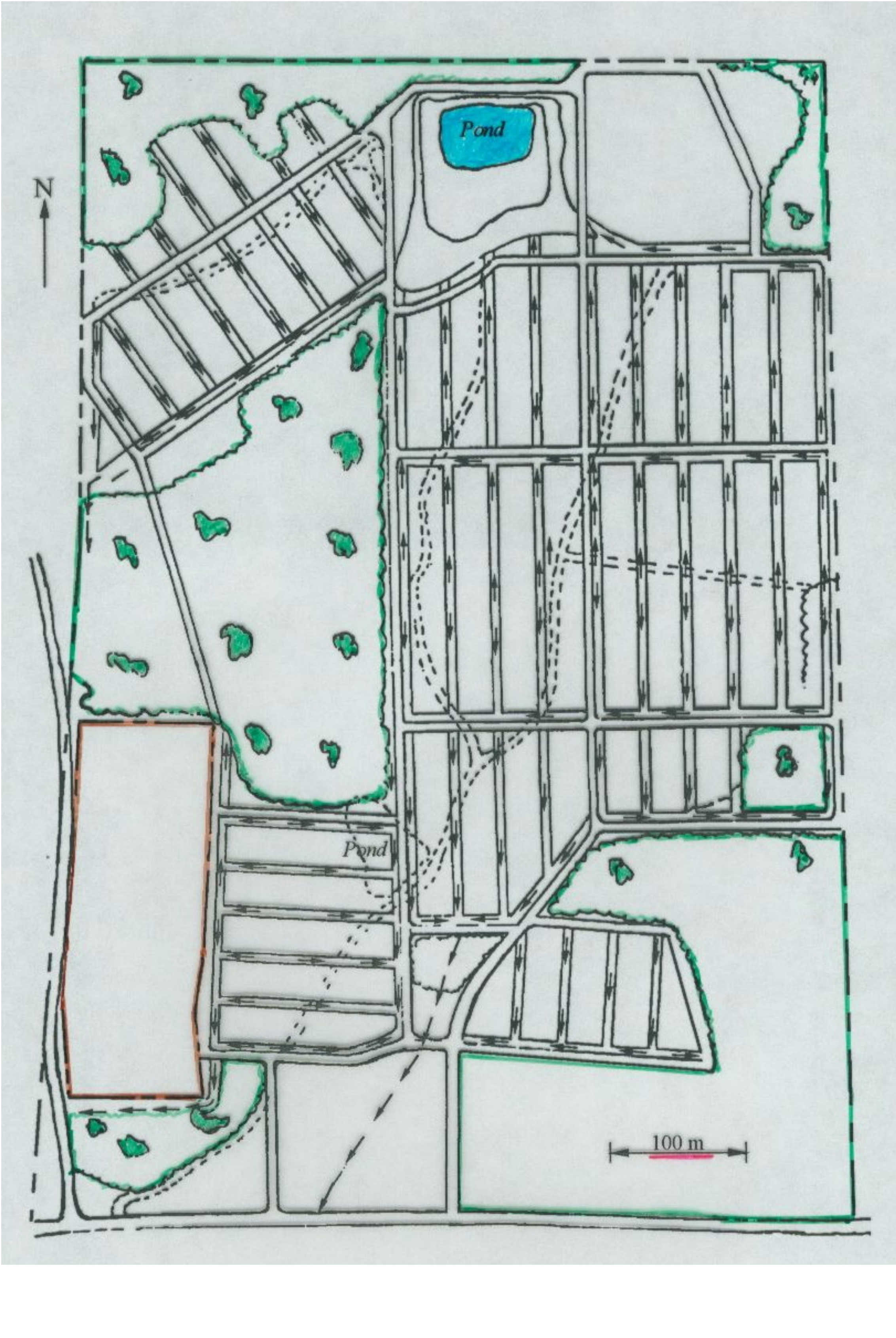
Local, functionally distinct areas within a field were identified with applied time series analysis.

THE FUTURE

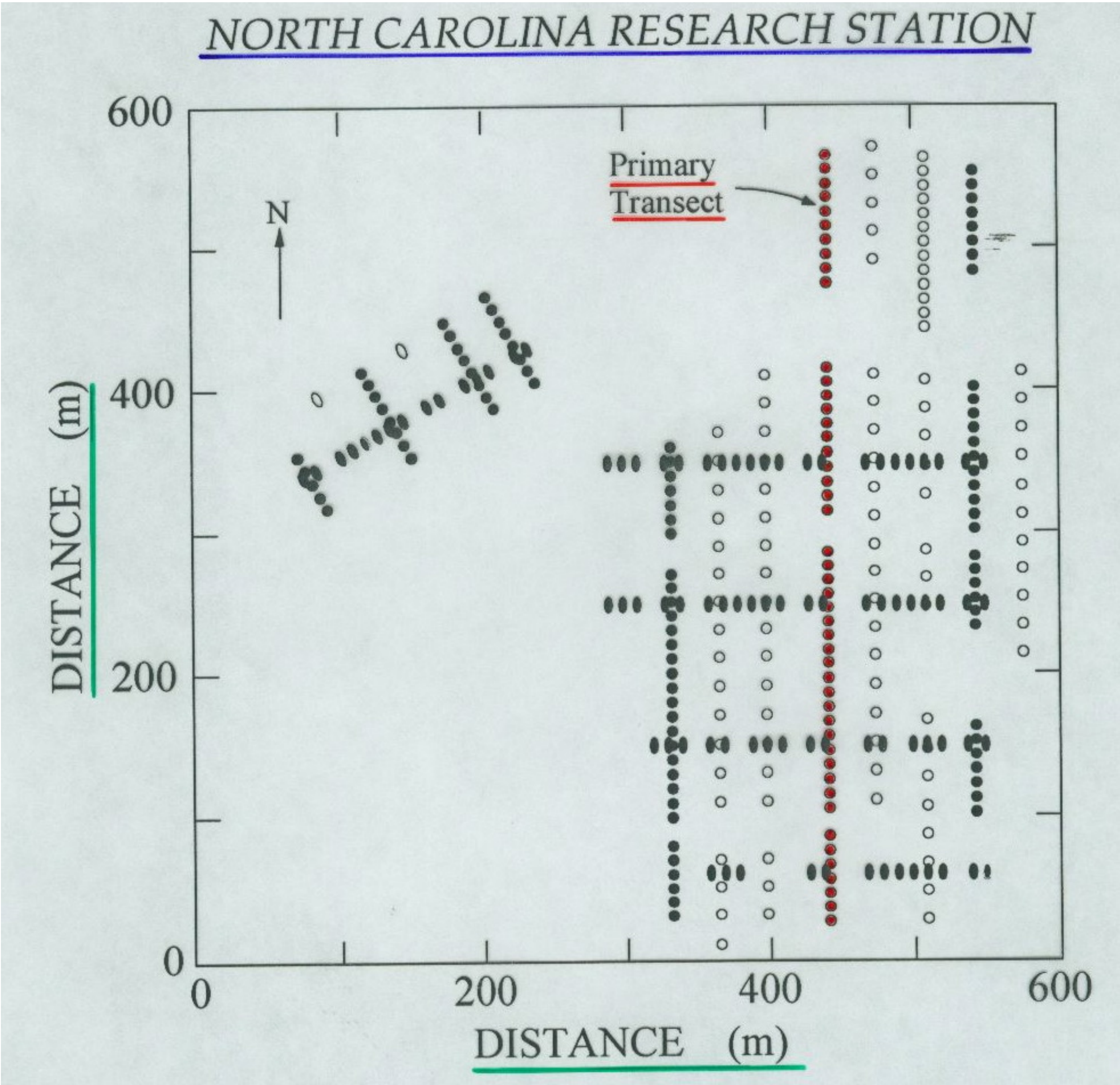
With the inclusion of physically based equations into state-space analysis, we anticipate the enigma of crop yield patterns will be solved.

WHEAT YIELD AND LANDSCAPE ATTRIBUTES

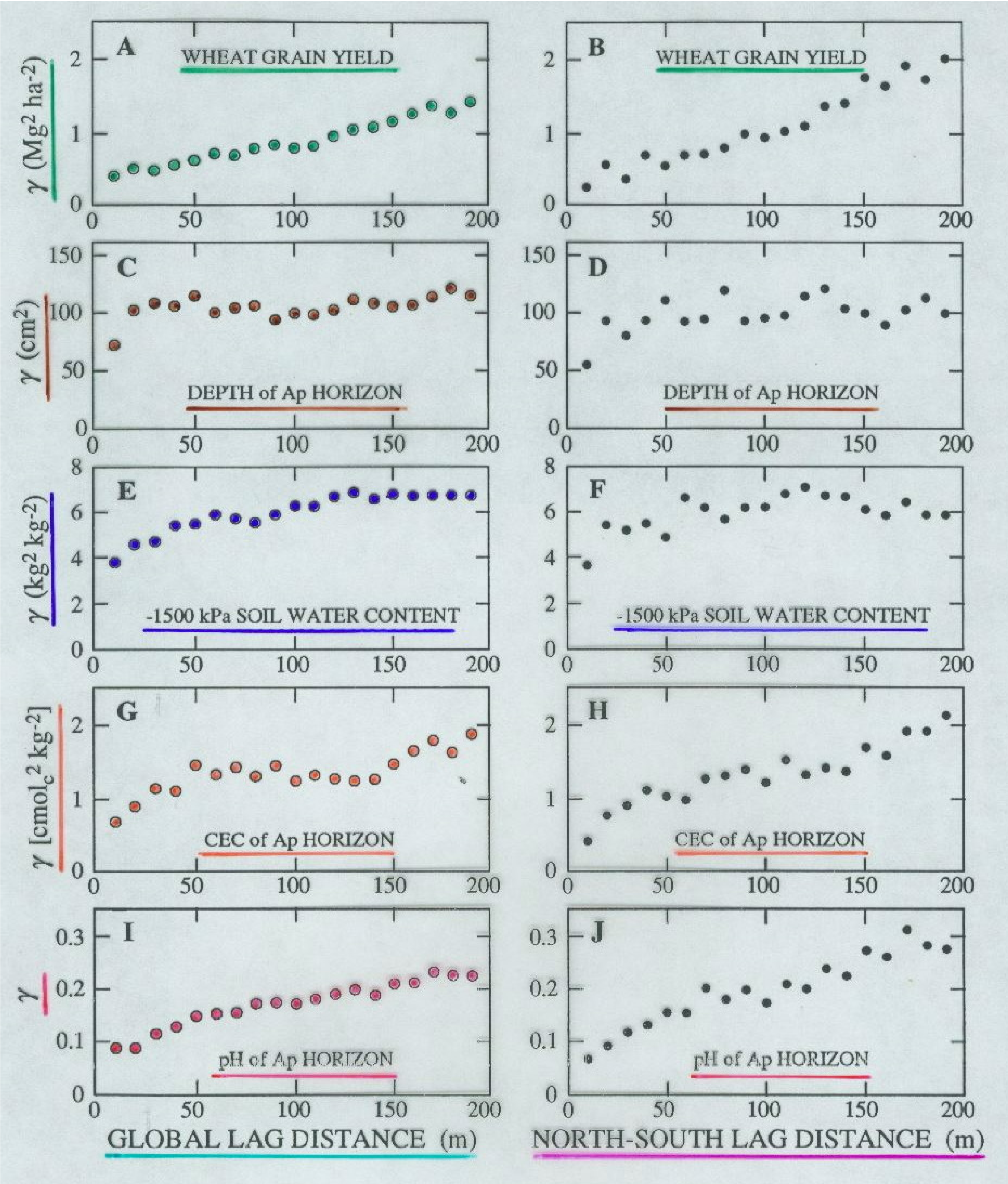
wheat yield across NCSU field station



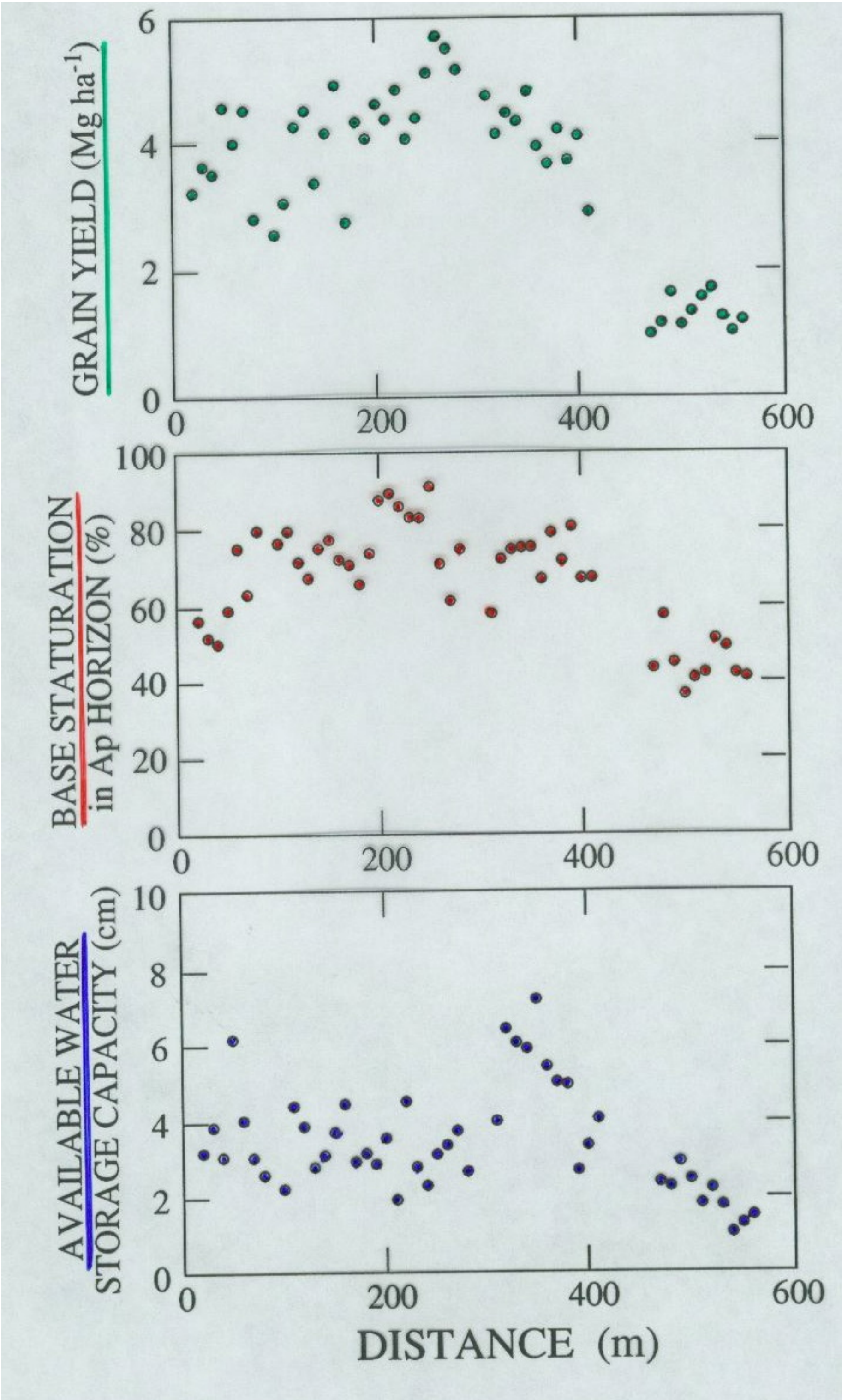
Field station transects



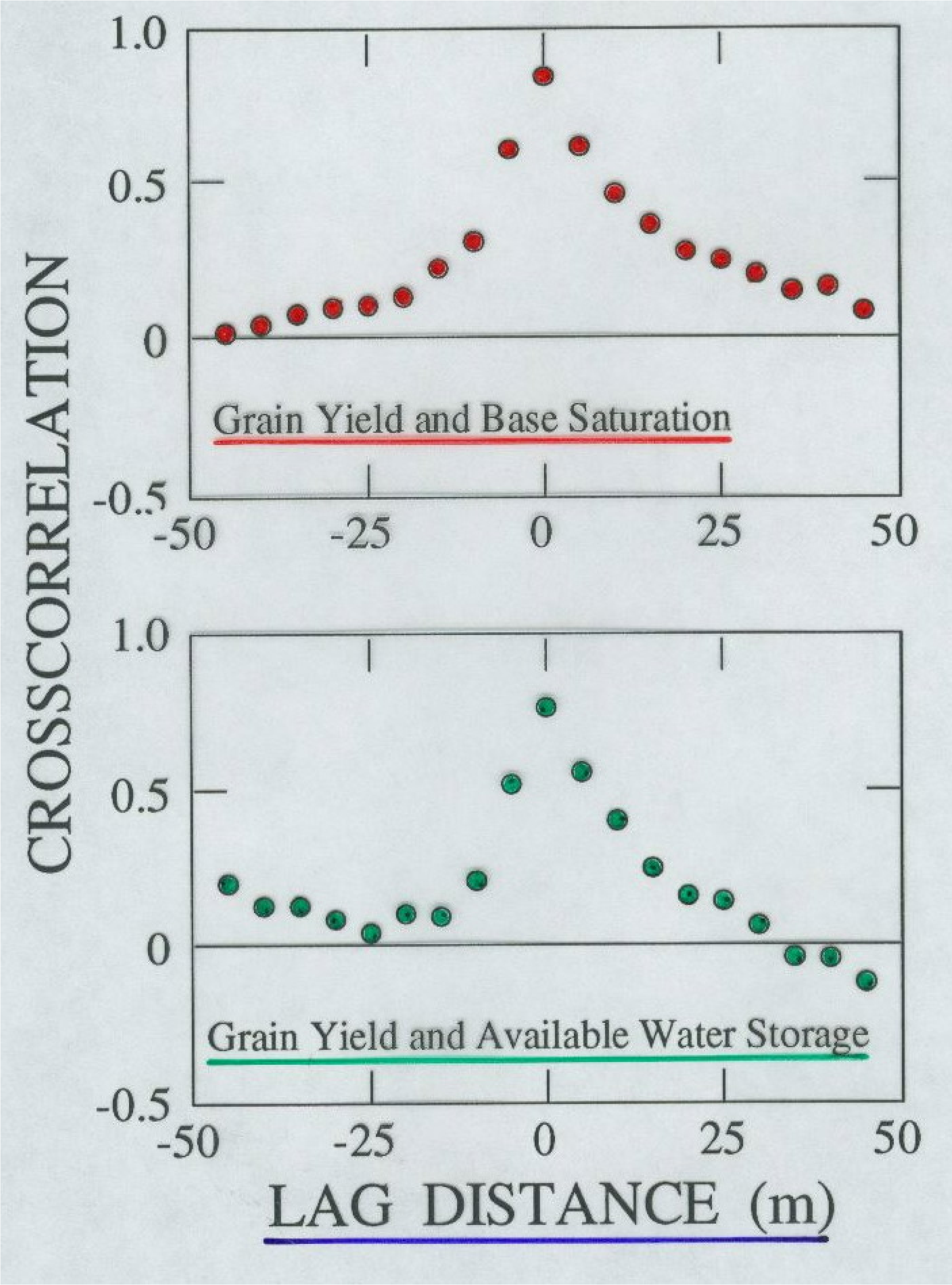
variograms field



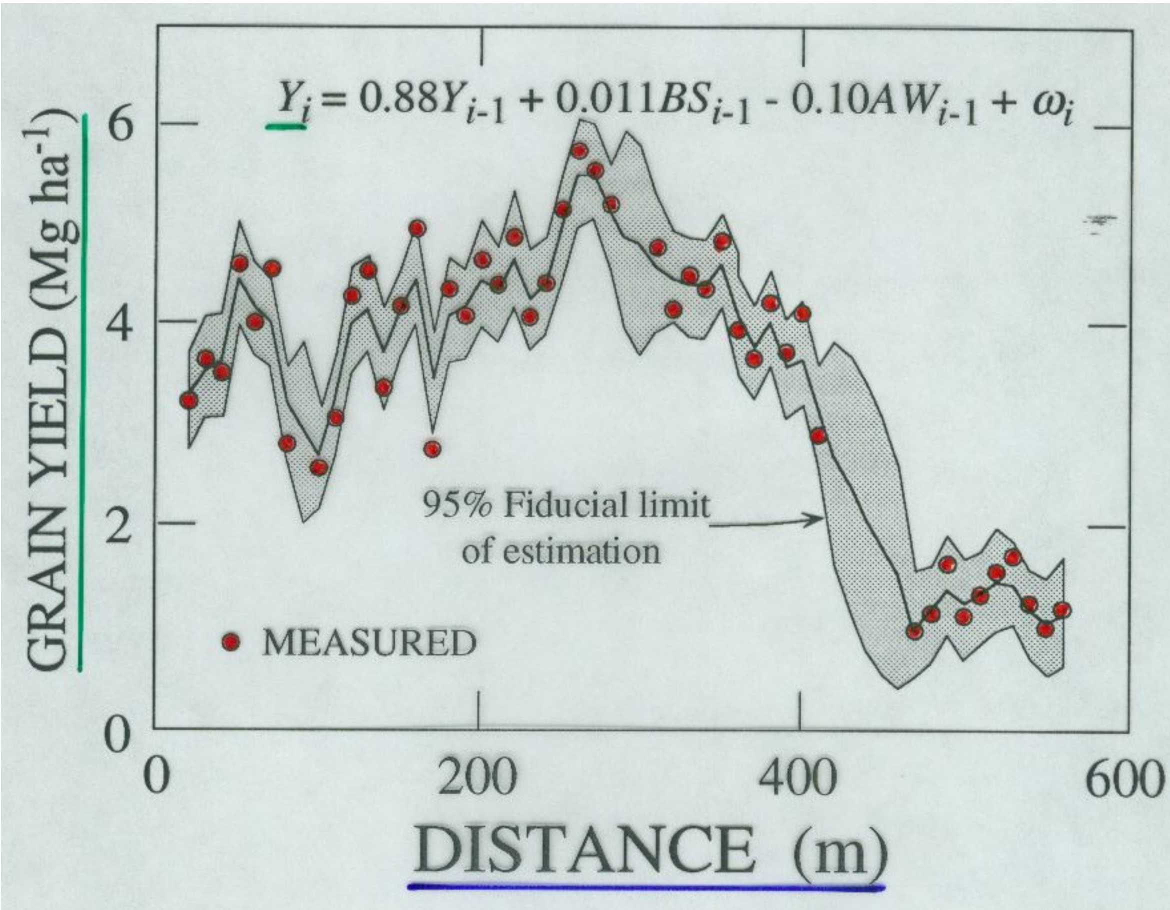
soil properties across transects



CCF soil properties



state-space wheat NCS



biological basis for time series

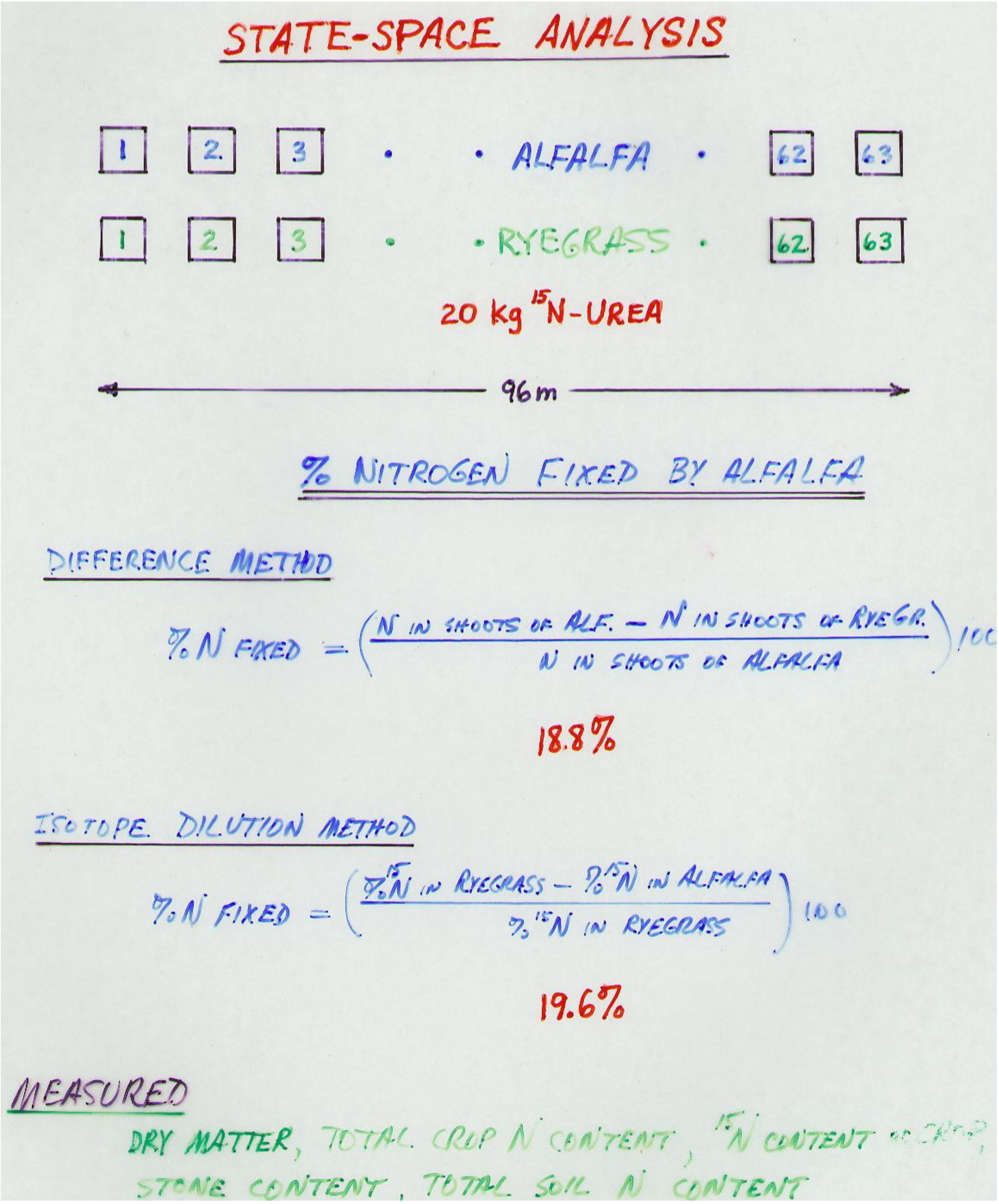
BIOLOGICAL BASIS FOR A TIME SERIES MODEL OF CROP YIELD

OBJECTIVE: UNDERSTAND N-FIXATION DISTRIBUTION ACROSS A CULTIVATED FIELD

WHEREVER LACK OF INFORMATION AND LIMITED KNOWLEDGE ABOUT EFFECTS OF AND INTERACTIONS BETWEEN VARIOUS PARAMETERS MAKE A DETERMINISTIC EXPLANATION OF THE FIELD SITUATION IMPOSSIBLE, PROCESSES IN FIELDS CAN BE DESCRIBED USING STOCHASTIC APPROACHES EXAMINING HOW OBSERVATIONS CHANGE IN SPACE.

NITROGEN FIXATION

state space analysis N fixation



STATE-SPACE ANALYSIS

1	2	3	·	·	ALFALFA	·	62	63
1	2	3	·	·	RYEGRASS	·	62	63

20 kg ^{15}N-UREA

← 96 m →

% NITROGEN FIXED BY ALFALFA

DIFFERENCE METHOD

$$\%\,N\ \text{FIXED} = \left(\frac{N\ \text{IN SHOOTS OF ALF.} - N\ \text{IN SHOOTS OF RYEGR.}}{N\ \text{IN SHOOTS OF ALFALFA}}\right)100$$

18.8%

ISOTOPE DILUTION METHOD

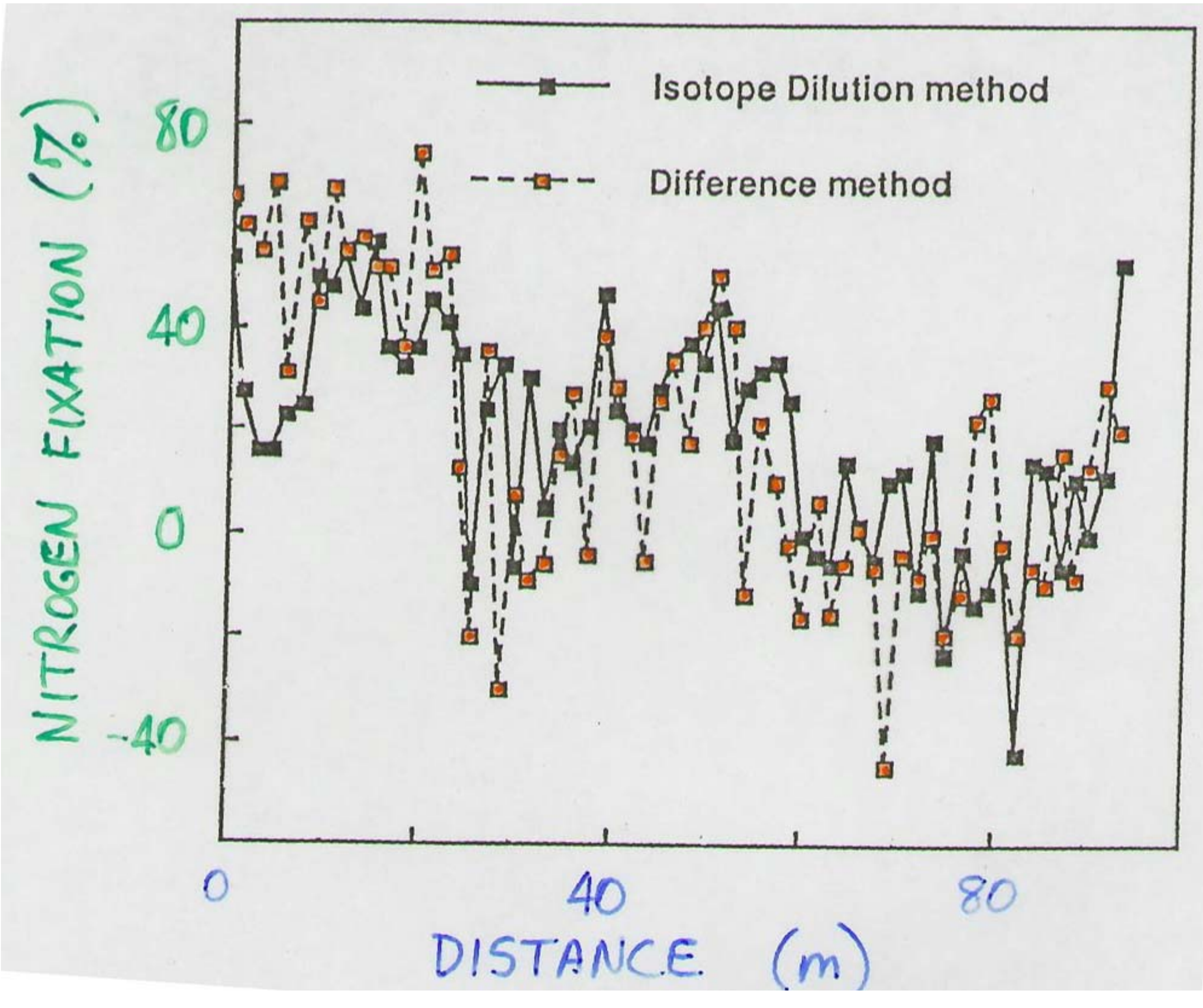
$$\%\,N\ \text{FIXED} = \left(\frac{\%\,^{15}N\ \text{IN RYEGRASS} - \%\,^{15}N\ \text{IN ALFALFA}}{\%\,^{15}N\ \text{IN RYEGRASS}}\right)100$$

19.6%

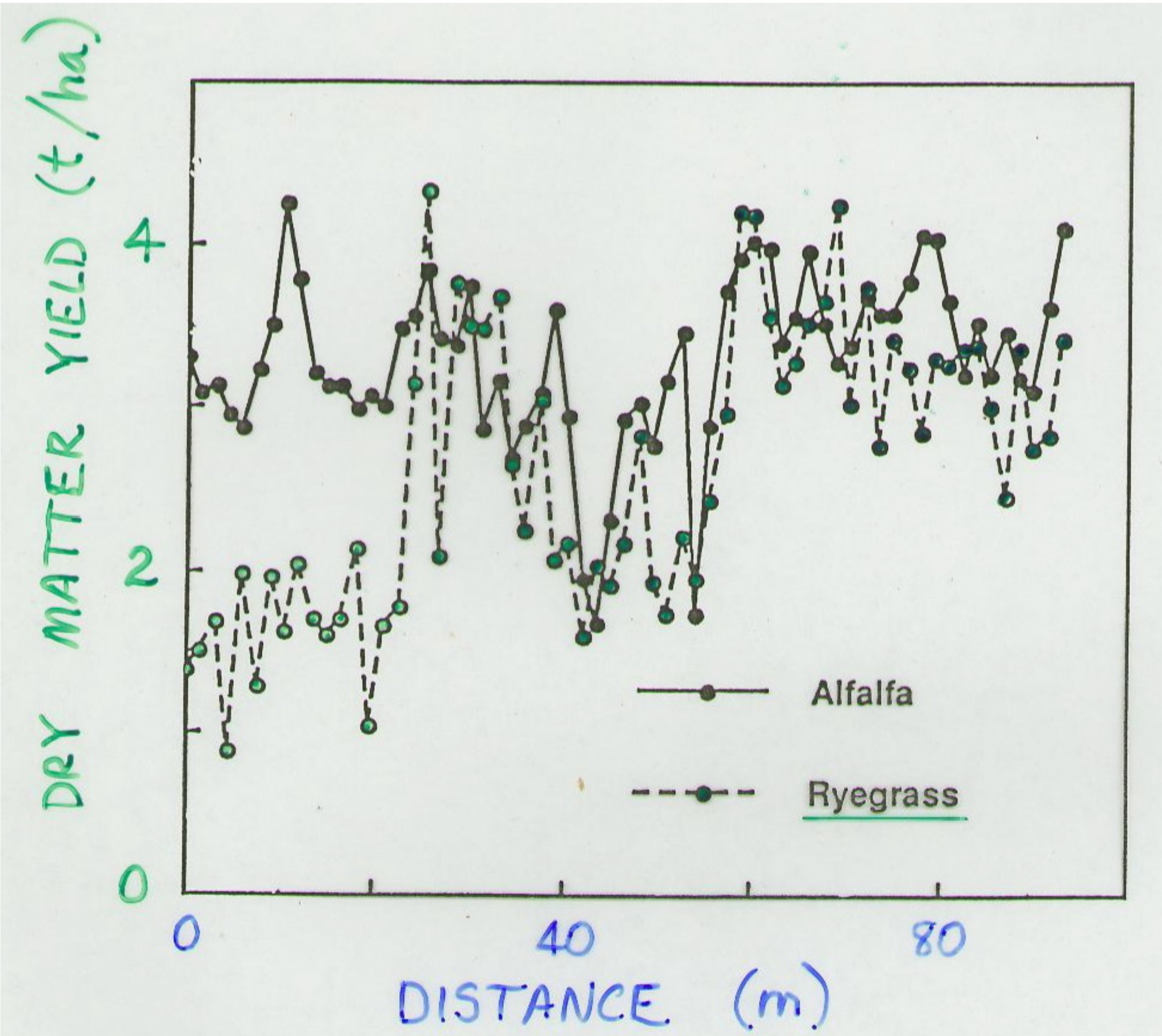
MEASURED

DRY MATTER, TOTAL CROP N CONTENT, ^{15}N CONTENT OF CROP, STONE CONTENT, TOTAL SOIL N CONTENT

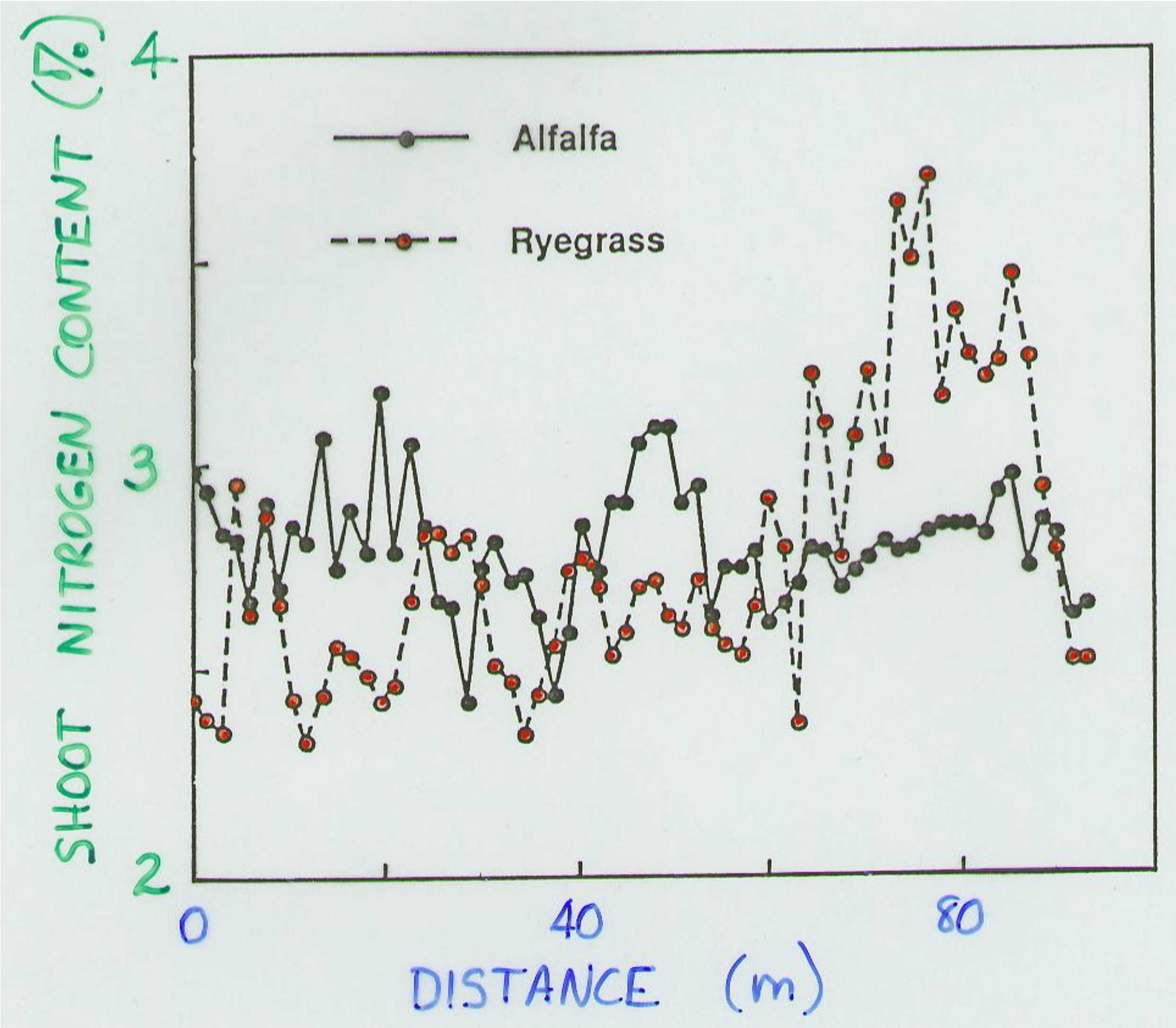
N fixation vs distance (2 methods)



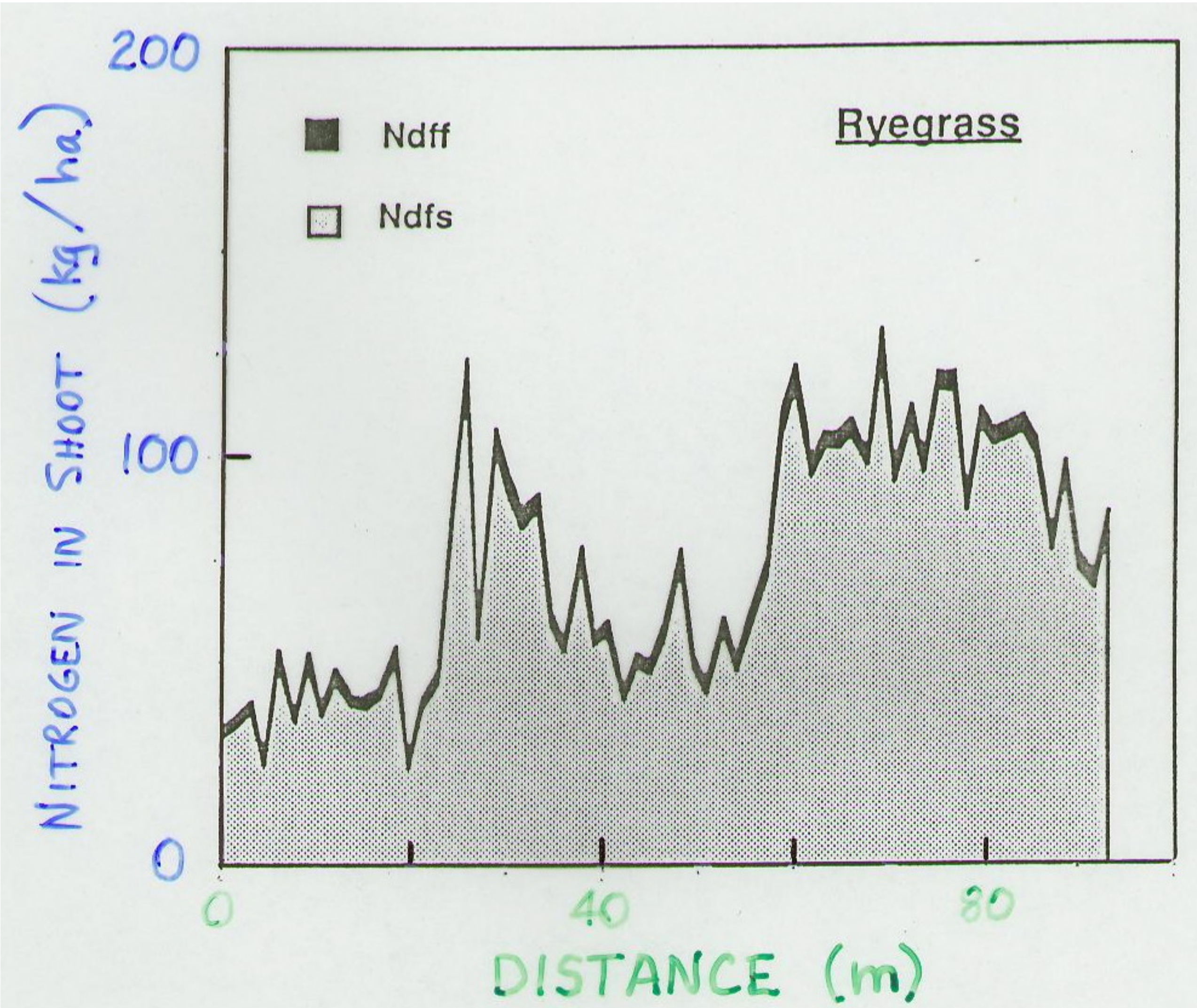
alfalfa & rye grass yield



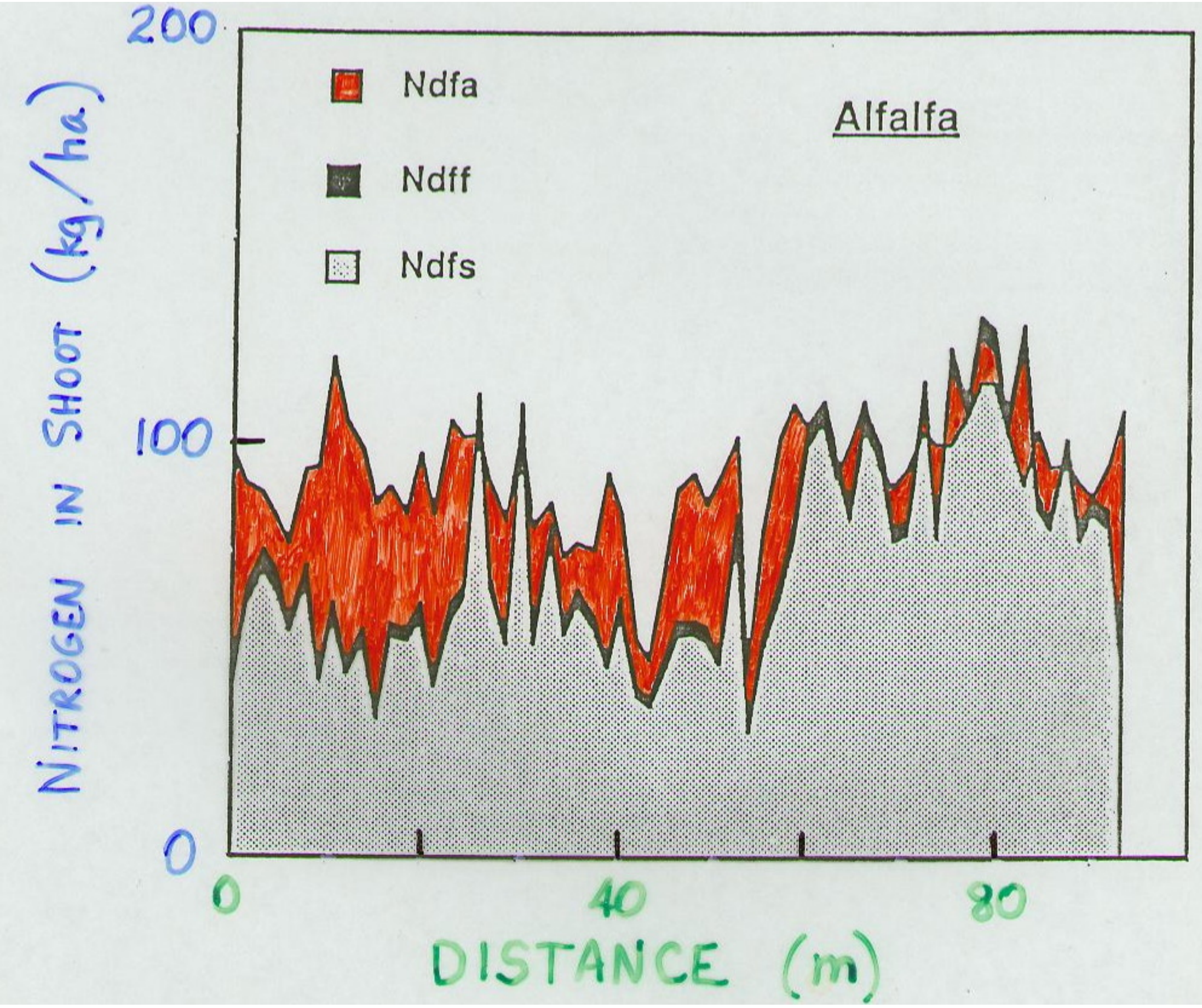
shoot N in rye grass & alfalfa



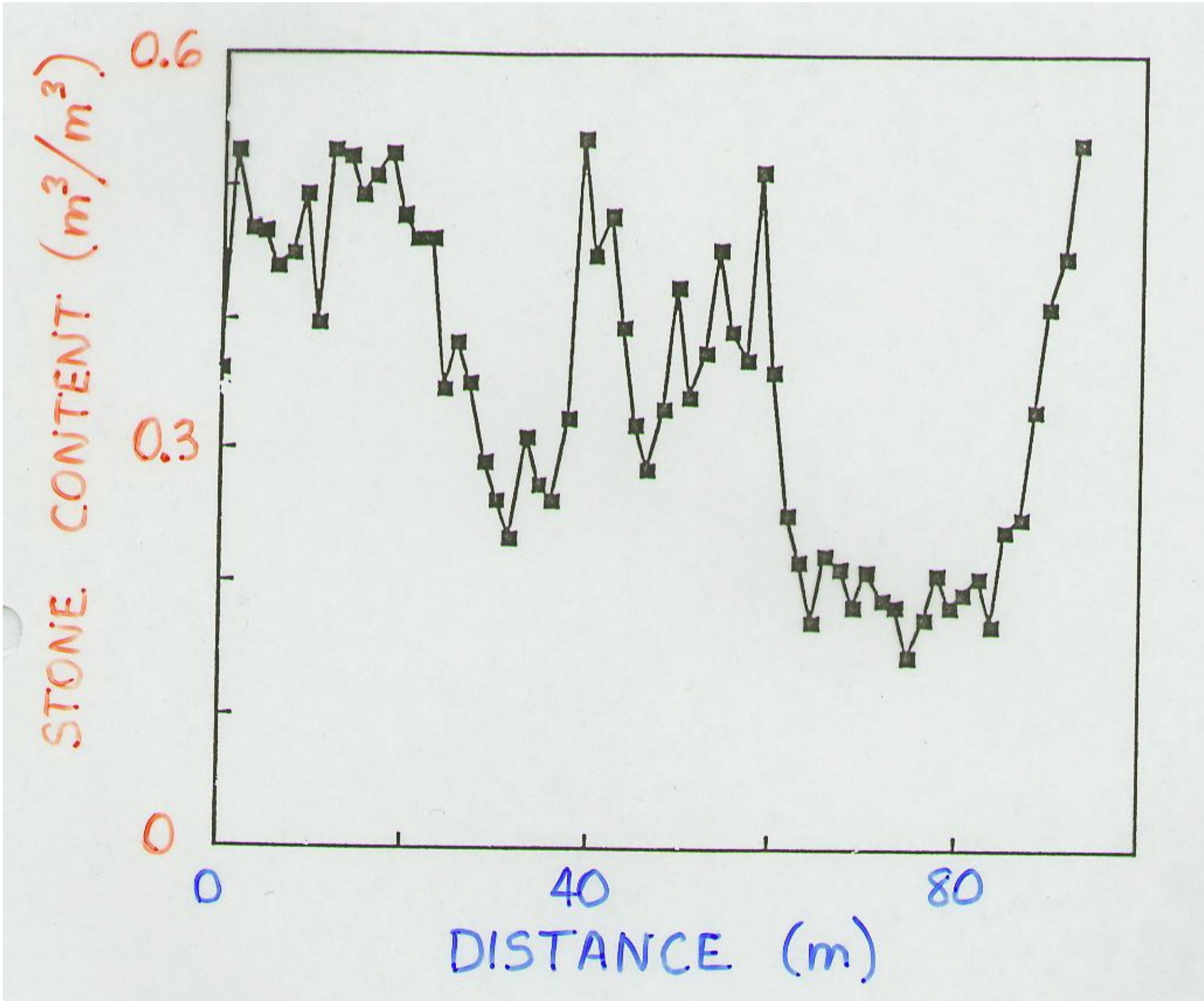
N in ryegrass shoot



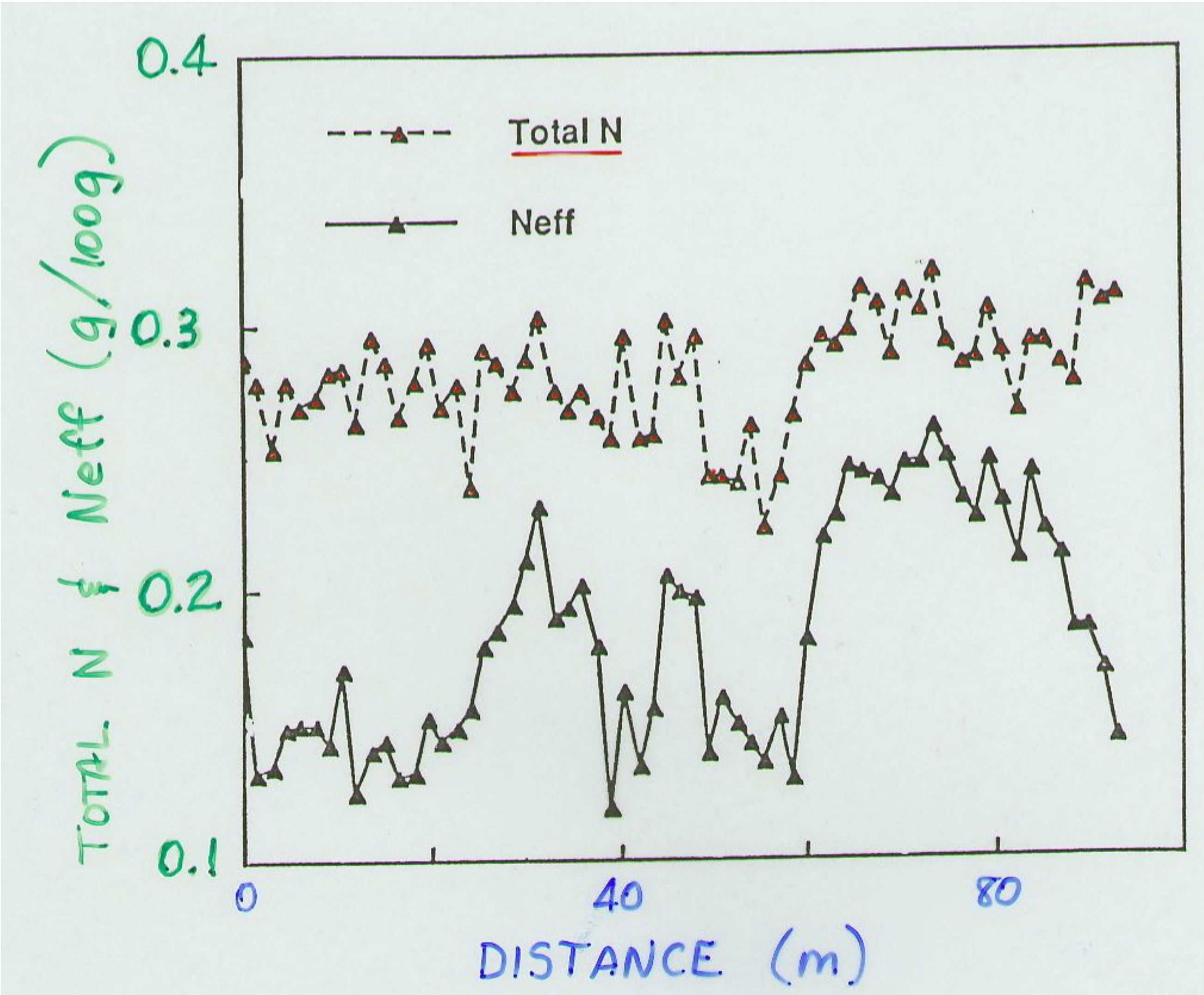
N in alfalfa shoot



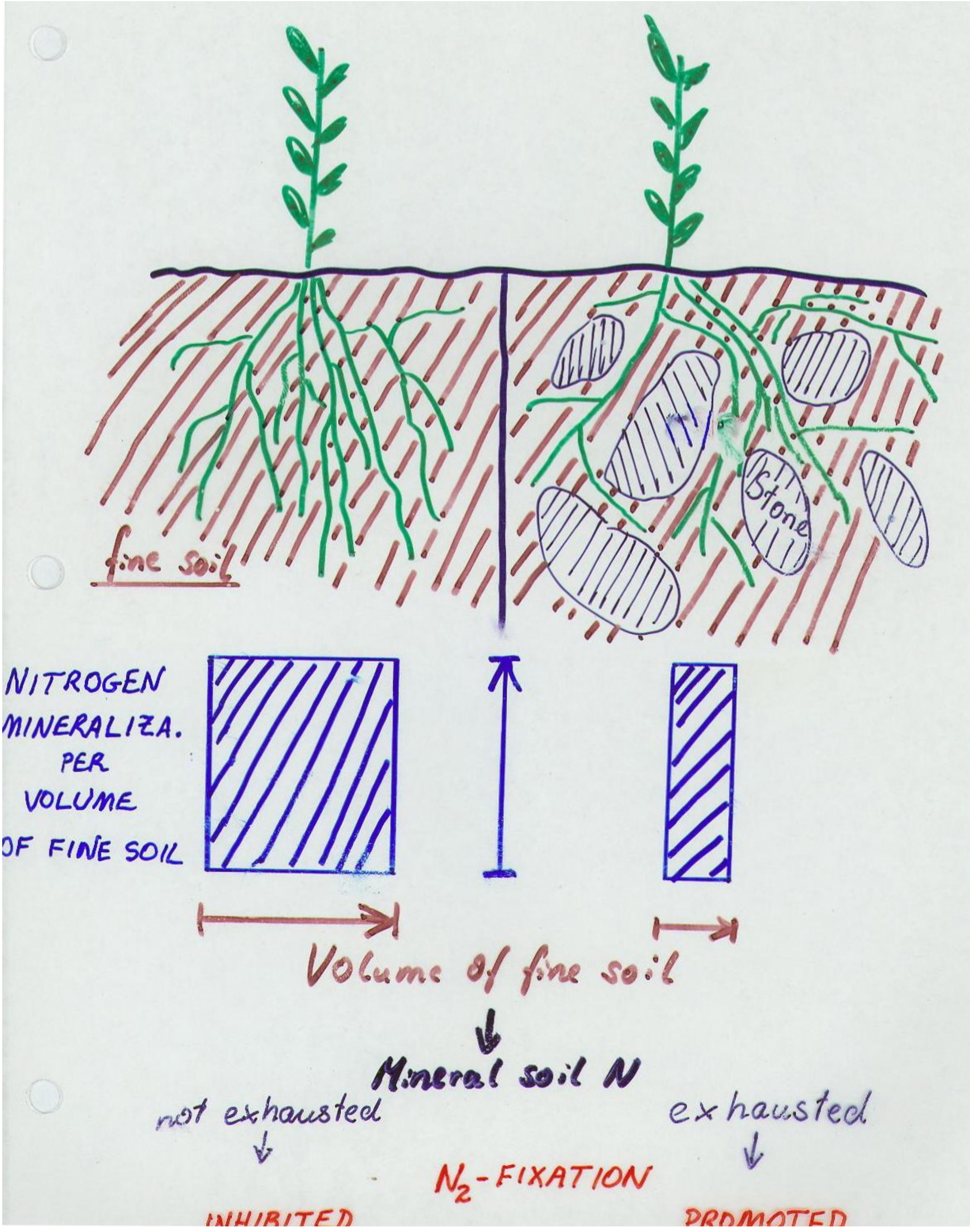
stone content



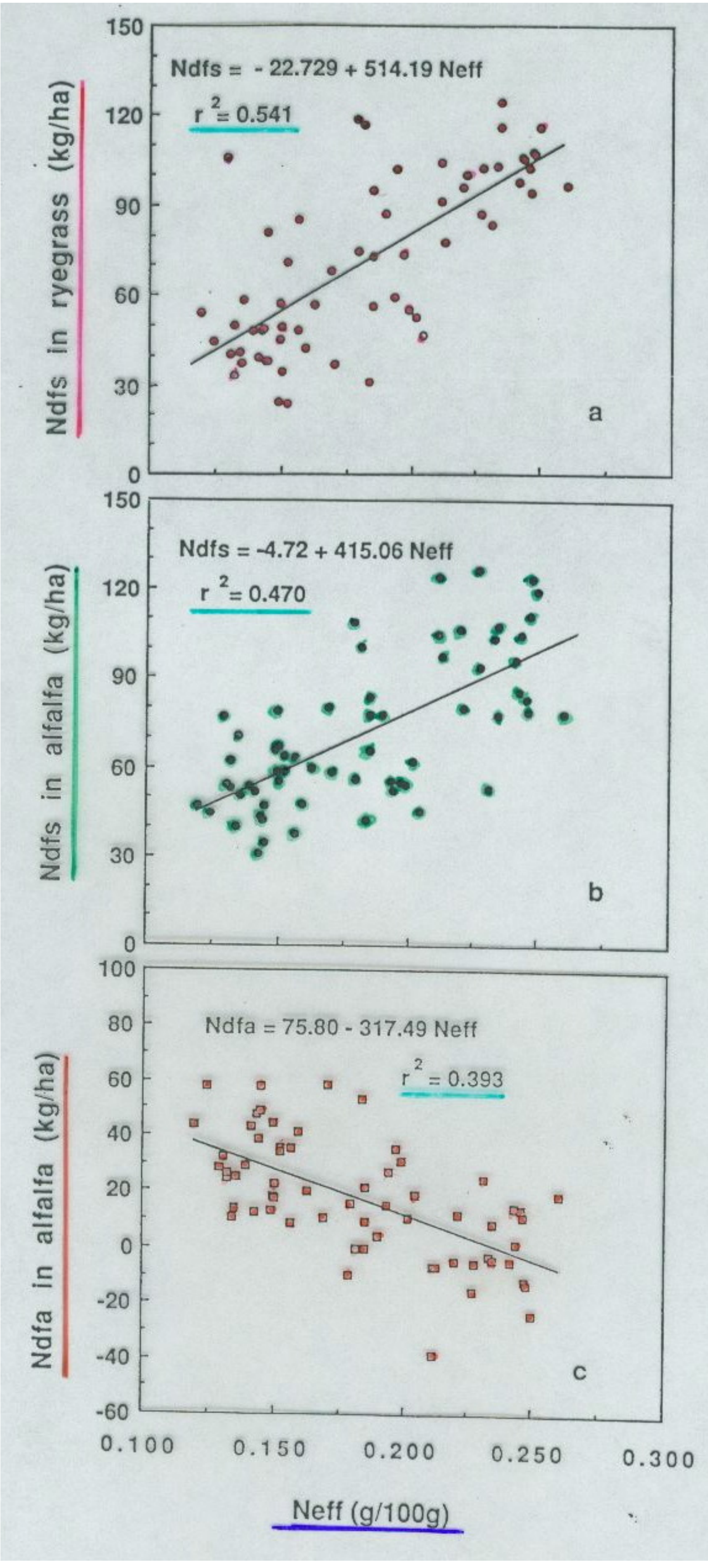
total N & Neff versus distance



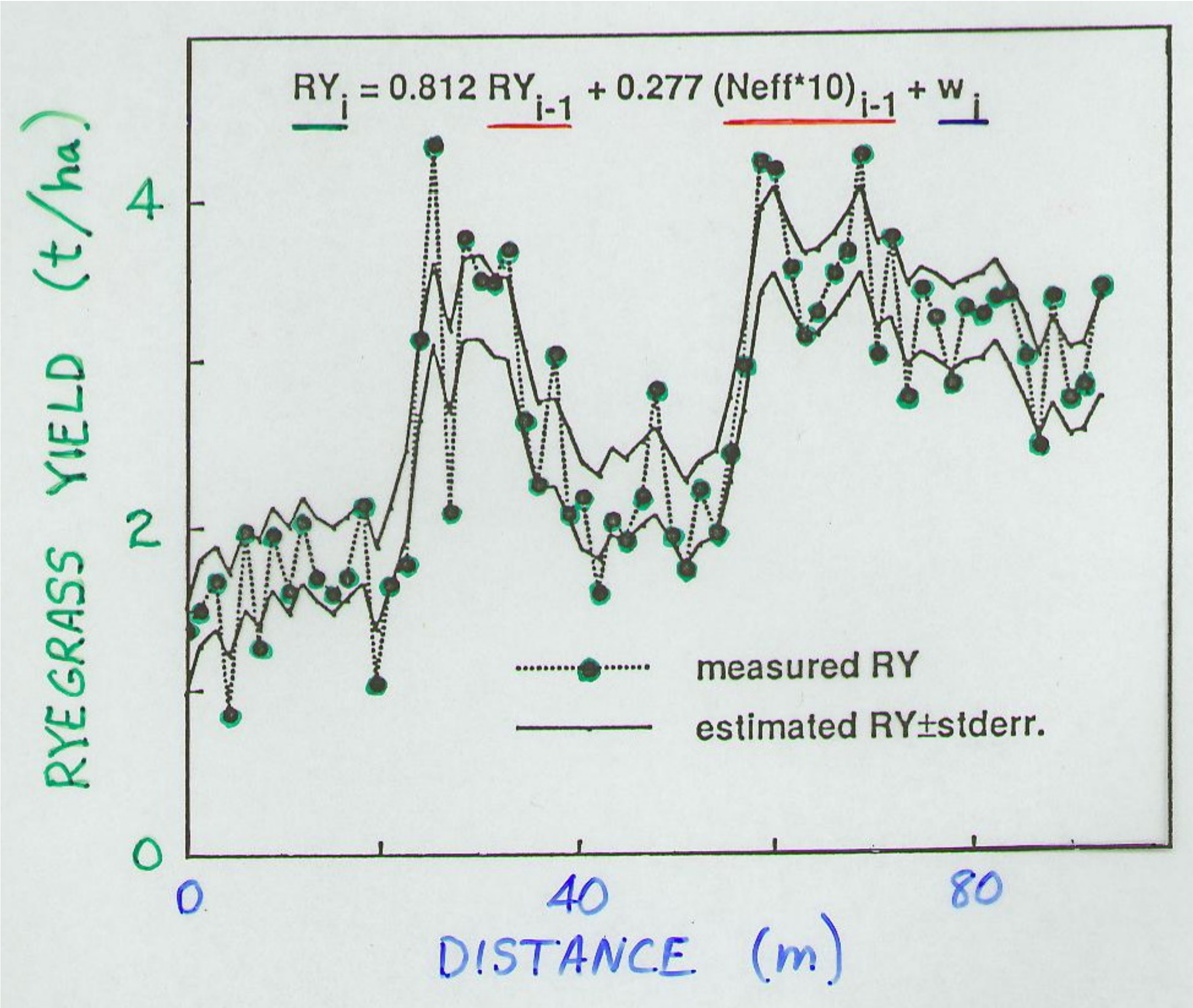
N2 fixation (stones in soil)



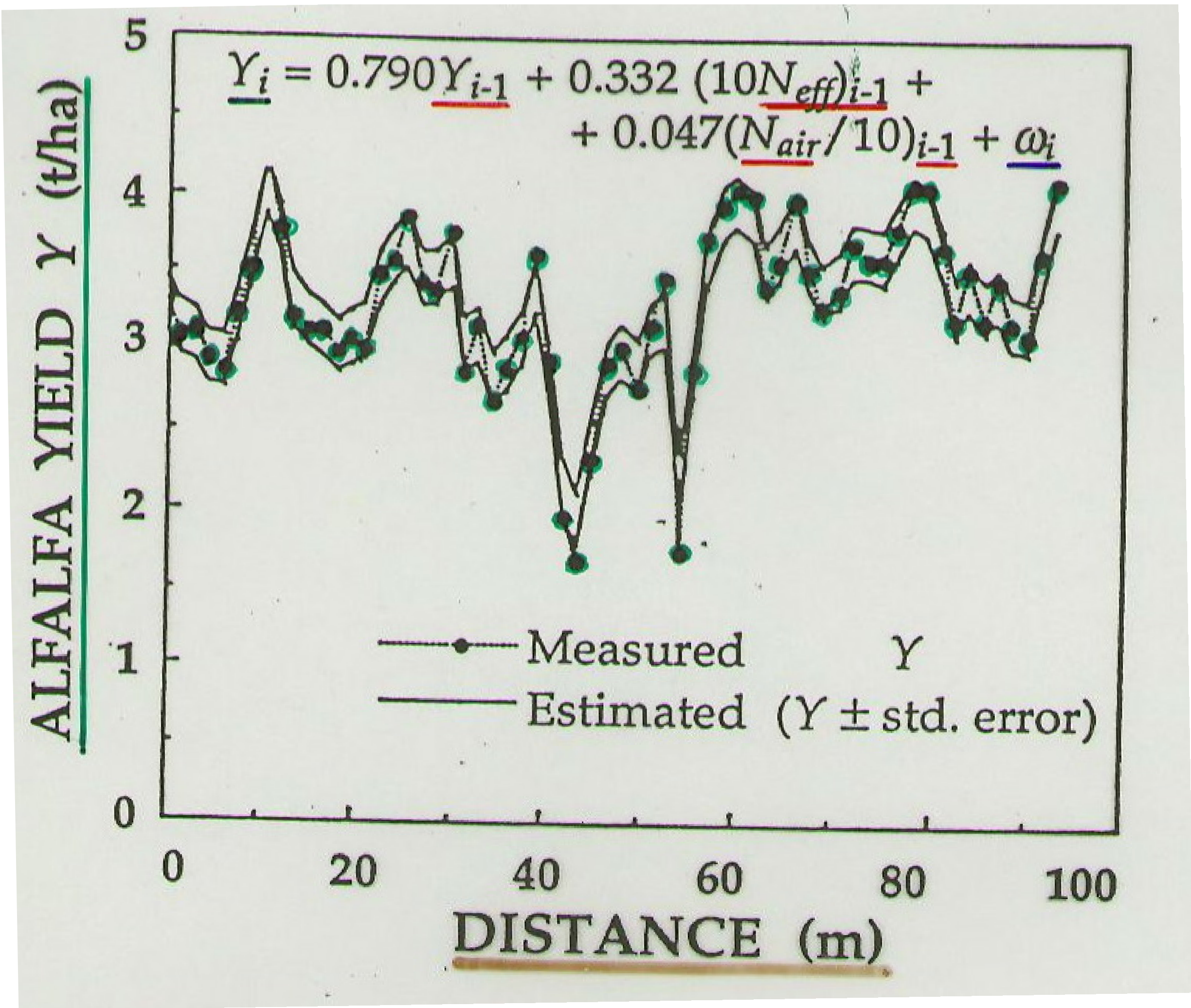
Ndfs versus Neff



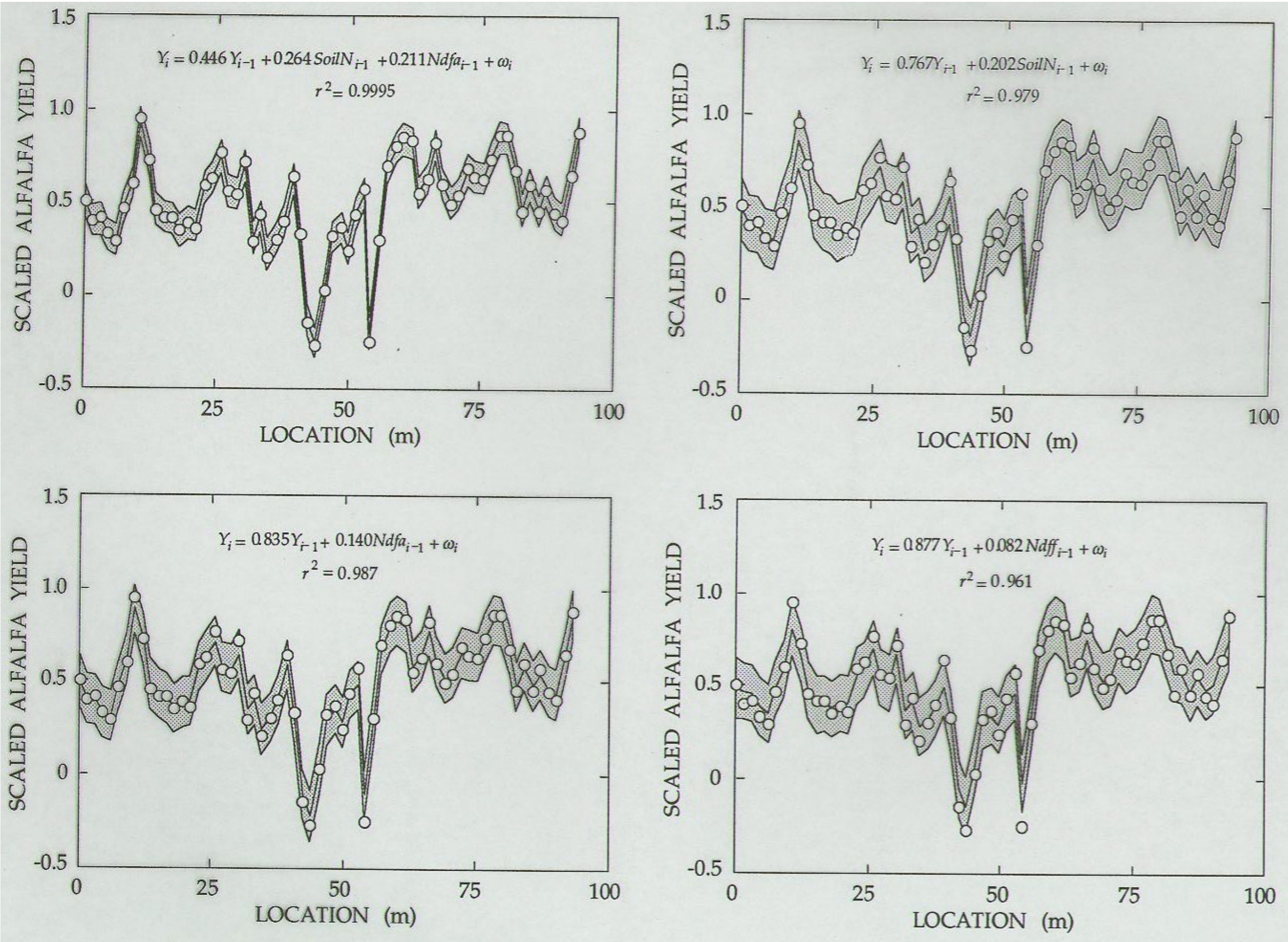
state-space ryegrass yield



state-space alfalfa yield



state-space est. alfalfa

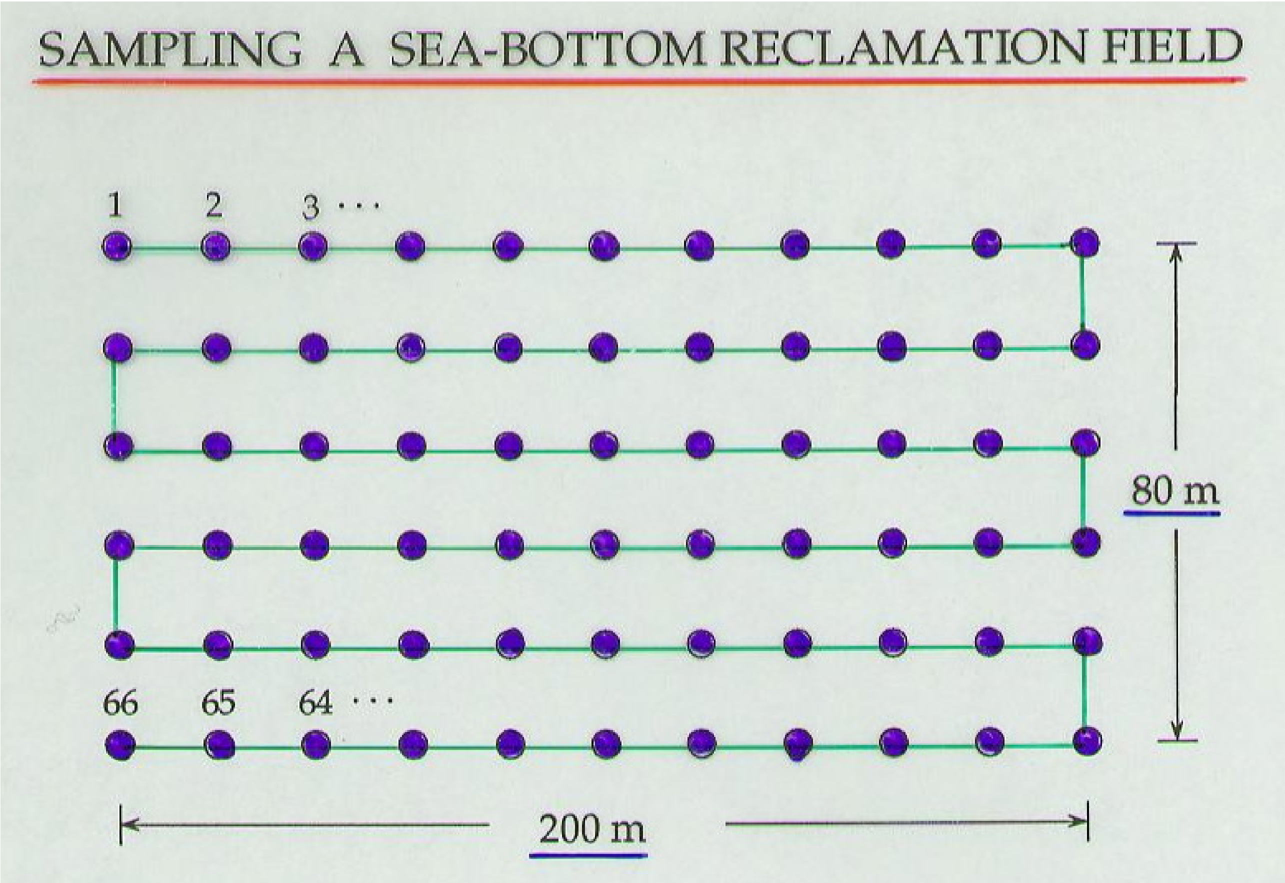


N2 fixation conclusions

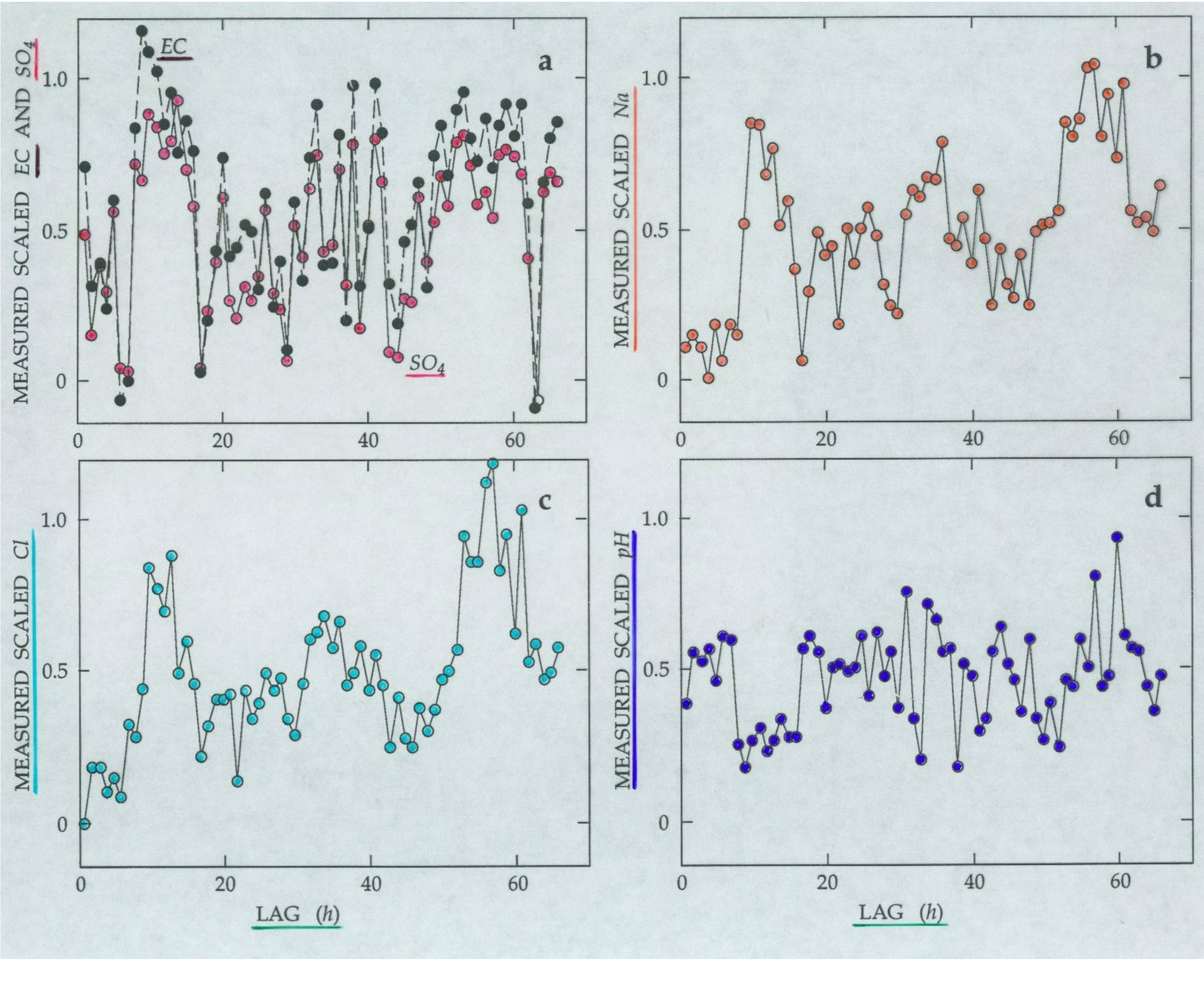
CONCLUSIONS

- MEANINGFUL FIELD EXPERIMENTS DO NOT HAVE TO BE CONDUCTED ON UNIFORM AREAS OF A FIELD.
- DIFFERENT TREATMENTS WERE NOT IMPOSED NOR NECESSARY.
- NITROGEN FIXATION, FERTILIZER UTILIZATION AND CROP RESPONSE ARE BETTER UNDERSTOOD BY SAMPLING ACROSS ENTIRE FIELDS TO CONSIDER THE SPATIAL VARIANCE AND CO-VARIANCE STRUCTURES.

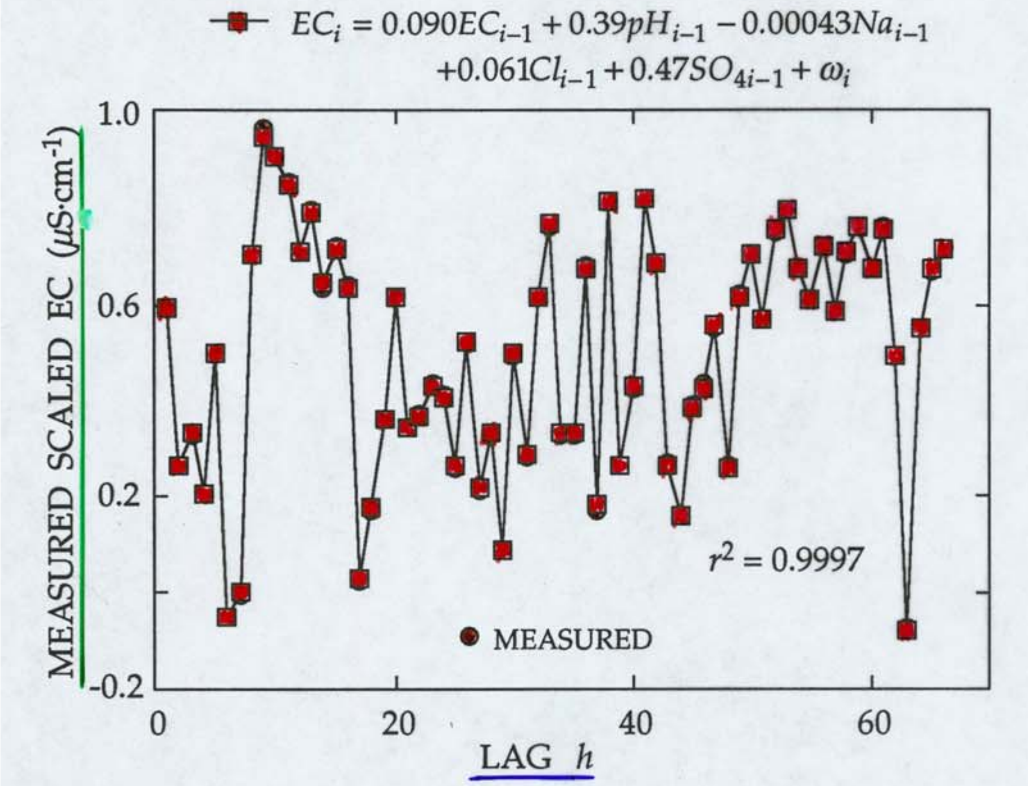
sampling a sea-botton

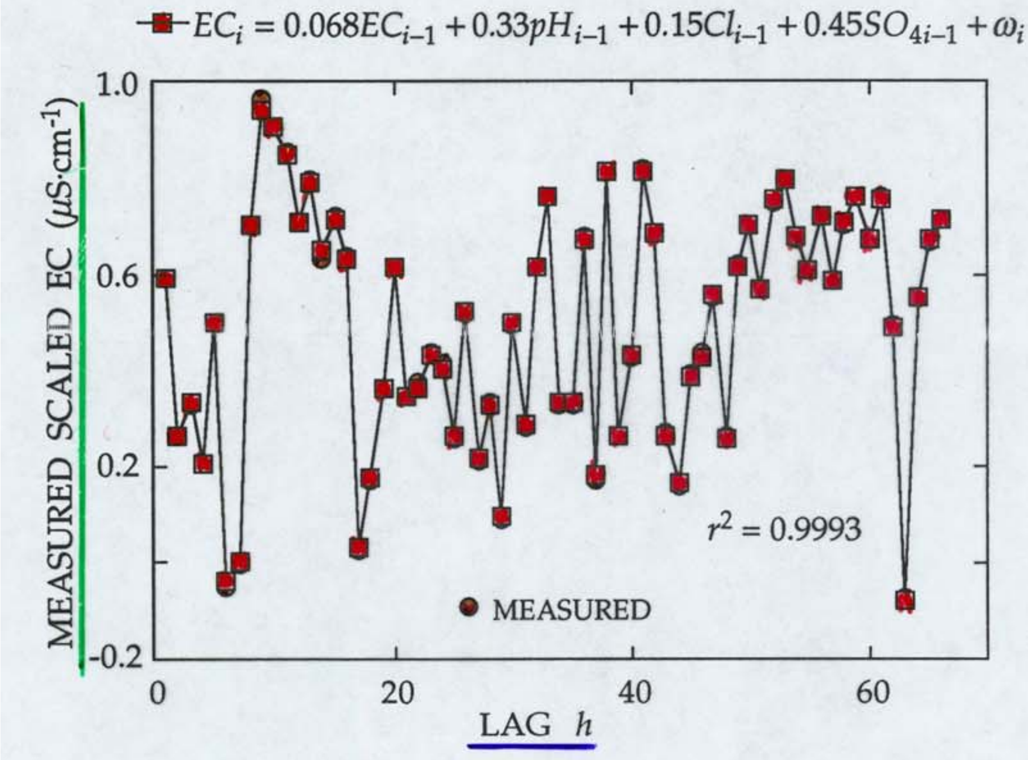


scaled sea data

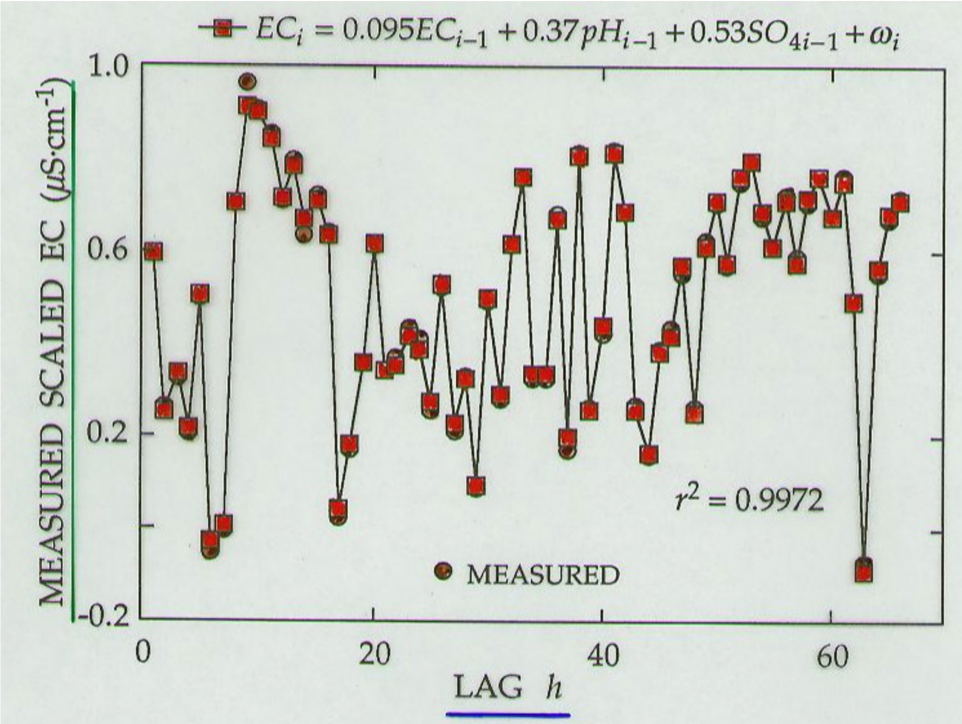


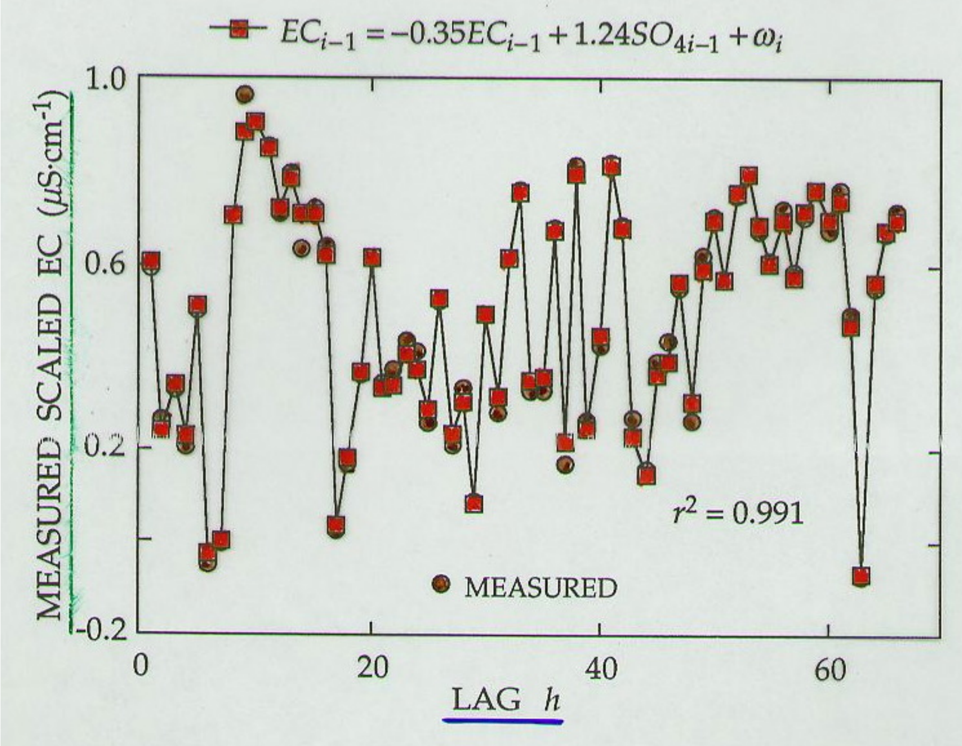
state-sp EC(all variables)



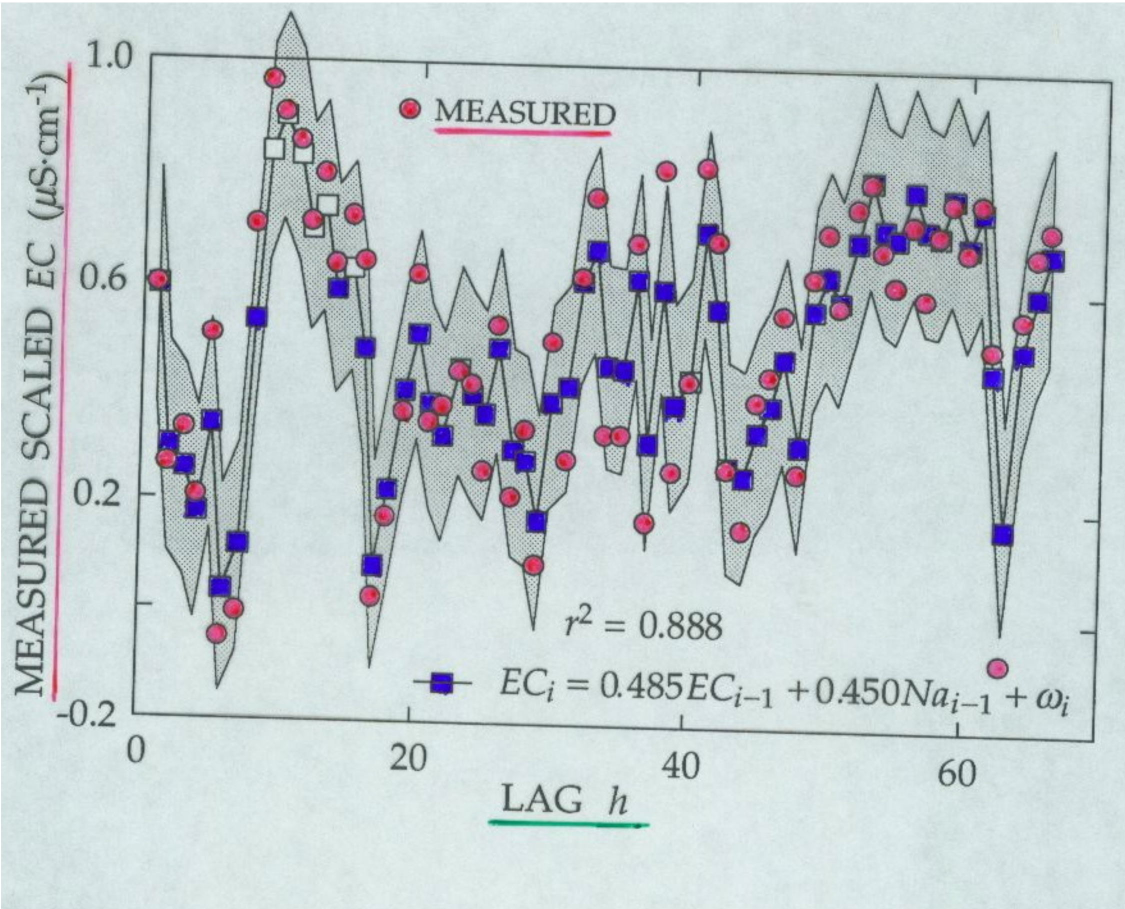


state-sp EC less variables

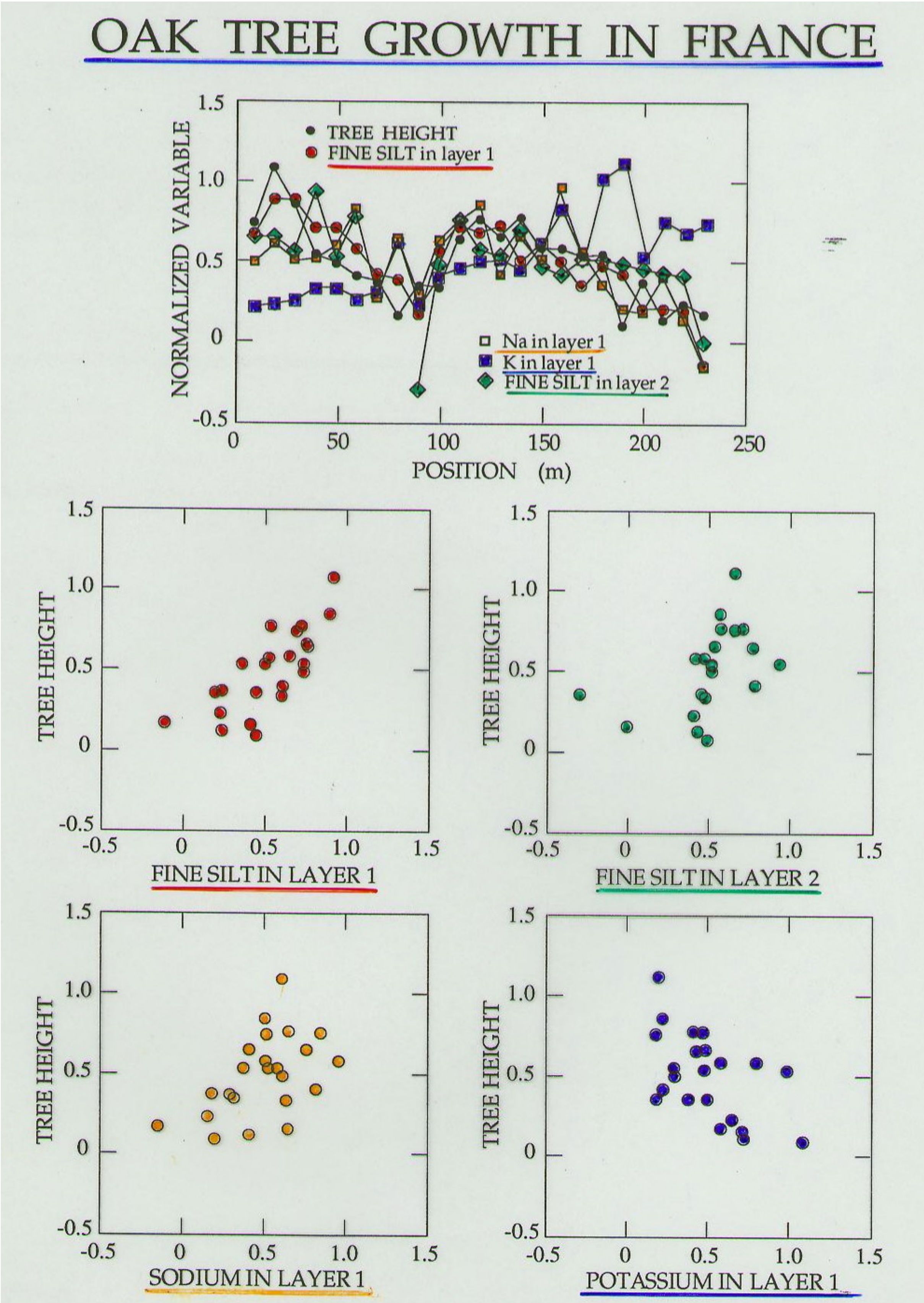




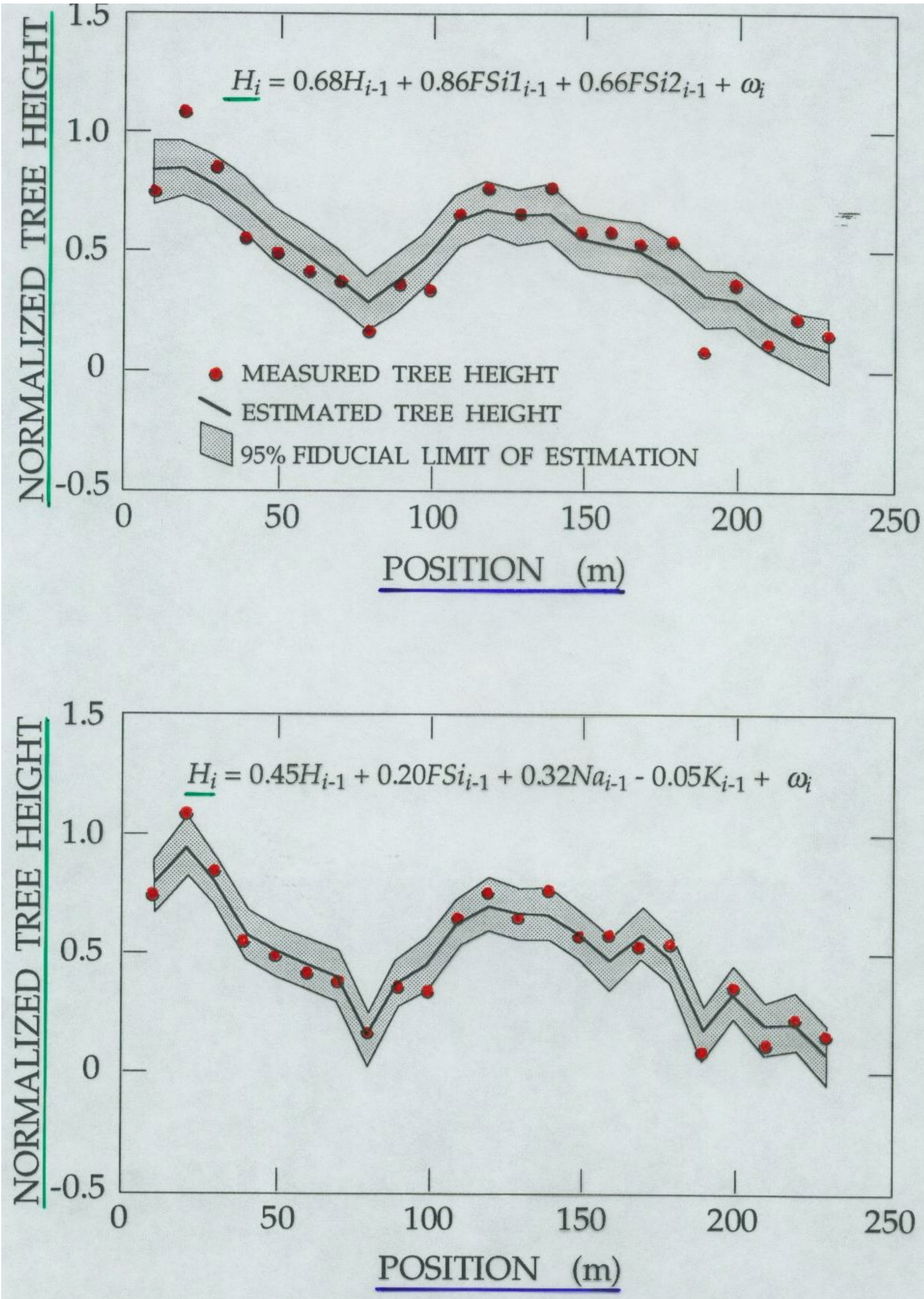
state-sp EC vs SO4



red oak growth



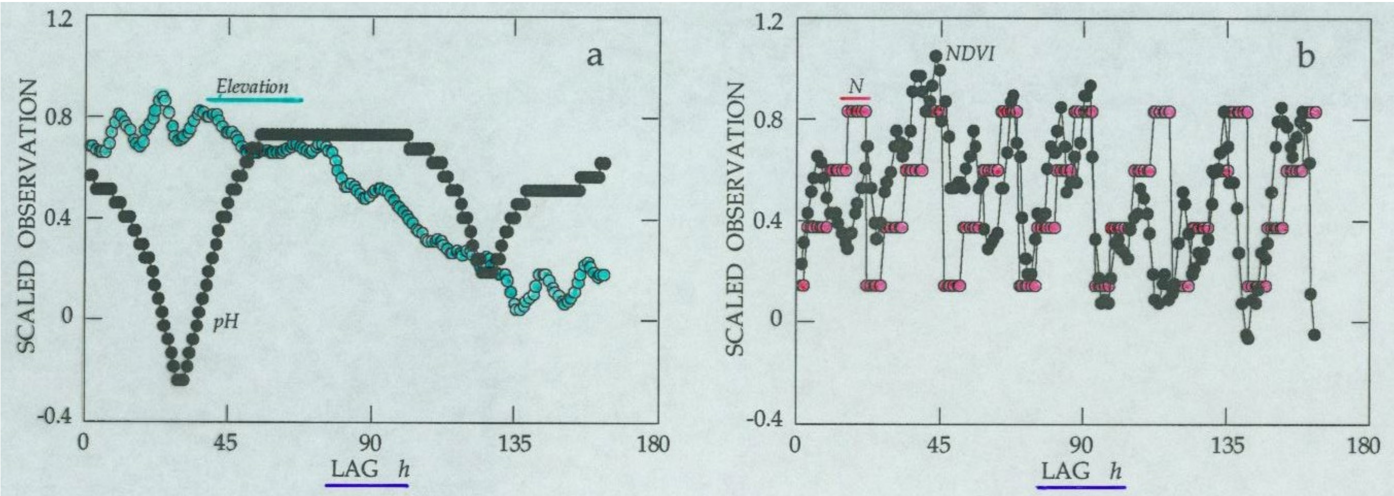
state-space oak tree



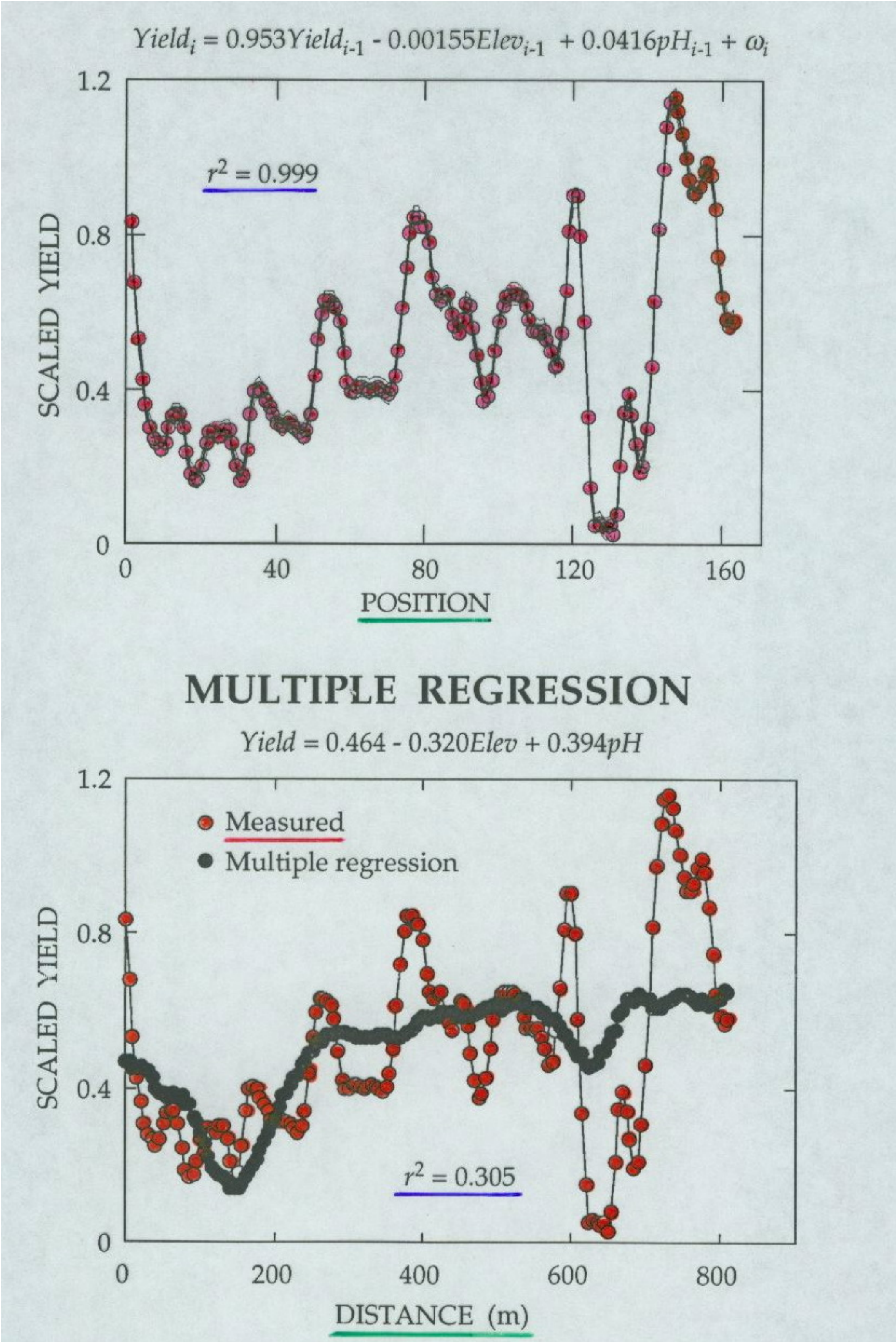
WHEAT YELD

AND SOIL PROPERTIES

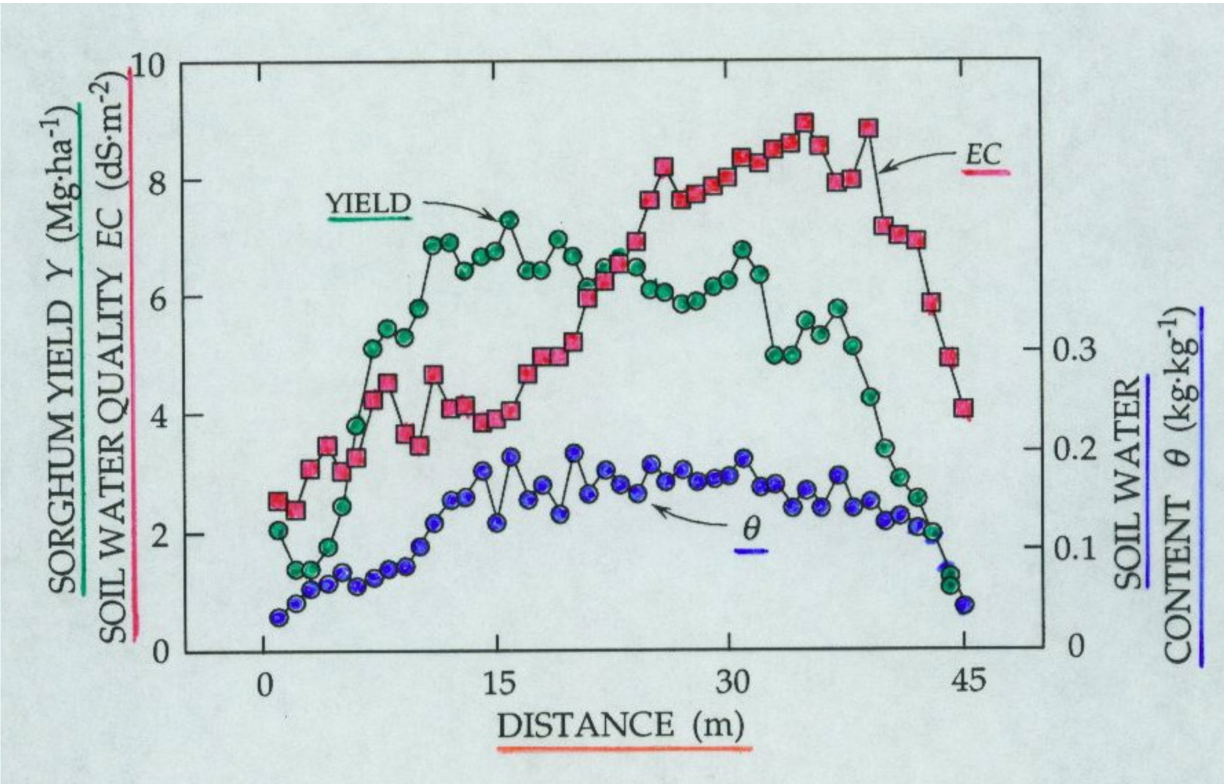
scaled wheat & soil properties



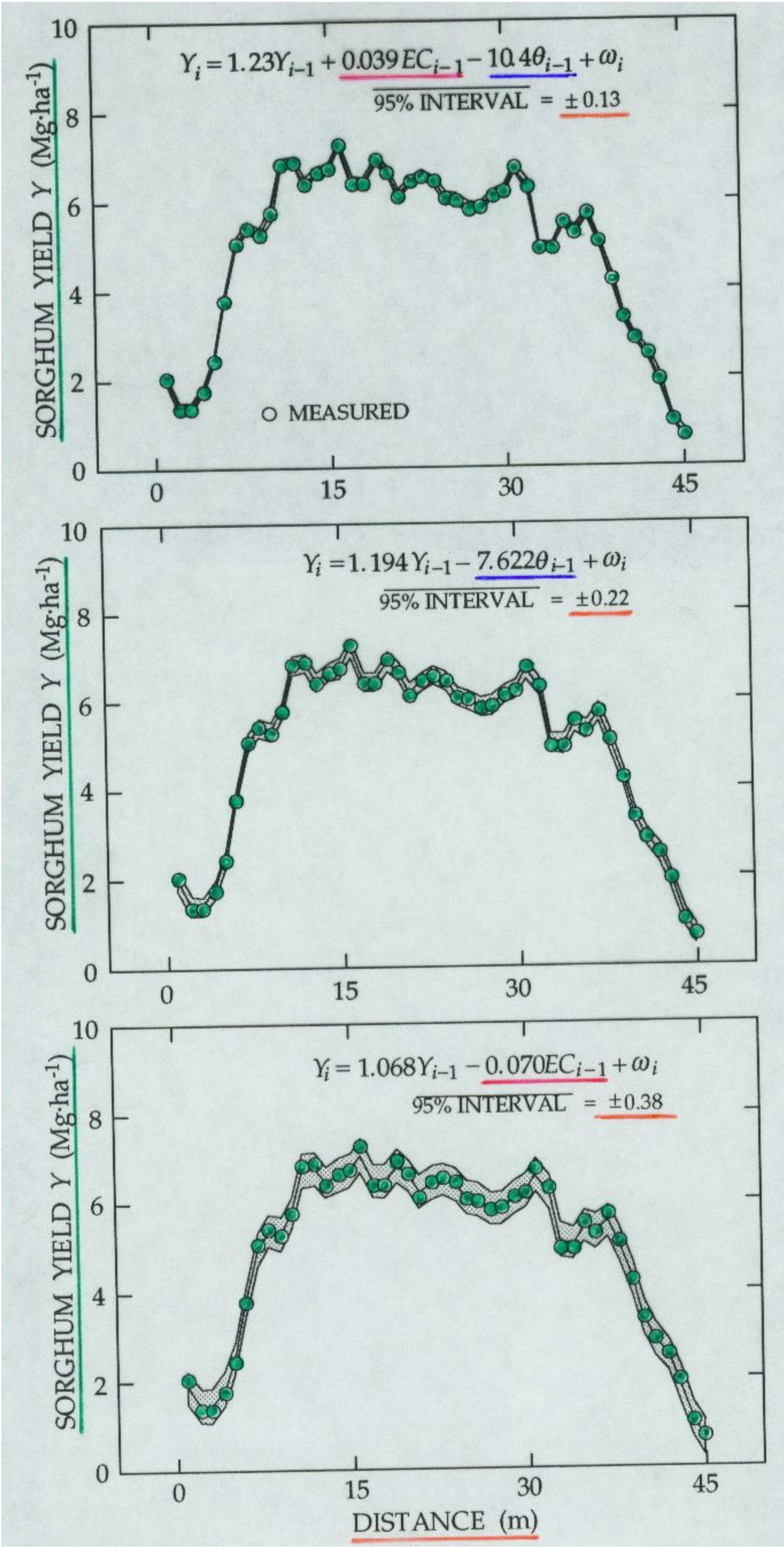
state-space & MR wheat



sorghum yield, EC and water



state-space yield,EC.water

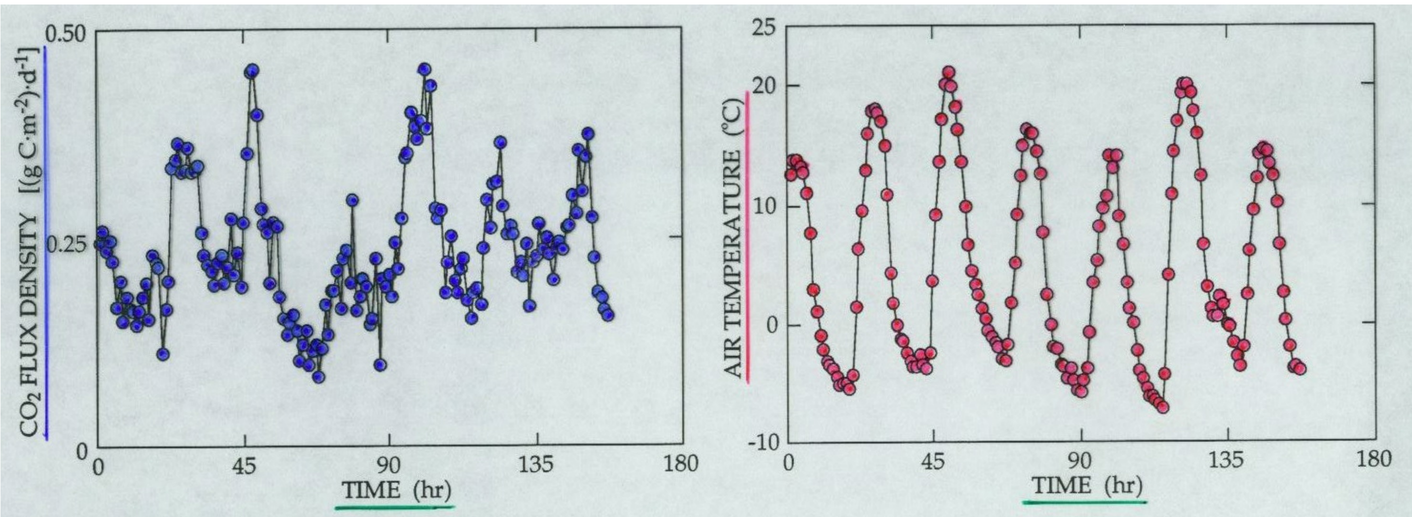


RESPIRATION

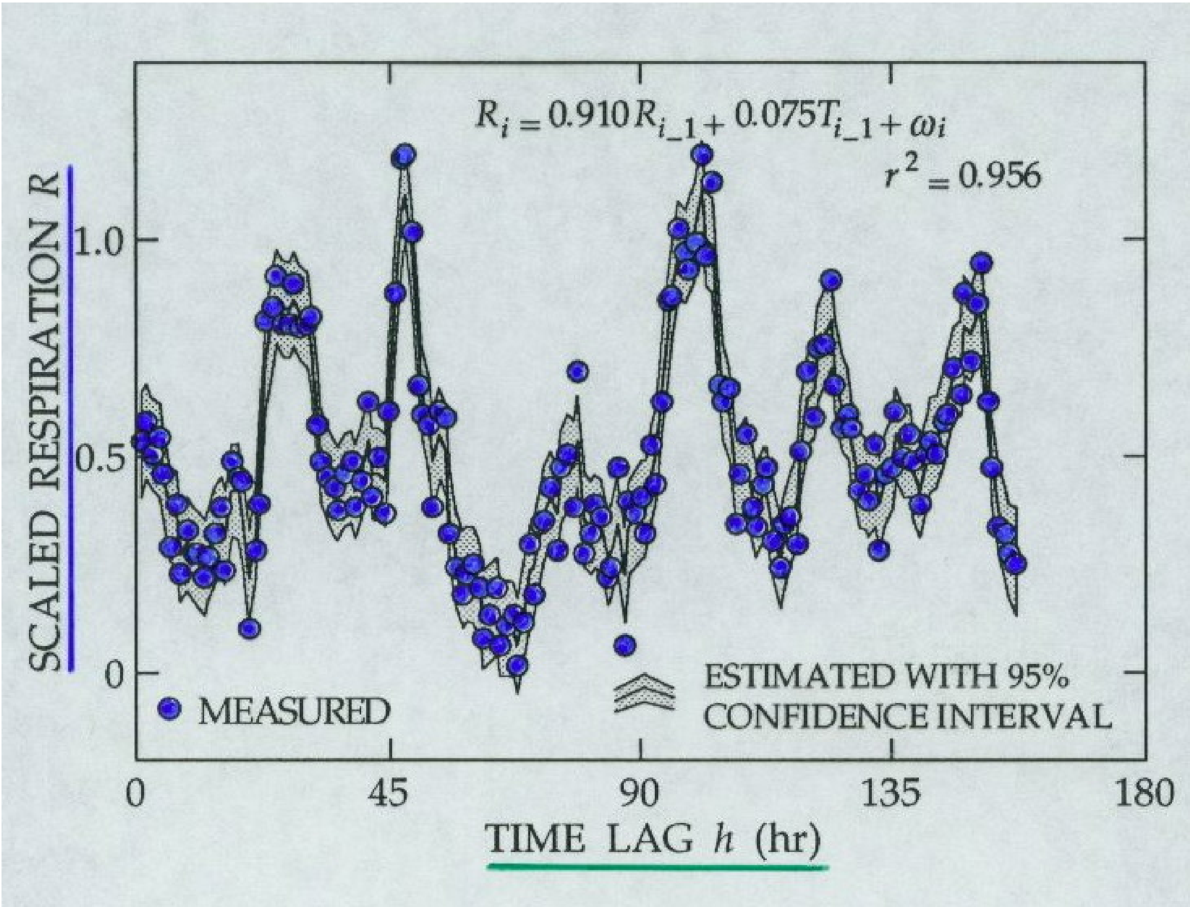
AND

AIR TEMPERATURE

Respiration and air temp data

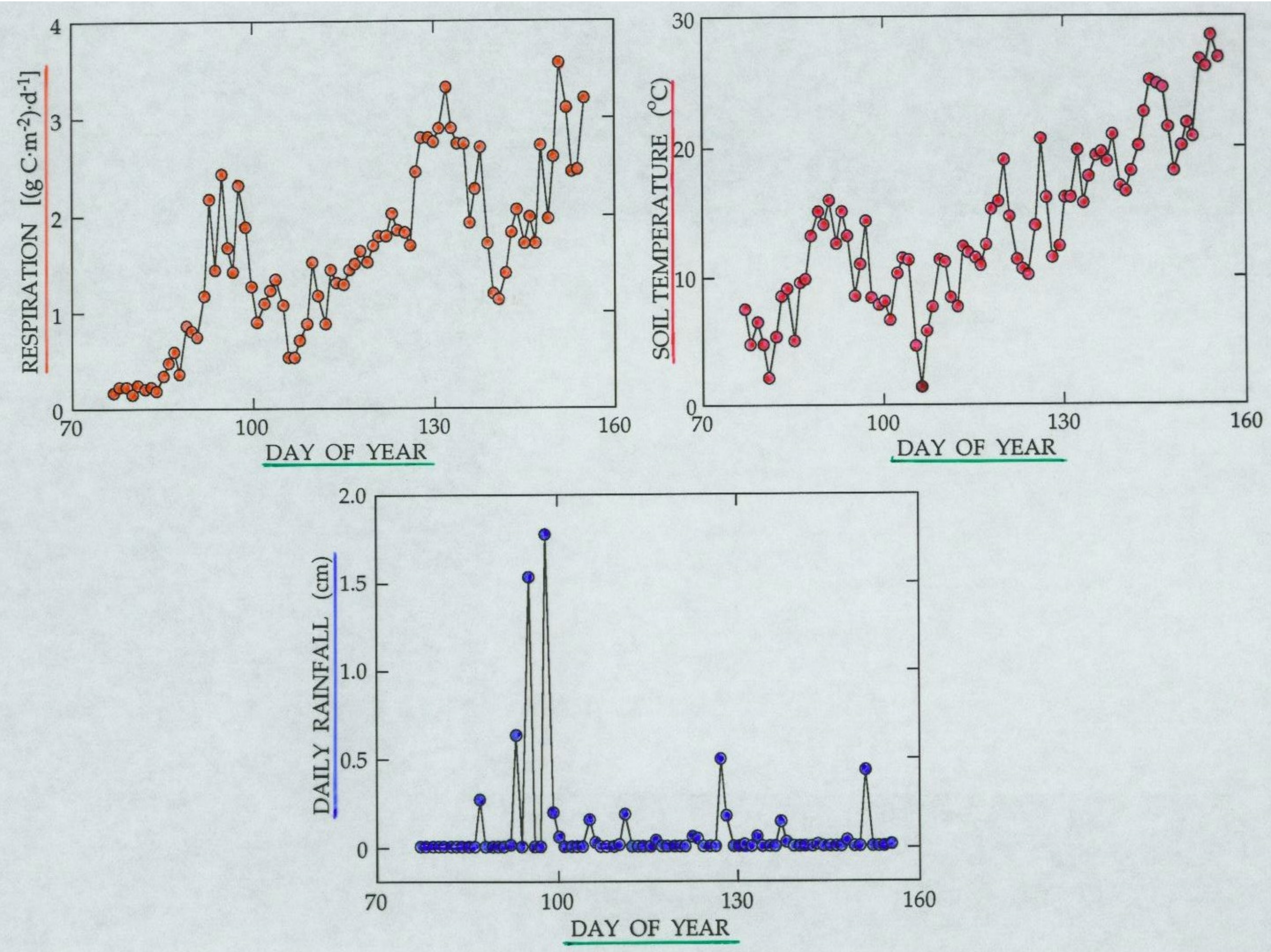


state-space respir & airT

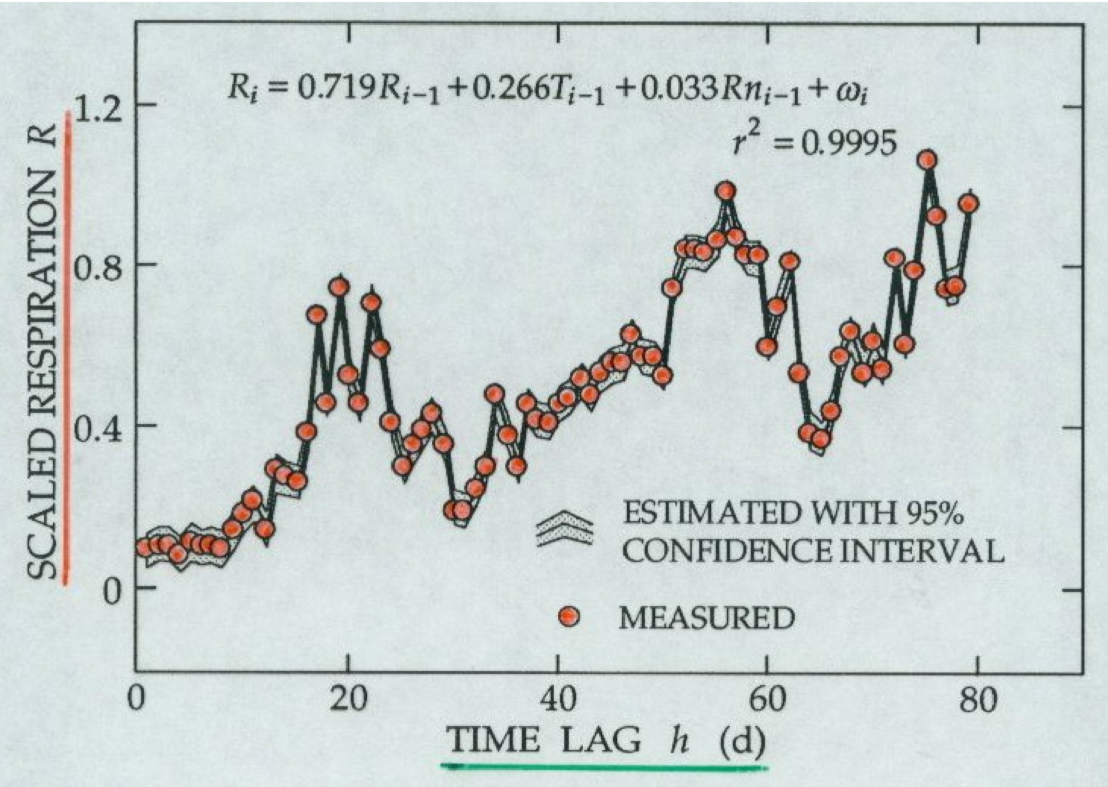


RESPIRATION, SOIL TEMPERATURE AND RAINFALL

respiration, temperature & rain data



state-space respiration, temperature & rain



Thus Far, next step

THUS FAR

- STATE VARIABLES SELECTED UPON AGRONOMIC EDUCATION, EXPERIENCE AND INTUITION
- EXPECTED STATE VARIABLES TO BE IMPORTANT AND CORRELATED
- HAD CORRELATIONS NOT BEEN FOUND, DIFFERENT VARIABLES SELECTED BY TRIAL AND ERROR

NEXT STEPS

- INVOKE PHYSICALLY BASED EQUATIONS INTO THE STATE-SPACE ANALYSIS
- BE GUIDED BY PROVEN EQUATIONS EXPRESSING PROCESSES OF KNOWN CHEMICAL, PHYSICAL AND BIOLOGICAL IMPORTANCE.
- TRANSFORM EQUATIONS DESCRIBING PROCESSES IN THE TOPSOIL OF A FARMER'S FIELD INTO STATE-SPACE FORMULATIONS.
- SIMULTANEOUSLY EXAMINE EQUATIONS AND THEIR PARAMETERS FOR BETTER UNDERSTANDING AND IDENTIFICATION OF LOCAL, FUNCTIONALLY SIMILAR AREAS IN A FARMER'S FIELD

COMBINATION OF PHYSICAL EQUATION AND OBSERVATIONAL EQUATION

state-space outline

A PHYSICALLY DERIVED STATE-SPACE EQUATION SOLVED IN COMBINATION WITH AN OBSERVATION EQUATION

- A THEORETICAL EQUATION WITH AN ERROR TERM EXPLICITLY EMBRACING ASSUMPTIONS MADE IN ITS DERIVATION
- AN OBSERVATION EQUATION WITH AN ERROR TERM EXPLICITLY EMBRACING INSTRUMENTATION CALIBRATION AND SOIL HETEROGENEITY
- AN EXAMINATION OF THE FREQUENCY OF OBSERVATIONS MADE IN SPACE AND TIME RELATIVE TO THE VARIANCES OF THE ESTIMATED PARAMETERS OF THE THEORETICAL EQUATION

state-space eqn derivation

Let $Y(z, t)$ be a state variable (e.g. soil water content, temperature, pH, solute concentration)

$$\frac{\partial Y(z,t)}{\partial t} = -\frac{\partial q_Y(z,t)}{\partial z}$$

q_Y is the mass (or energy) flux density of the state variable and z and t are soil depth and time

Integrating from the soil surface to depth Z,

$$-\frac{\partial}{\partial t}\left[\int_0^Z Y(z,t)dz\right] = q_Y(Z,t) - q_Y(0,t)$$

Defining

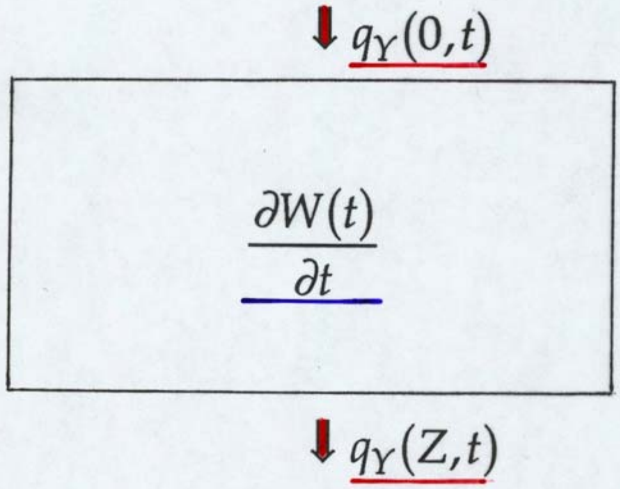
$$W(t) = \int_0^Z Y(z,t)dz$$

we have:

$$\frac{\partial W(t)}{\partial t} = q_Y(0,t) - q_Y(Z,t)$$

schematic physical eqn to state-space

Schematically,



- We assume that a relation between the state variable $Y(z, t)$ at depth Z and $W(t)$ is known

Hence,

$$\frac{dW(t)}{dt} = f[W(t)] + \varepsilon(t)$$

where ε is noise signifying the equation is not exact

state space formulation

STATE-SPACE FORMULATION

$$\frac{dX(t)}{dt} = f[X(t)] + \varepsilon(t)$$

$$Z_m(t_k) = X(t_k) + v(t_k) \qquad k=0,1,2,3,\cdots N$$

where $Z_m(t_k)$ is the measured value of the state variable X (that represents W) at a discrete time t_k and v is the measurement error

state-space K(theta) single location

Example - $K(\theta)$ from observations within a single profile.

Simplifying Richards' equation in terms of stored water W between the soil surface and depth b for redistribution of soil water after infiltration with no evaporation at the soil surface

$$\frac{\partial W}{\partial t} = -K(W)\left(\frac{\partial H}{\partial z}\right)_{z=b}$$

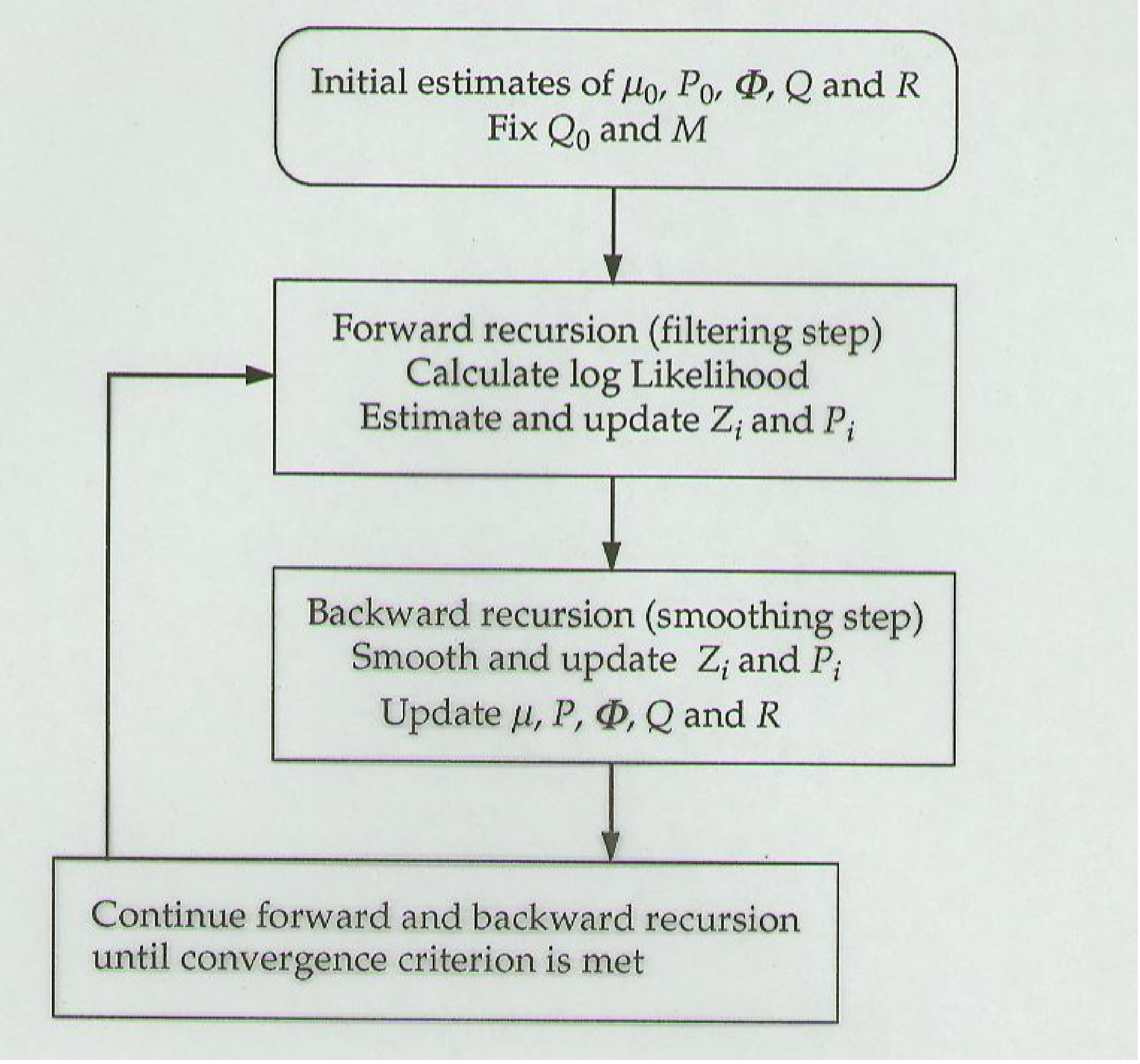
STATE-SPACE FORMULATION

$$X(t) = -A\exp[BX(t)]\left(\frac{\partial H}{\partial z}\right) + \varepsilon_s(t)$$

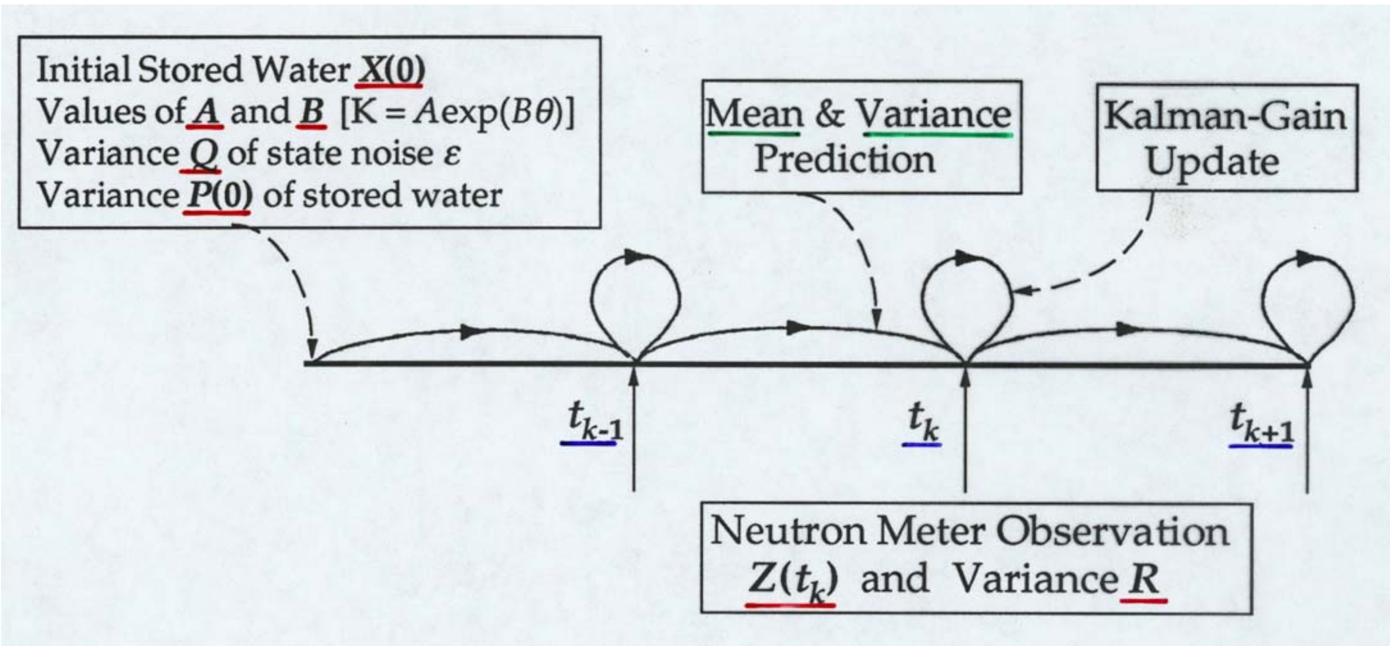
$$Z_m(t_k) = X(t_k) + v_m(t_k)$$

where $K(W)$ is of the form $A\exp(B\theta)$

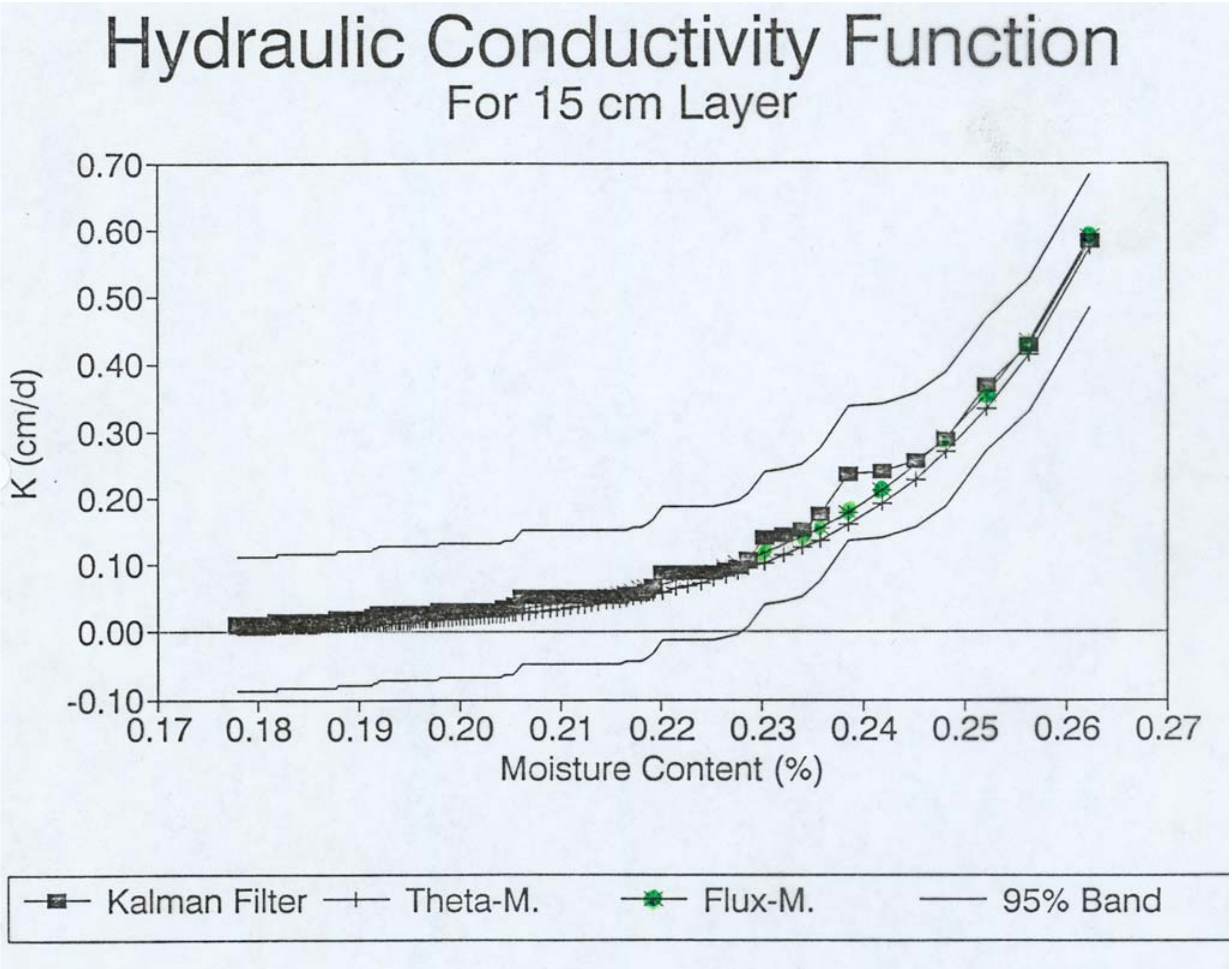
Kalman filter scheme



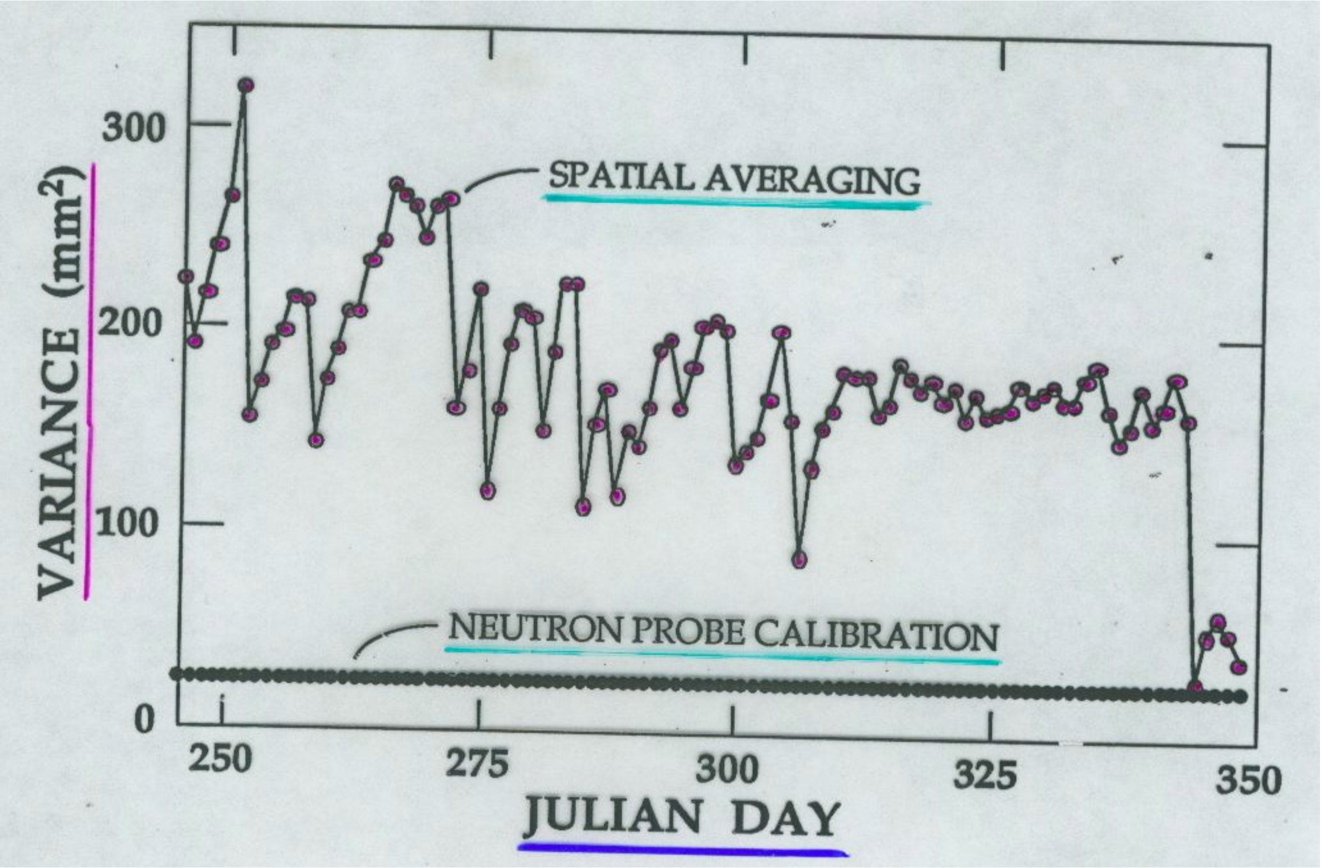
soil water kalman filter scheme



K(theta) with fiducial limits



variances of neutron meter & equation



irrigating slowly permeable soils

IRRIGATING SLOWLY PERMEABLE FIELD SOILS

ASSUME:

- SALT IS NOT TAKEN UP BY THE PLANT OR ABSORBED BY THE SOIL
- LEACHING ONLY OCCURS WHEN THE SOIL IS NEARLY WATER-SATURATED (A FINE-TEXTURED CLAY SOIL WITHOUT STRUCTURE)
- NO SOLUTES ARE IN THE RAIN WATER – ONLY IN THE IRRIGATION WATER

LET:

I = RATE OF IRIGATION (cm·yr^{-1})

P = Rainfall

E = EVAPOTRANSPIRATION

L = LEACHING FLUX DENSITY

AT DEPTH z BELOW ROOT ZONE, THE WATER BALANCE IS:

$$I + P - E = L$$

Long term salt

Example - Long-term solute dynamics in an irrigated soil (Rose et al., 1979).

Rate of change of salinity averaged over a soil profile of depth b is

$$b\overline{\theta}_S \frac{d\overline{C}}{dt} = q_0 C_0 - q_a C_a$$

where $\overline{\theta}_S$ and $\overline{C}$ are the saturated soil water content and soil solute concentration, q_0 the average water flux density at the soil surface caused by irrigation, C_0 the average solute concentration of the irrigation water, q_a the soil water flux density at the bottom of the profile and C_a the soil solute concentration at depth b.

Assume that values of b, $\overline{\theta}_S$, q_0 and C_0 are deterministically known and reliably measured.

Values of q_a C_a and $\overline{C}$ are not reliably known.

state-space formulation slowly permeable

- Assuming $q_a C_a$ is some function of $\overline{C}$,

$$b\overline{\theta}_S \frac{d\overline{C}}{dt} = q_0 C_0 - A\left[1 - \exp\left(B\overline{C}\right)\right]$$

- We seek values of $\overline{C}$ from our field measurements

STATE-SPACE FORMULATION

$$X_t = \frac{q_0 C_0 - A\left[1 - \exp\left(B X_t\right)\right]}{b\overline{\theta}_S} + v_S$$

Solving for A and B, the rate at which solute leaves the profile is known

state-space thermal diffusivity

Example - The thermal diffusivity λ from observations within a soil profile.

Starting with

$$\frac{\partial(cT)}{\partial t} = \frac{\partial}{\partial z}\left[\lambda \frac{\partial T}{\partial z}\right]$$

$$\int_0^b \left[\partial(cT) / \partial t\right] dz = -\left(\lambda \frac{\partial T}{\partial z}\right)\Bigg|_{z=0}$$

$$b\bar{c}\frac{d\bar{T}}{dt} = A\exp\left(B\bar{T}\right)$$

STATE-SPACE FORMULATION

$$X_t = \frac{A\exp(BX_t)}{b\bar{c}} + v_S$$

$$Z_m(t_k) = X(t_k) + v(t_k) \qquad k=0,1,2,3,\cdots N$$

Here, the stochastic state variable X_t represents the average soil temperature $\bar{T}$, and Z_m is the average soil temperature from therocouple measurements

state-space D(theta) several locations

Example - $D(\theta)$ from observations within several profiles.

Water stored $S(t)$ within a soil profile from depths 0 to b was measured daily with a neutron meter during evaporation from a bare soil during a period 100 days at 5 locations along a 75-m transect. Fifteen small irrigations (each < 20 mm) were applied between 4 Sept. to 12 Dec.

With the gravitational force neglected

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[D(\theta)\frac{\partial \theta}{\partial z}\right]$$

$$E_t = \frac{\pi^2 S D(S/b)}{4b^2} \qquad for \quad \frac{Dt}{b^2} > 0.3$$

$$\frac{dS}{dt} = P_t - \left(\frac{\pi}{2b}\right)^2 S D(S)$$

state-space formulation of diffusivity

STATE-SPACE FORMULATION

For an exponential diffusivity function $D(S/b) = A\exp(BS/b)$,

$$X_t = P_t - \left(\frac{\pi}{2b}\right)^2 X_t A\exp(BX_t/b) + v_S$$

$$Z_m(t_k) = X_{t_k} + v_m(t_k)$$

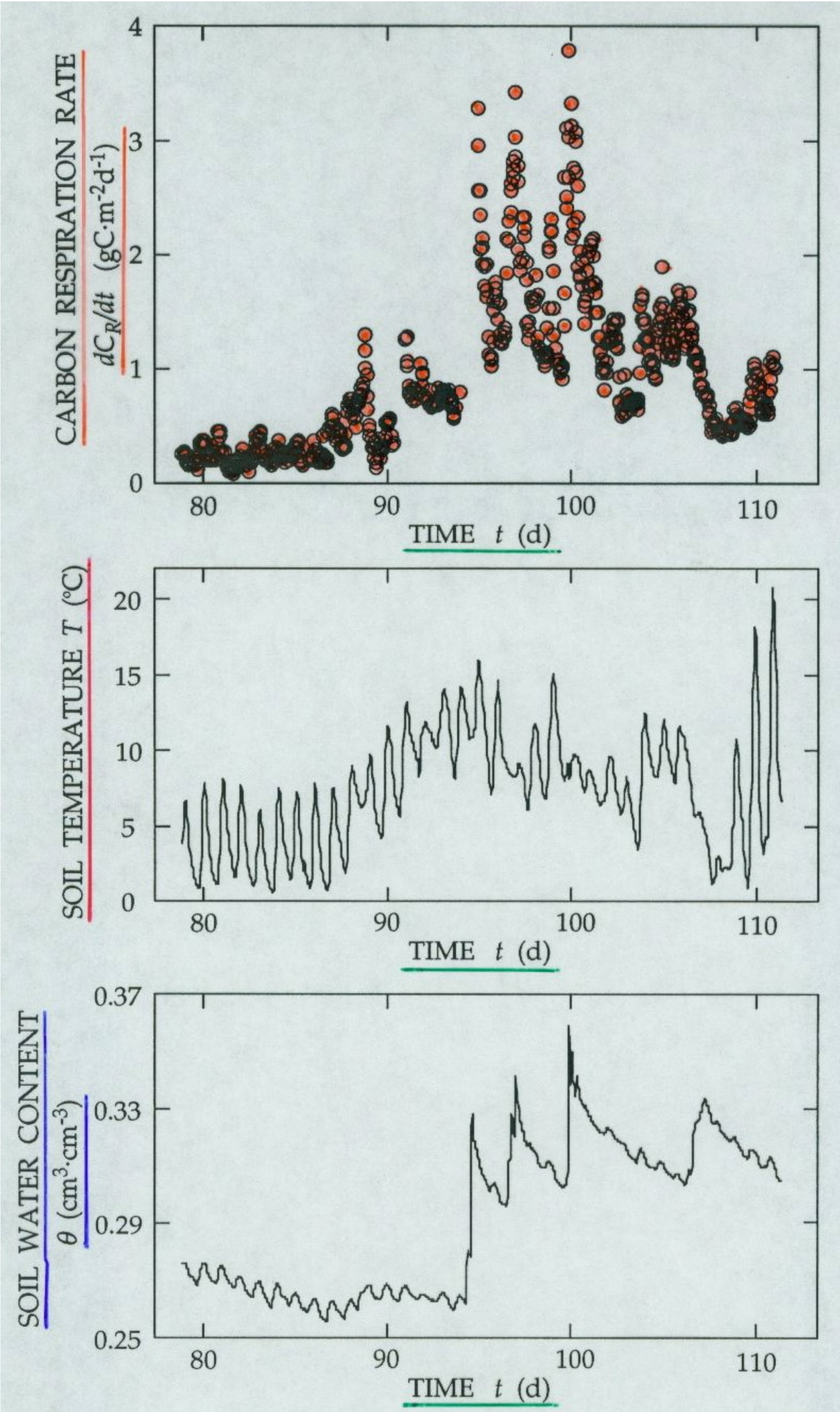
RESPIRATION

SOIL TEMPERATURE

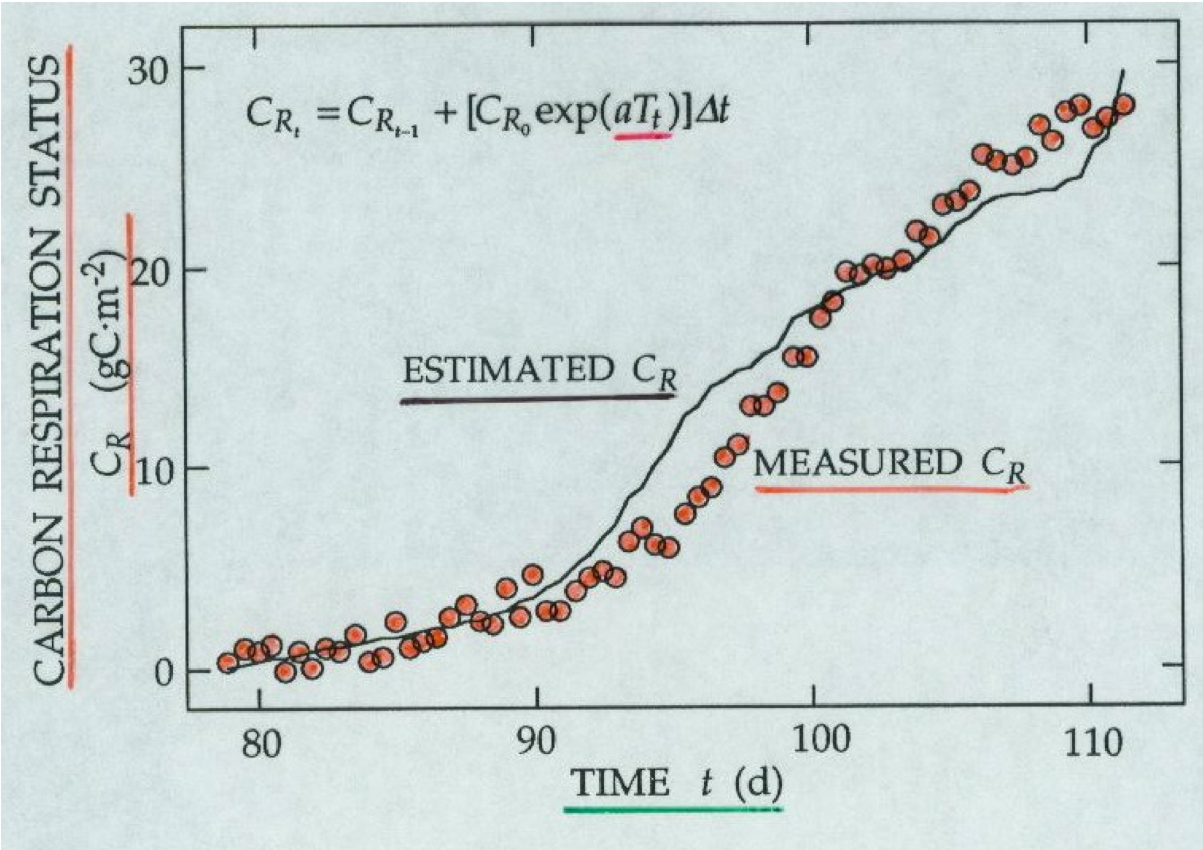
AND

SOIL WATER CONTENT

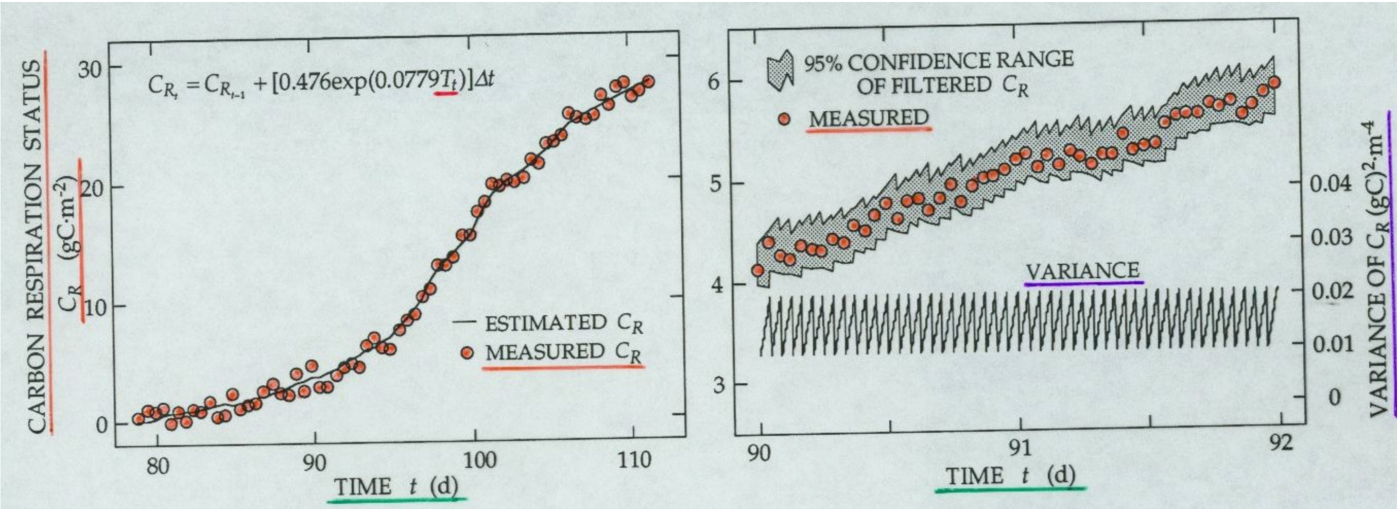
respiration, Temp & theta data



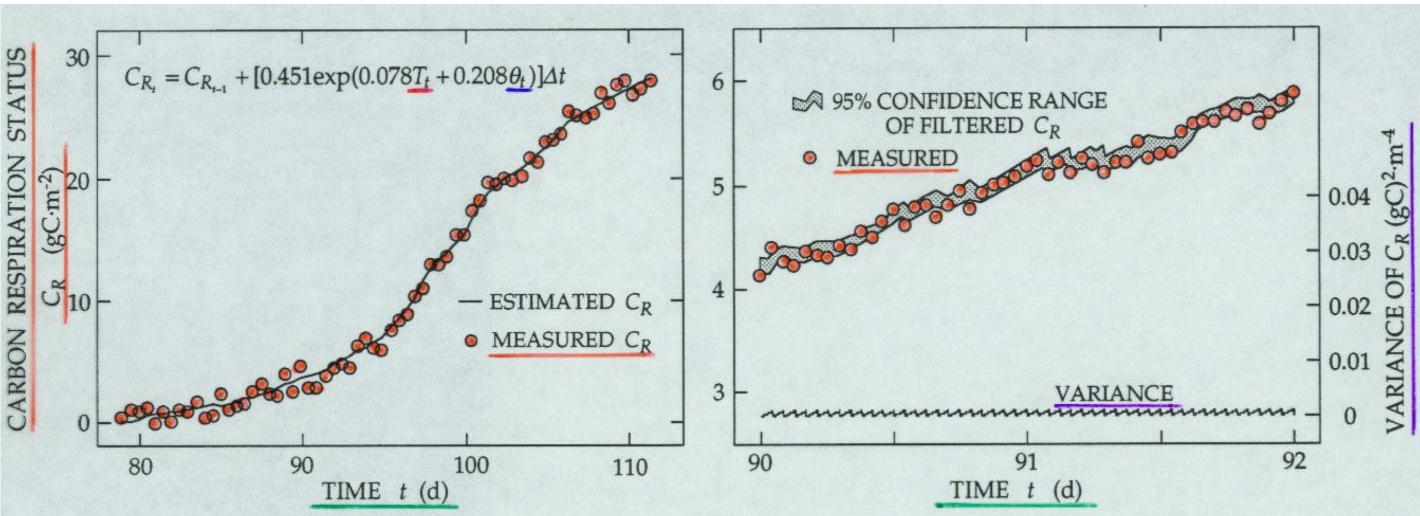
respiration versus Temp



state space respiration versus Temp



state space respir vs T, q

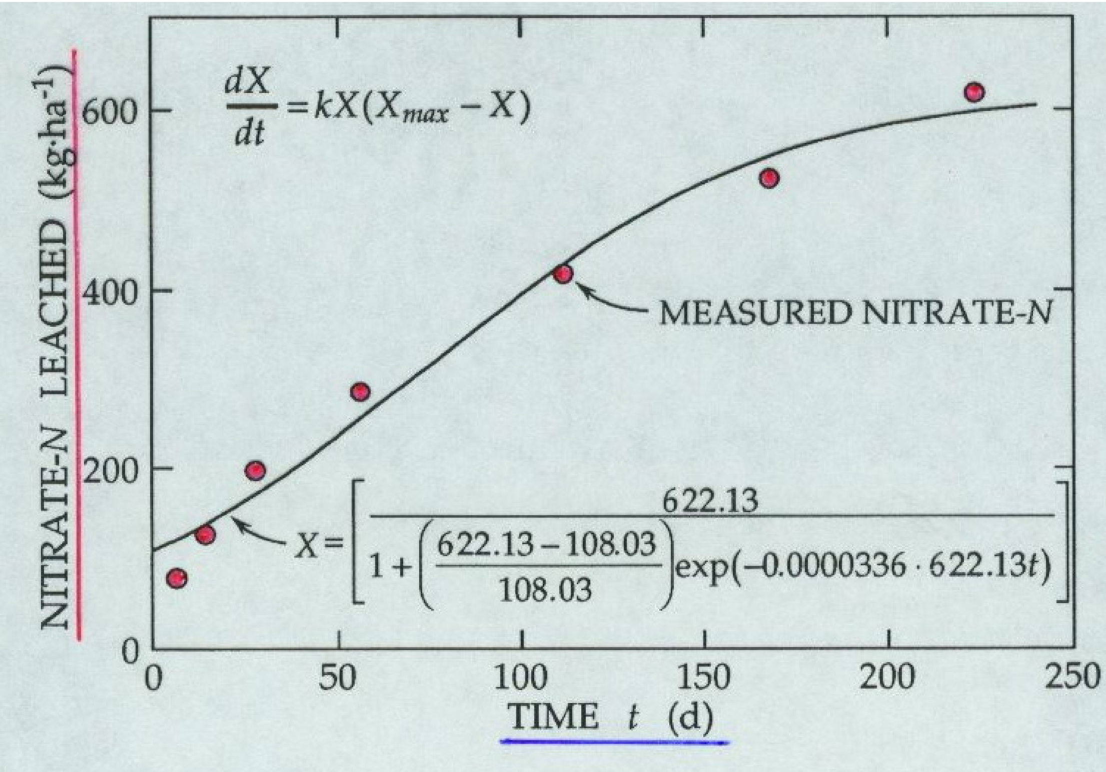


TIME SERIES

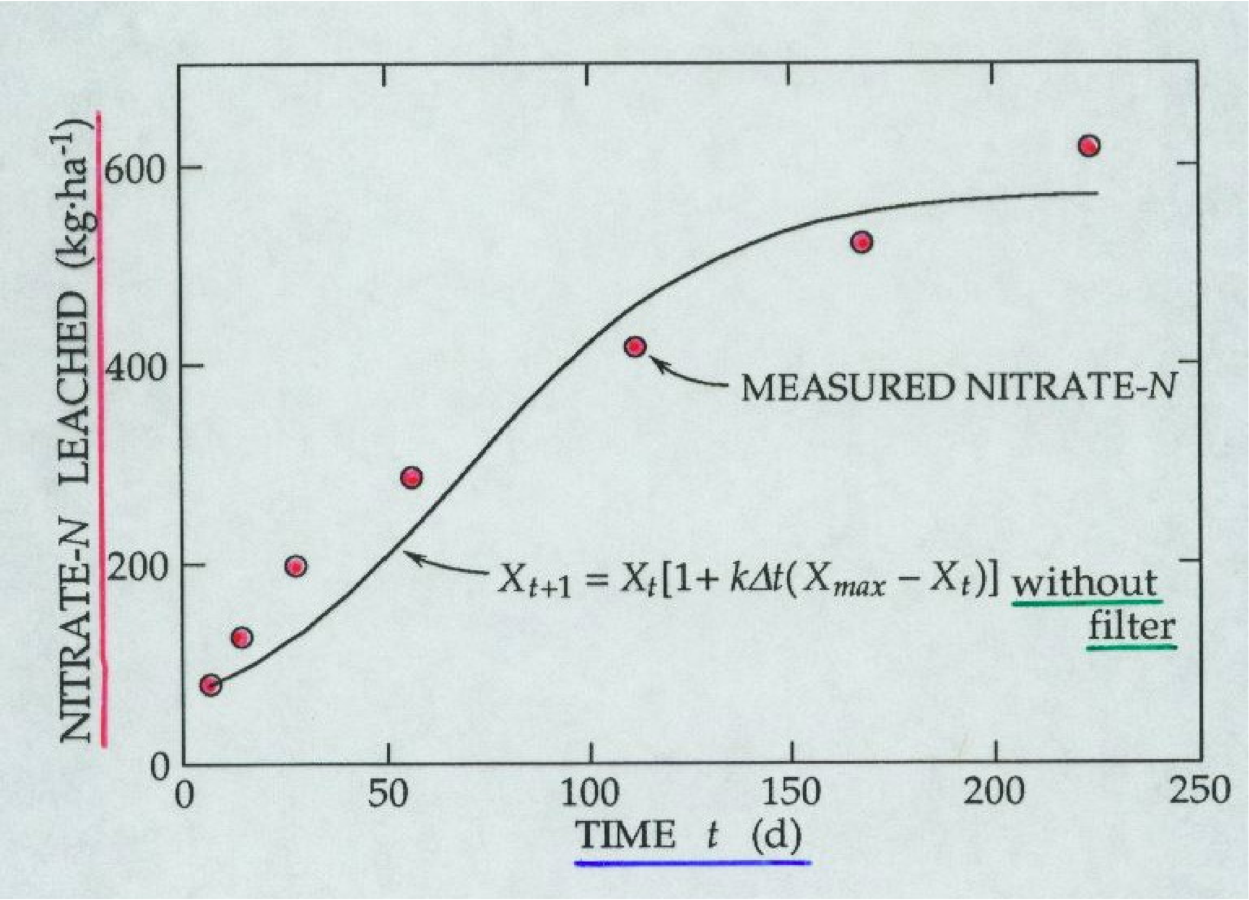
OF

SOIL NITROGEN MINERALIZATION

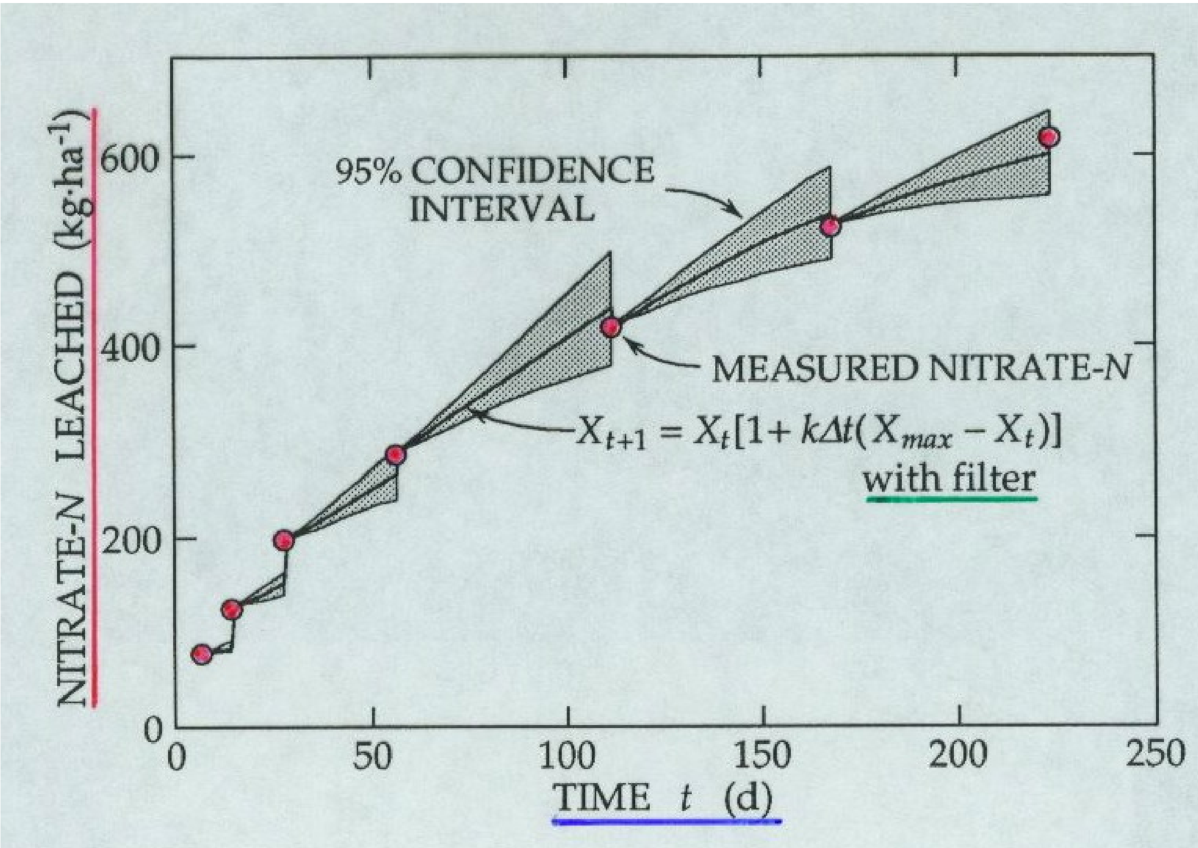
N leaching analytic equation



N leaching no filter



N leaching with filter



WATER WITH

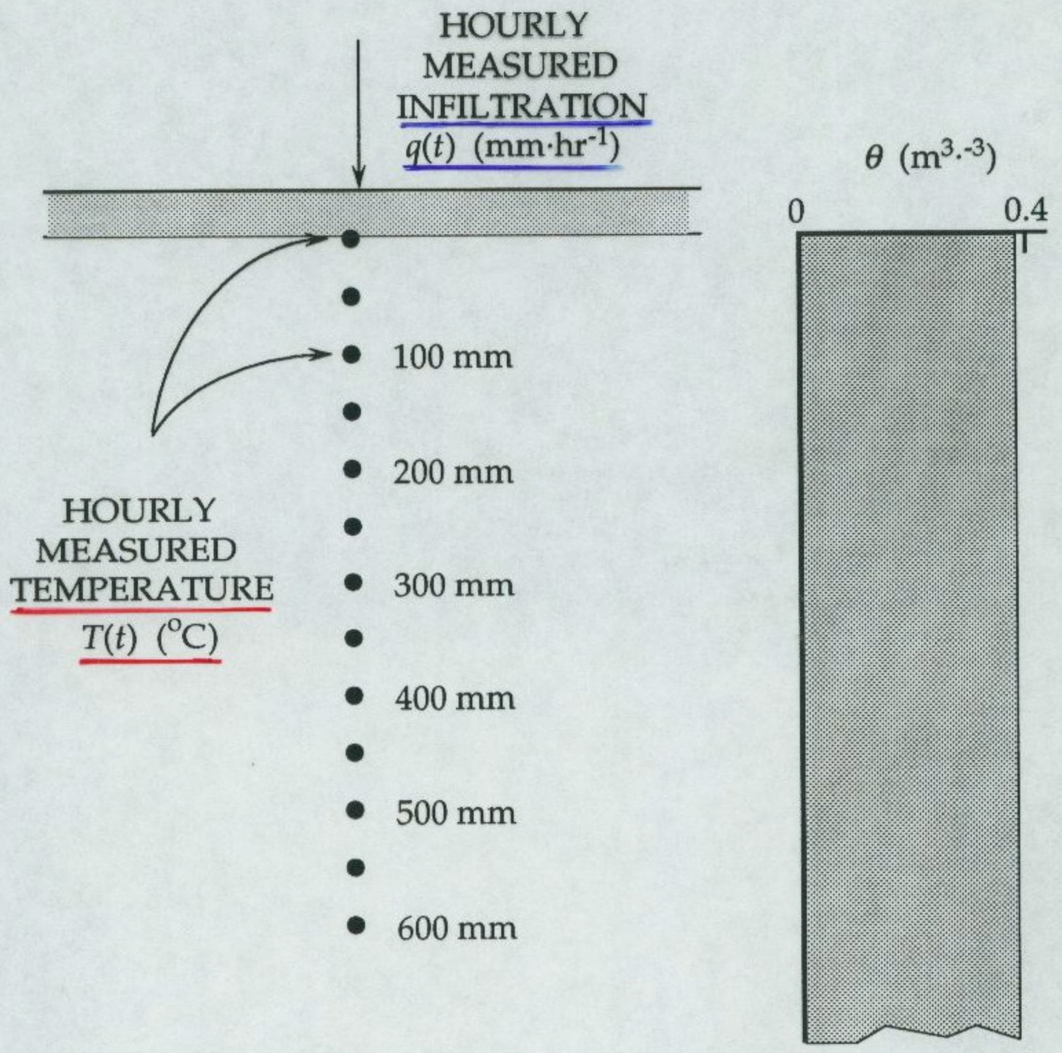
DAILY TEMPERATURE FLUCTUATIONS

INFILTRATING

THE

SOIL SURFACE

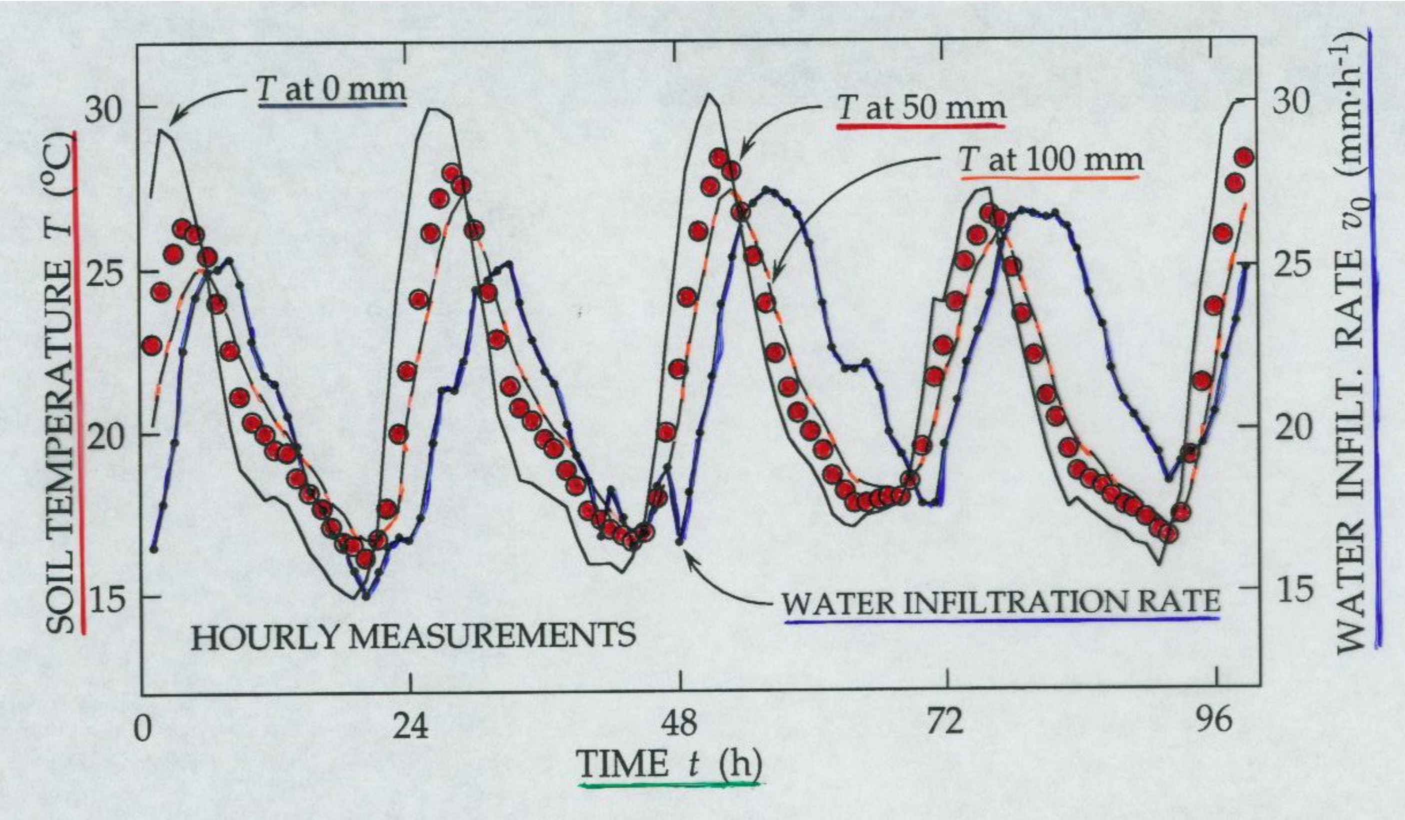
infiltrating water field expt



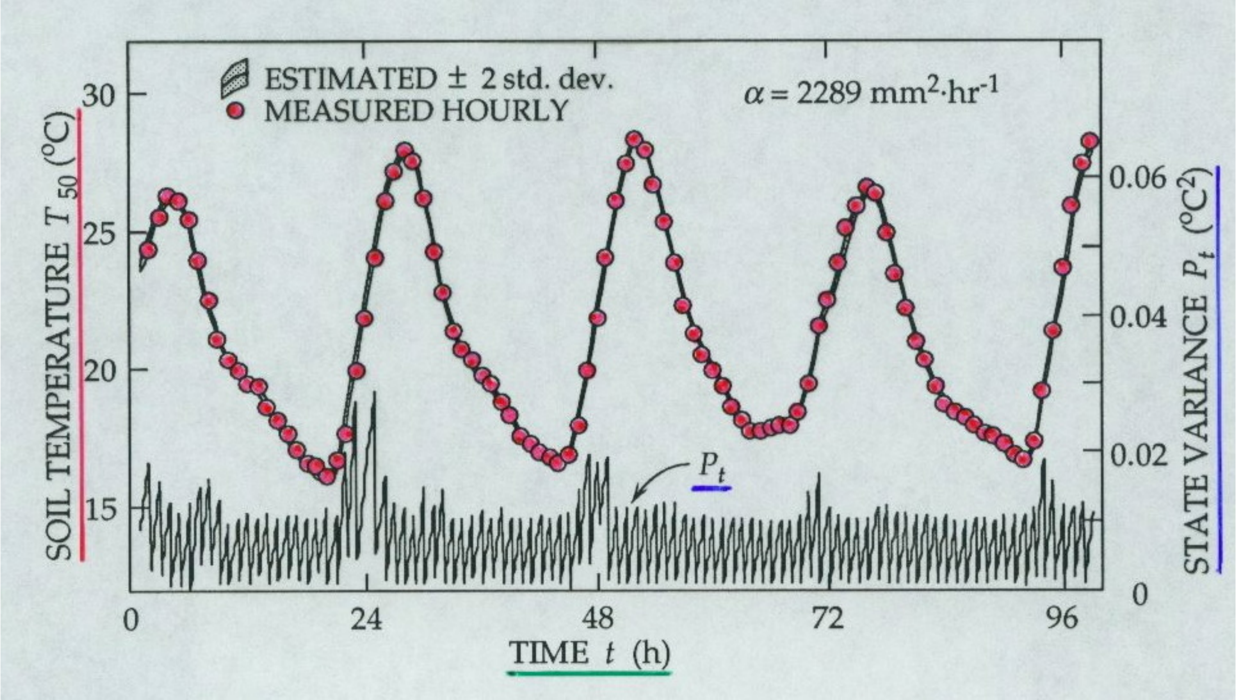
$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2} - \beta \frac{\partial T}{\partial z}$$

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left[\left(a + bv^{n}\right)\right] - \beta \frac{\partial T}{\partial z}$$

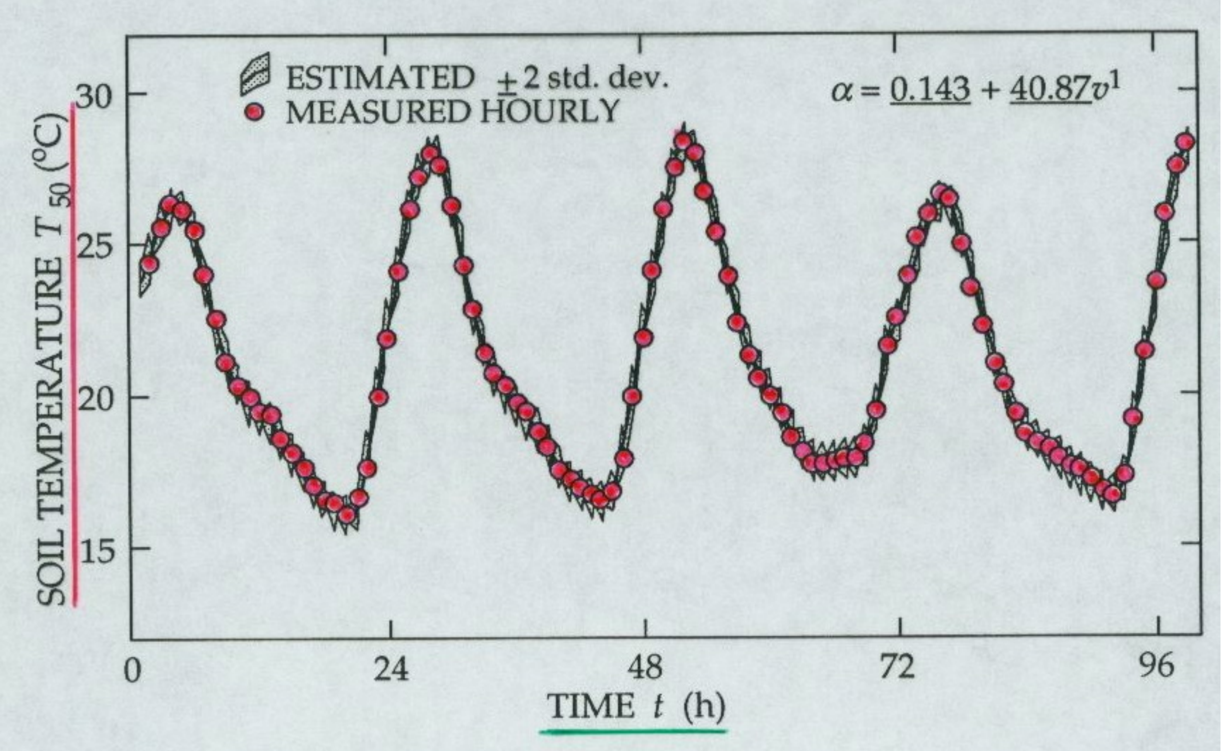
infiltrating water data

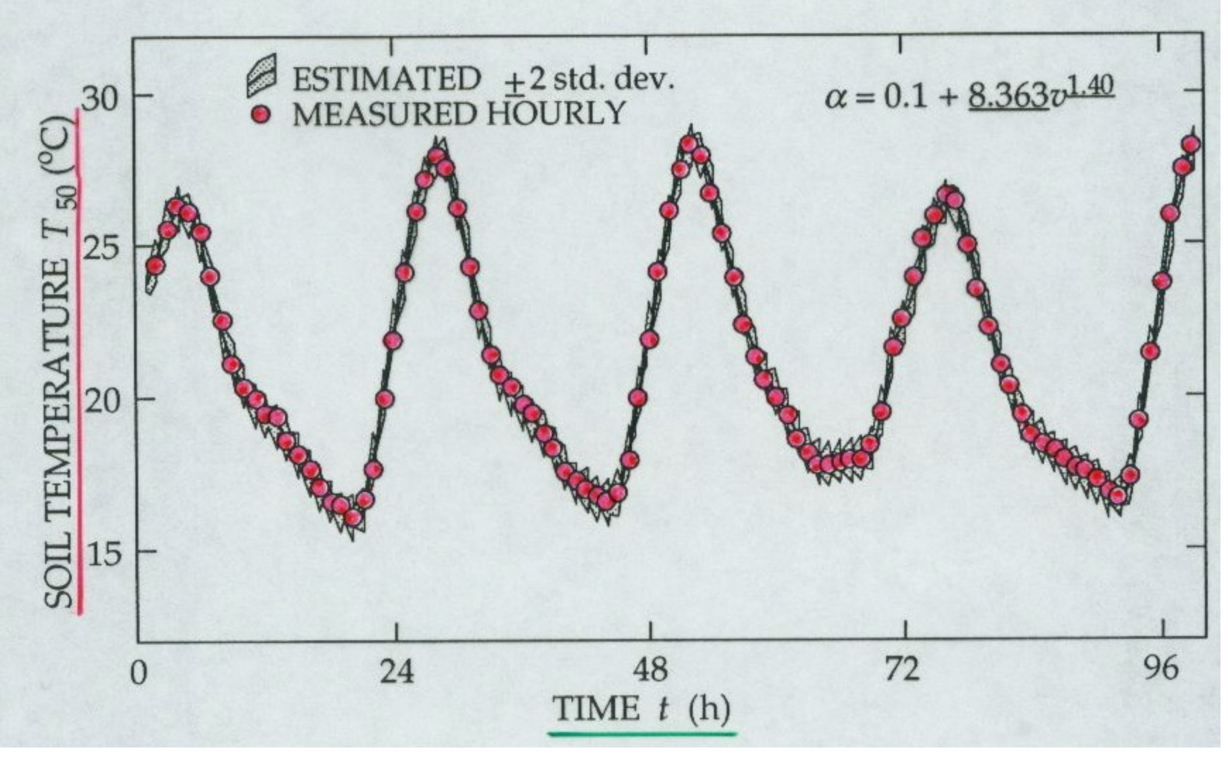


infiltrating constant diffusivity alpha



infiltrating variable alpha with a,b,n





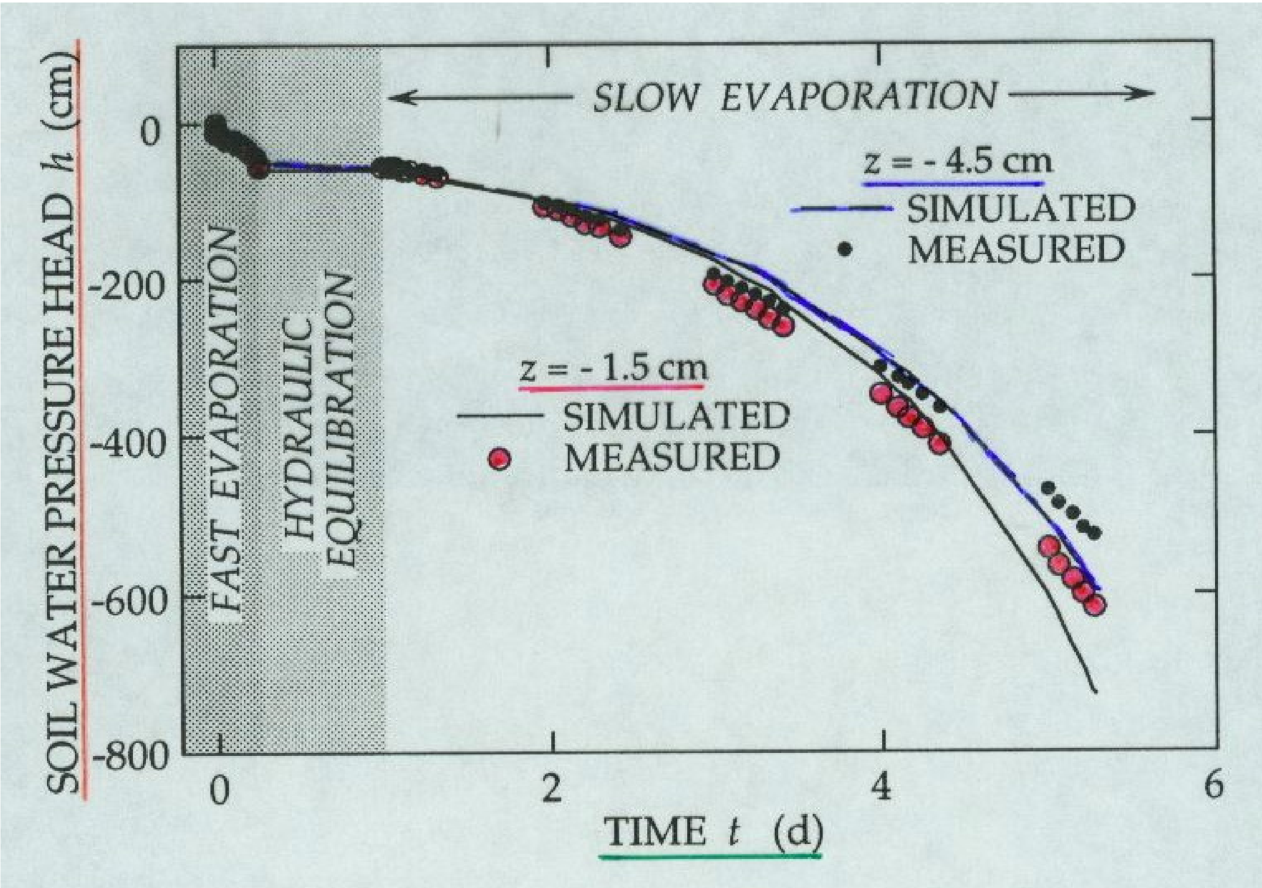
temp table

Optimization results for the three different scenarios of soil temperature and water infiltration data (Jaynes,1990).

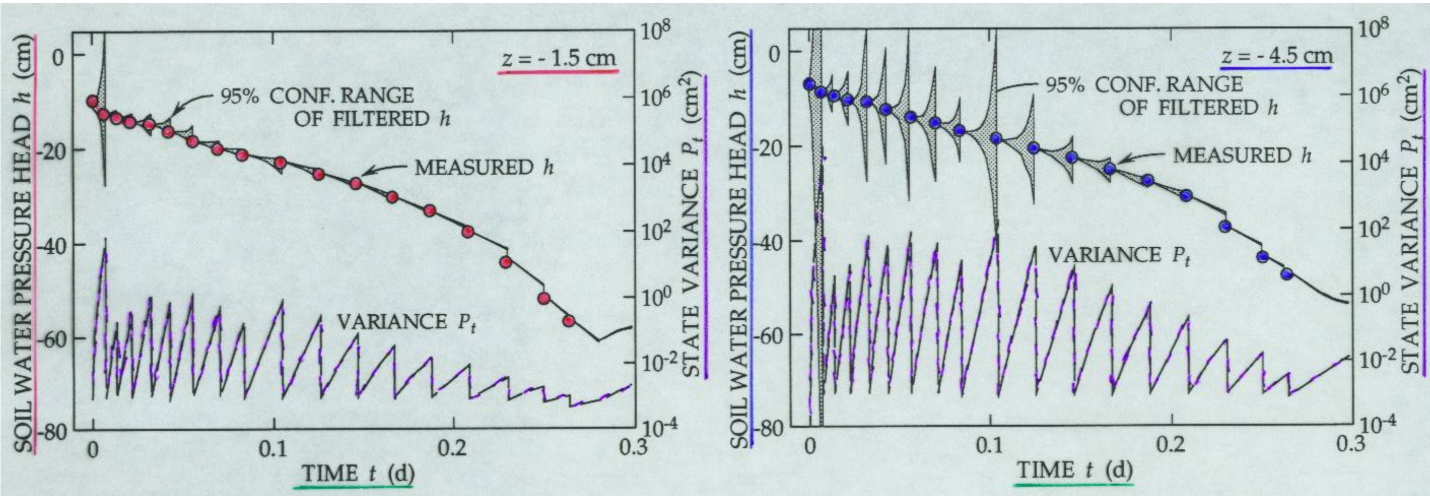
Scenario	α ($mm^2 \cdot hr^{-1}$)		OF ($°C^2$)
constant α	2289		7.174
$\alpha = a + bv$	a	b	
	0.143	40.87	5.146
$\alpha = 0.1 + bv^n$	b	n	
	8.363	1.40	4.643

ESTIMATING UNSATURATED SOIL HYDRAULIC CONDUCTIVITY USING THE EVAPORATION METHOD ON SOIL CORES IN THE LABORATORY

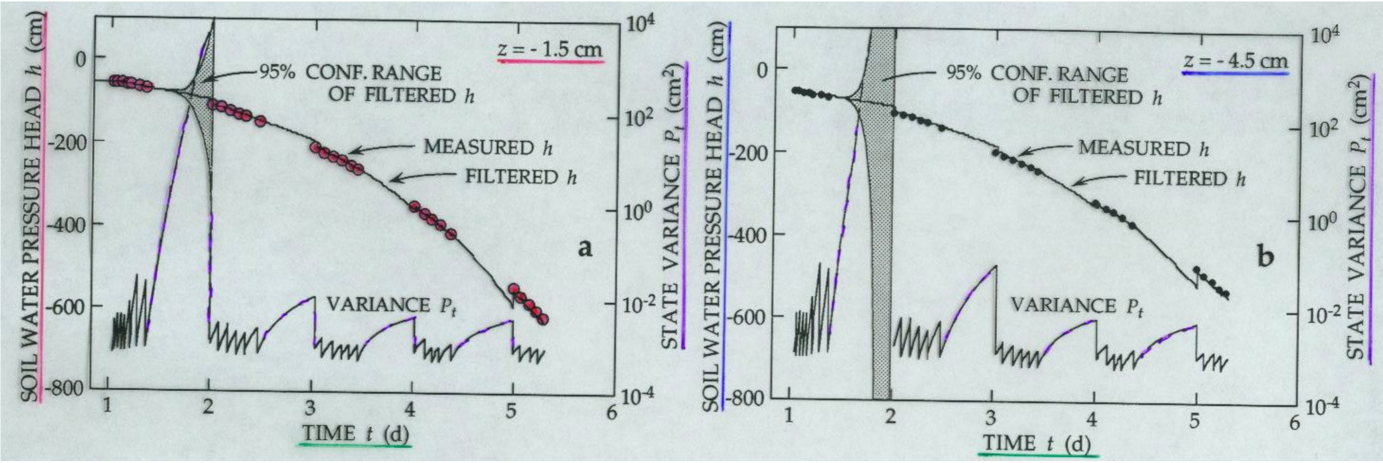
inverse simulation pressure



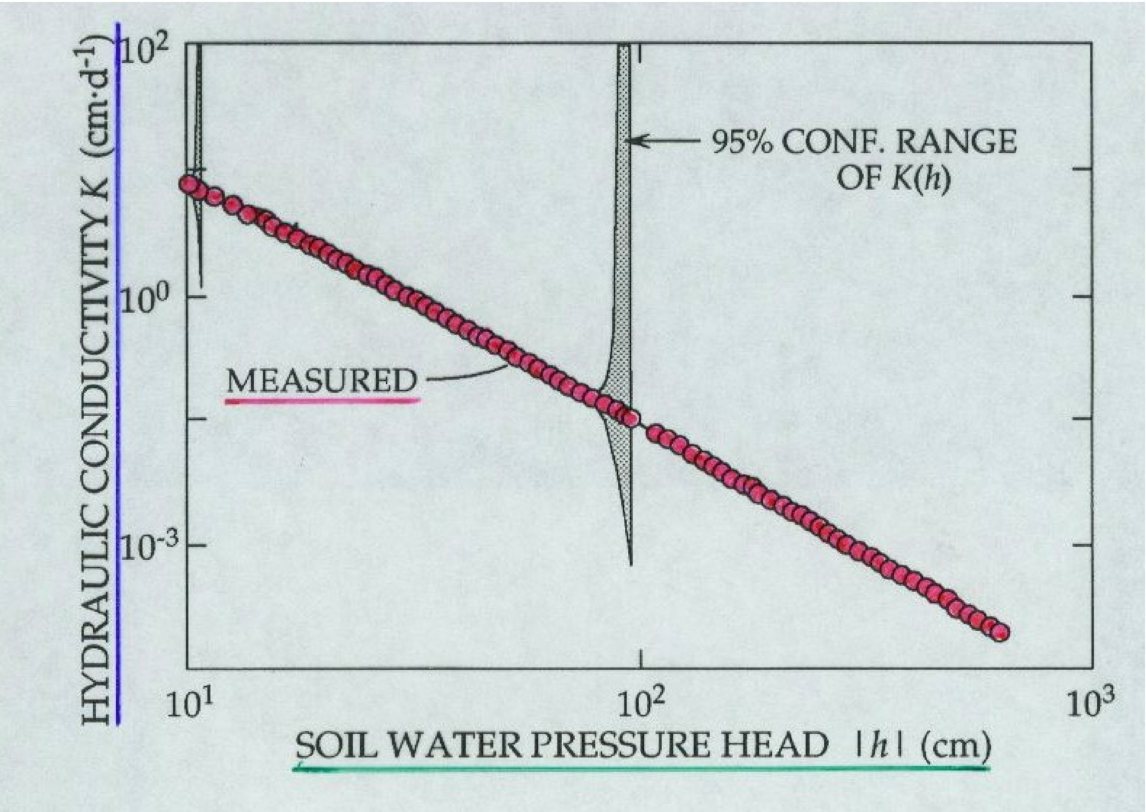
state-space press hrs



state-space press days

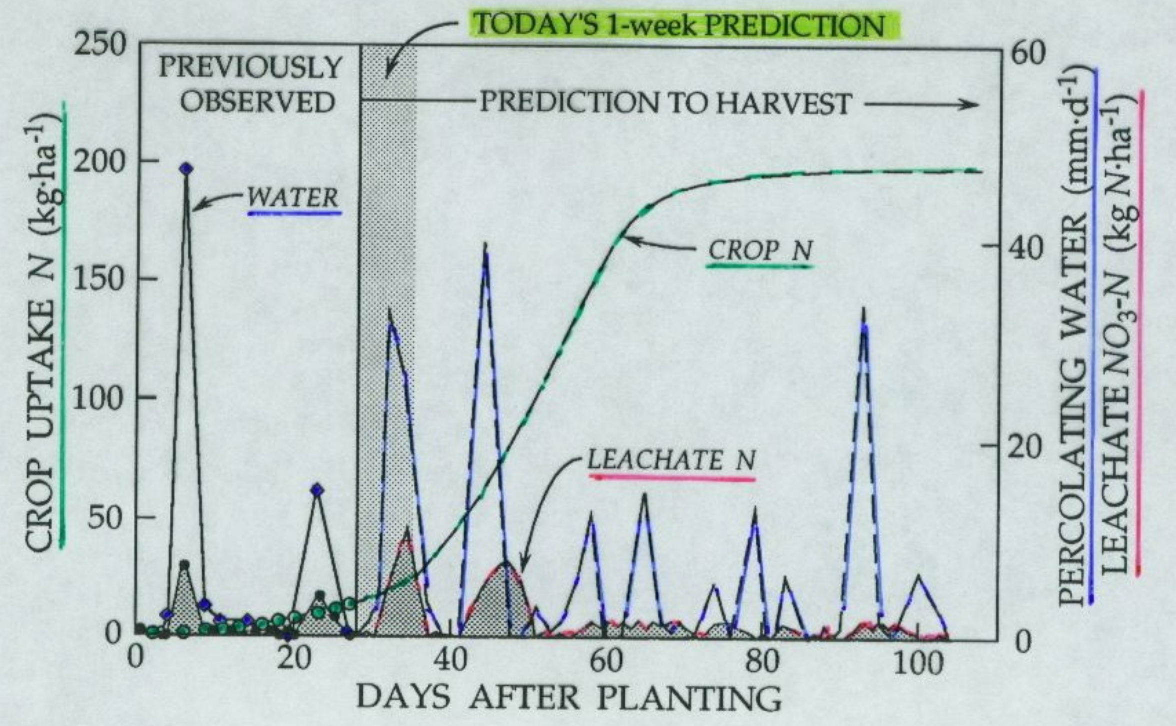


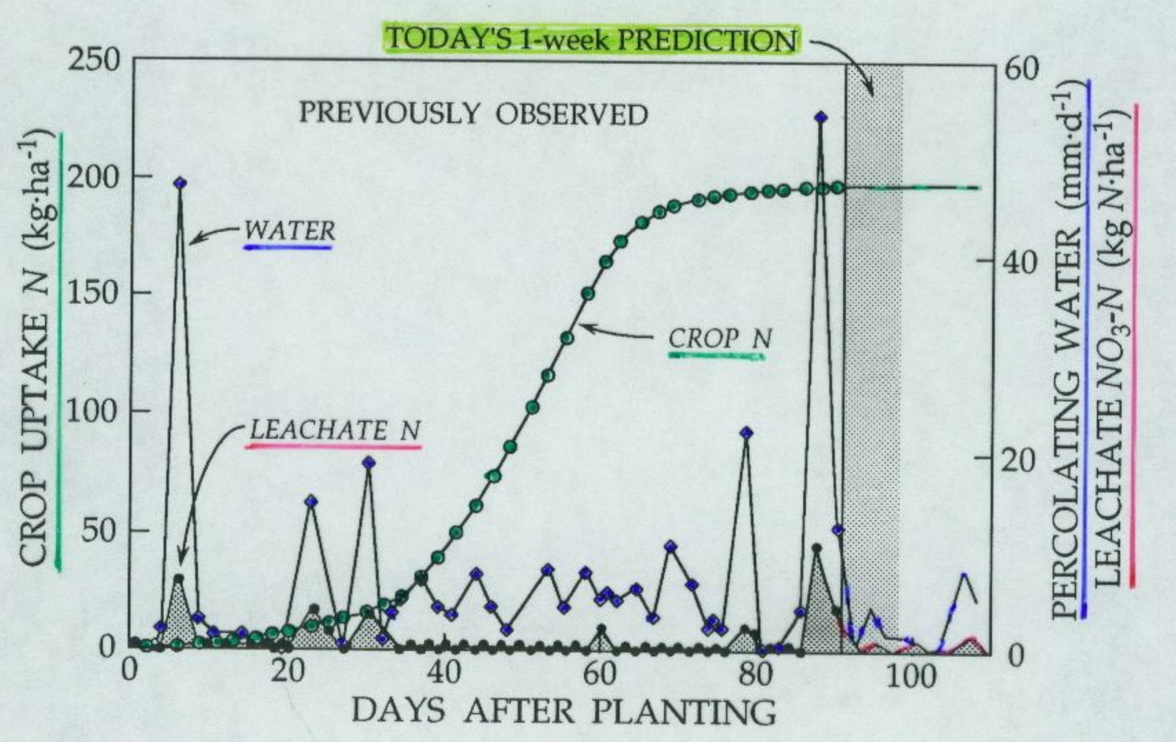
K vs theta


HYDRAULIC CONDUCTIVITY K (cm·d-1)
SOIL WATER PRESSURE HEAD |h| (cm)
95% CONF. RANGE OF K(h)
MEASURED
10^2
10^0
10^-3
10^1
10^2
10^3

MANAGEMENT-ORIENTED MODELING

Manage-Oriented-Modeling





advantages of st space approach

ADVANTAGES OF STATE-SPACE APPROACH

Regardless of the instrument or field sampling technique used to observe a soil physical, chemical or biological process, most samples represent some sort of depth-averaged value.

- Hence, it is not only convenient but more correct to use equations that describe depth-averaged phenomena.
- In the future we envision state-space equations to be used in other disciplines of soil science. The development of soil horizons, growth and water extraction of plant roots, and soil depths over which microbiologically-induced and chemical reactions predominantly occur are some examples.
- We also expect that progress could be made using time-averaged equations to examine critical periods during which soil processes occur.

advantages of st.space

ADVANTAGES OF STATE-SPACE APPROACH

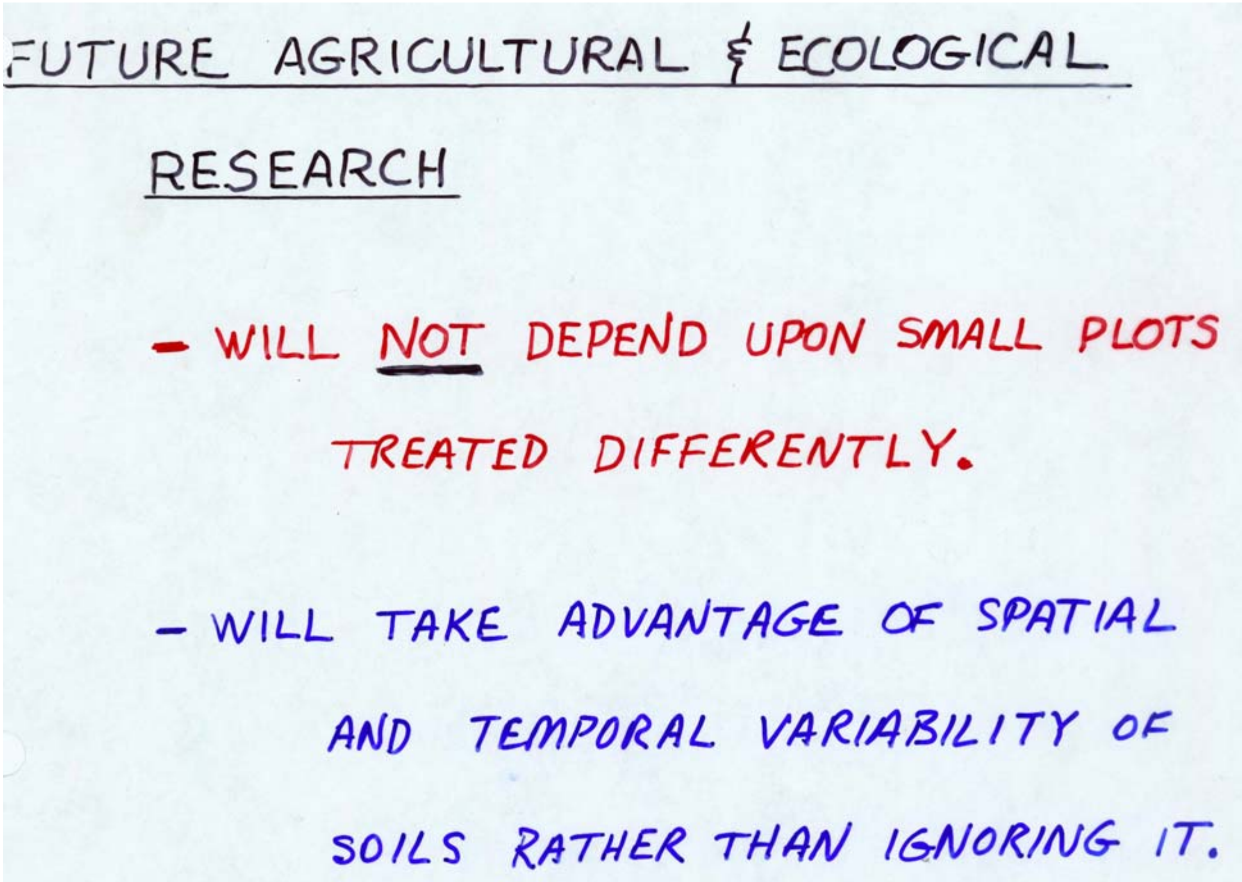
- Explicit acknowledgment that the equation is definitely approximate and contains a model error.

- Explicitly solving for the model variance, and through its examination, ascertain the impact of simplifications, and identify improvements for a more realistic equation.

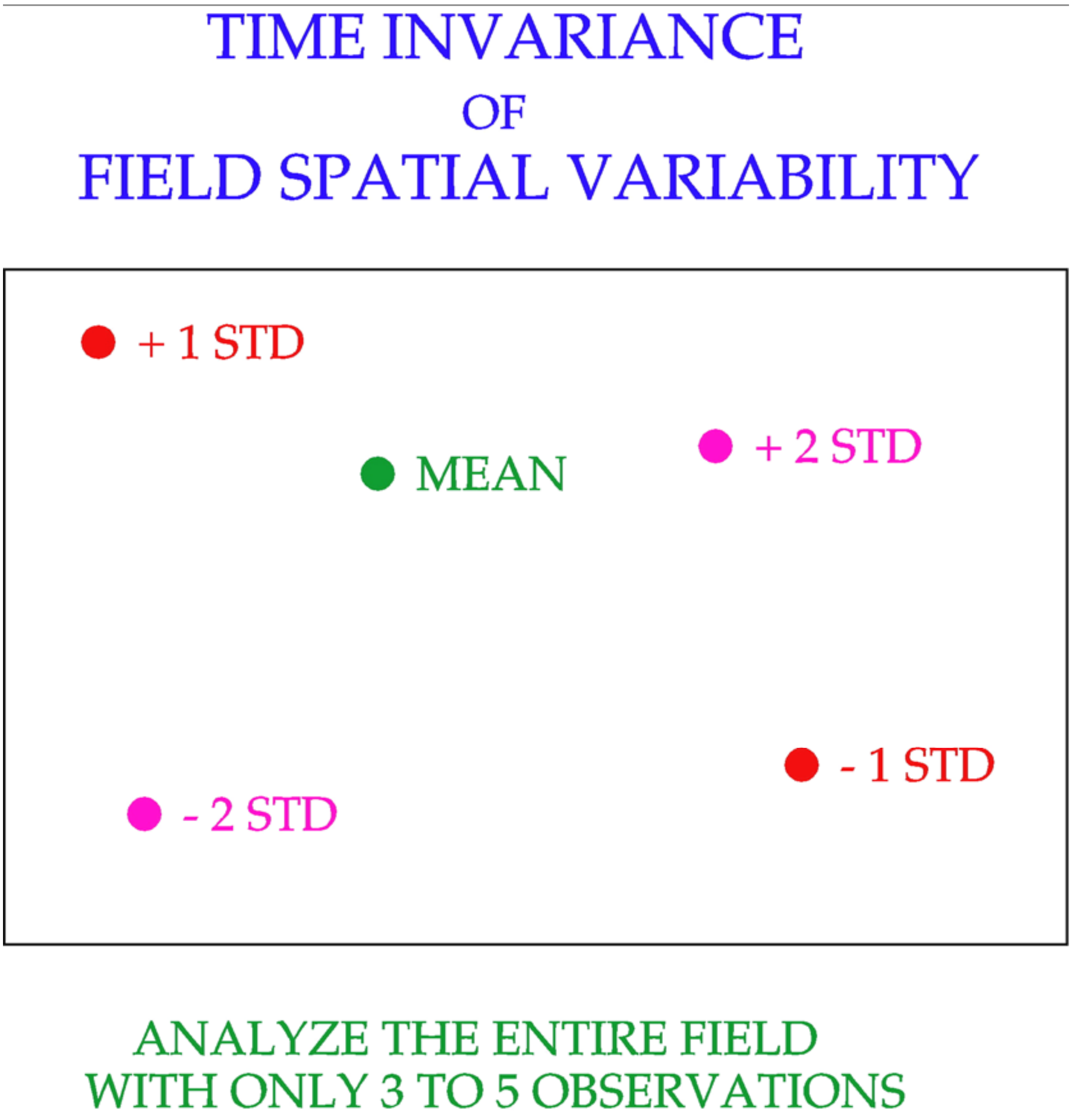
- The inclusion of an observation error. It can be treated as a known and measured quantity or alternatively, treated as an unknown.

  - A known observation error allows a reconsideration of the state variable in the equation or an improvement in instrumentation or calibration.
  - Treating the observation error as an unknown, its behavior in space and time can be related to spatial and temporal correlation lengths.

future agr. Research dependence



Time invariance



future

Future work

- Characterize soil properties in relation to soil mapping units
- Ascertain spatial and temporal variance structures within soil mapping units
- Examine spatial and temporal covariances between soil parameters and agroecological parameters
- Develop ability to translate from one space or time scale to another
- Shift from deterministic to stochastic methods to improve our technology to manage natural resources

Develop field technology to answer:

- What sample size?
- How many samples?
- How far apart?
- How often?

achievements

WHAT DO WE HOPE TO ACHIEVE ?

– TODAY	SUSTAINABLE AGRICULTURE AND QUALITY ENVIRONMENT
– YESTERDAY	BIOTECHNOLOGY AND CULTIVAR DEVELOPMENT
– LAST WEEK	FOOD PRODUCTION
– LAST CENTURY	FOOD & HEALTH FOR CIVILIZATION
– LAST MILLENIUM	?
– LAST 300 MILLENIA	*ACHIEVMENTS OF CIVILIZATION* V. GORDON CHILDE (1882 – 1957)

1. IRRIGATION
2. THE PLOW
3. HARNESSING ANIMAL POWER
4. SAILING BOATS
5. WHEELED VEHICLES
6. ORCHARD HUSBANDRY
7. FERMENTATION
8. PRODUCTION & USE OF COPPER
9. BRICKS
10. THE ARCH
11. GLAZING
12. CONFIDENTIAL SEAL OF A LETTER
13. SOLAR CALENDAR
14. ALPHABET
15. WRITING
16. NUMERICAL NOTATION
17. PRODUCTION OF BRONZE
18. SMELTING IRON
19. AQUEDUCTS FOR CITY WATER
20. ? ? ?

20th Achievement

20TH ACHIEVEMENT OF CIVILIZATION

A GLOBAL POPULATION SUFFICIENTLY EDUCATED

TO

MANAGE ITS CONTINENTAL RESOURCES

WITHOUT SOIL EXHAUSTION

AND

WITH SUSTAINED WATER QUALITY

doggie

"FUTURE SOIL PHYSICIST"