The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

1867-37

College of Soil Physics

22 October - 9 November, 2007

Soil physics - some of the past and today's primary opportunities

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Past and Present

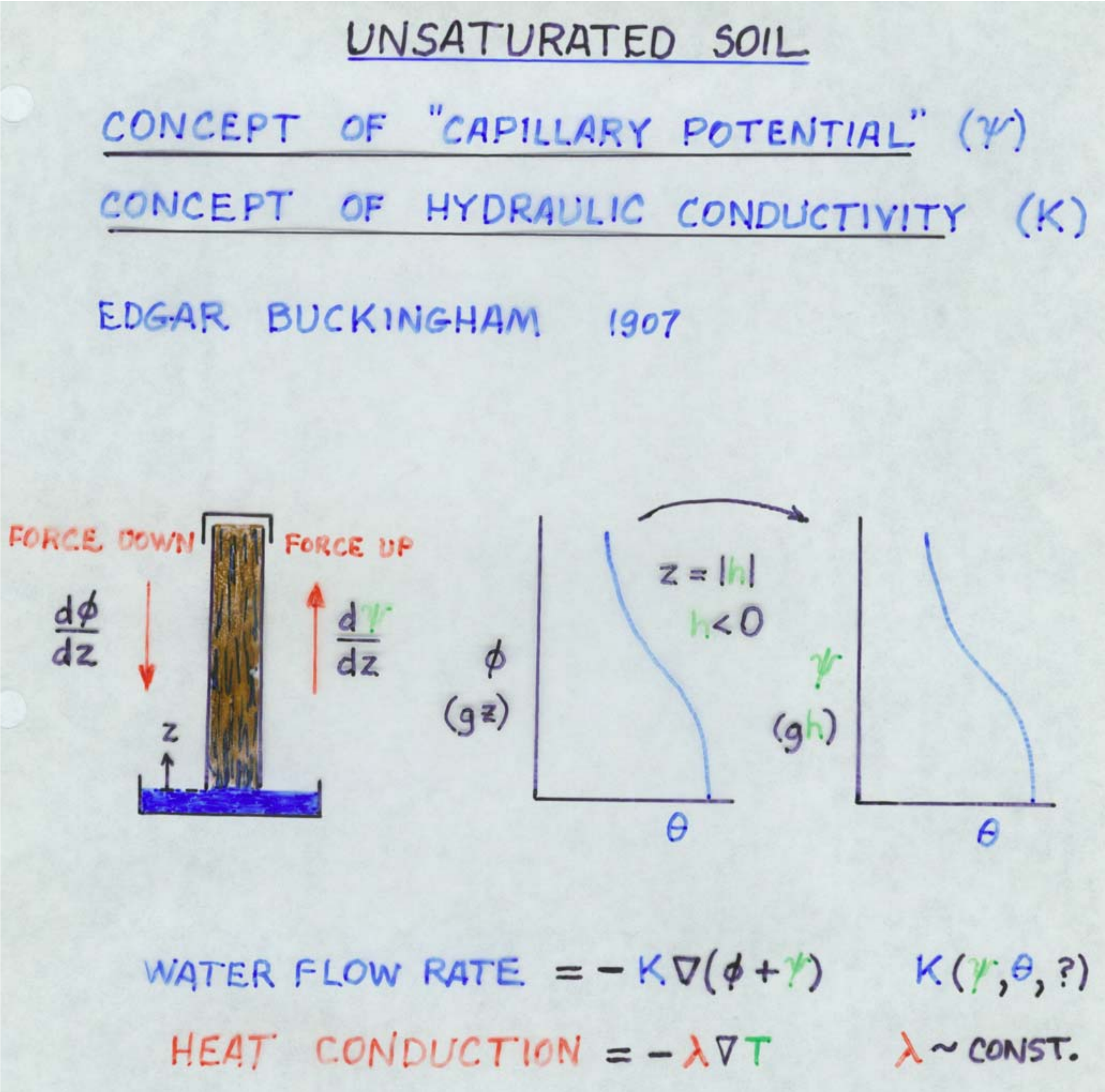
SOIL PHYSICS

Some of the Past

and

Today's Opportunities

Buckingham


UNSATURATED SOIL
CONCEPT OF "CAPILLARY POTENTIAL" (ψ)
CONCEPT OF HYDRAULIC CONDUCTIVITY (K)
EDGAR BUCKINGHAM 1907
FORCE DOWN
$\frac{d\phi}{dz}$
FORCE UP
$\frac{d\psi}{dz}$
z
ϕ (gz)
$z = |h|$
$h < 0$
θ
ψ (gh)
θ
WATER FLOW RATE $= -K\nabla(\phi + \psi)$
$K(\psi, \theta, ?)$
HEAT CONDUCTION $= -\lambda\nabla T$
$\lambda \sim$ CONST.

Richards

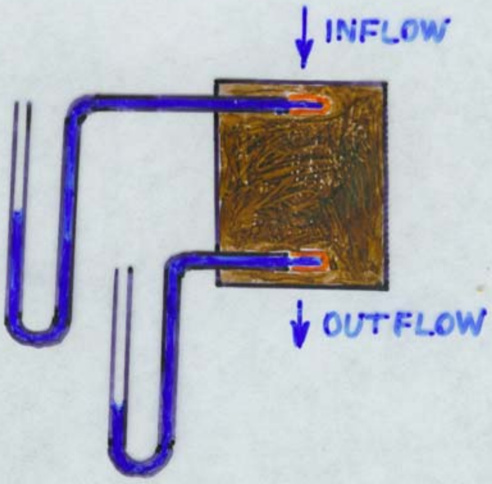
EQUATION FOR TRANSIENT SOIL WATER CONDITIONS

LORENZO A. RICHARDS 1931

- BUCKINGHAM EQN. + CONS. OF MASS EQN.

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K \frac{\partial(\phi + \psi)}{\partial z}\right]$$

- MEASURED $K(\theta)$ & $\theta(\psi)$



50 years ago

About a dozen physicists were studying soils

- Neither soil scientists nor agriculturists
- Used expertise to analyze basic processes
- Studied topics according to physics expertise

Not versed in pedology, chemistry and biology

- Glass beads, sands and coarse-textured soils
- Tested ideas & equations in the laboratory
- Worked in office or lab, not farmers' fields
- Aloof from pedologists and soil scientists

50 years ago education

Difficult to obtain a soil physics education

- Soils professors did not teach soil physics
- One had to seek physicist interested in soils

Only a few soil physics textbooks

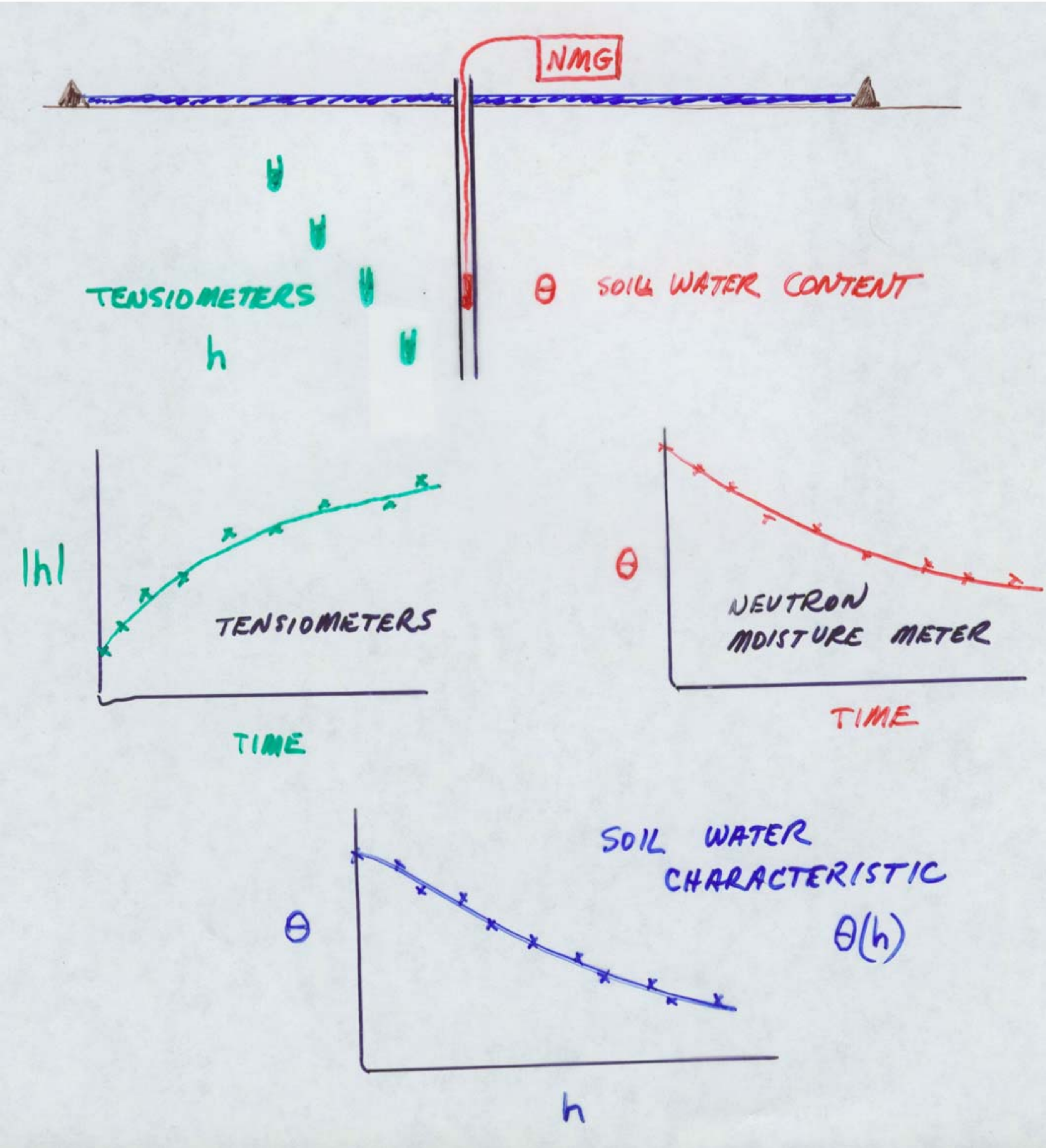
- Ideas empirically or qualitatively presented
- Presented without calculus
- Personal computers were not available

Primitive laboratory and field instruments

- Balances and drying ovens
- Augers, tensiometers, water table recorders, mercury thermometers and a shovel

30 yr ago Field measured K

MEASURING $K(\theta)$ & $\theta(h)$ IN THE FIELD

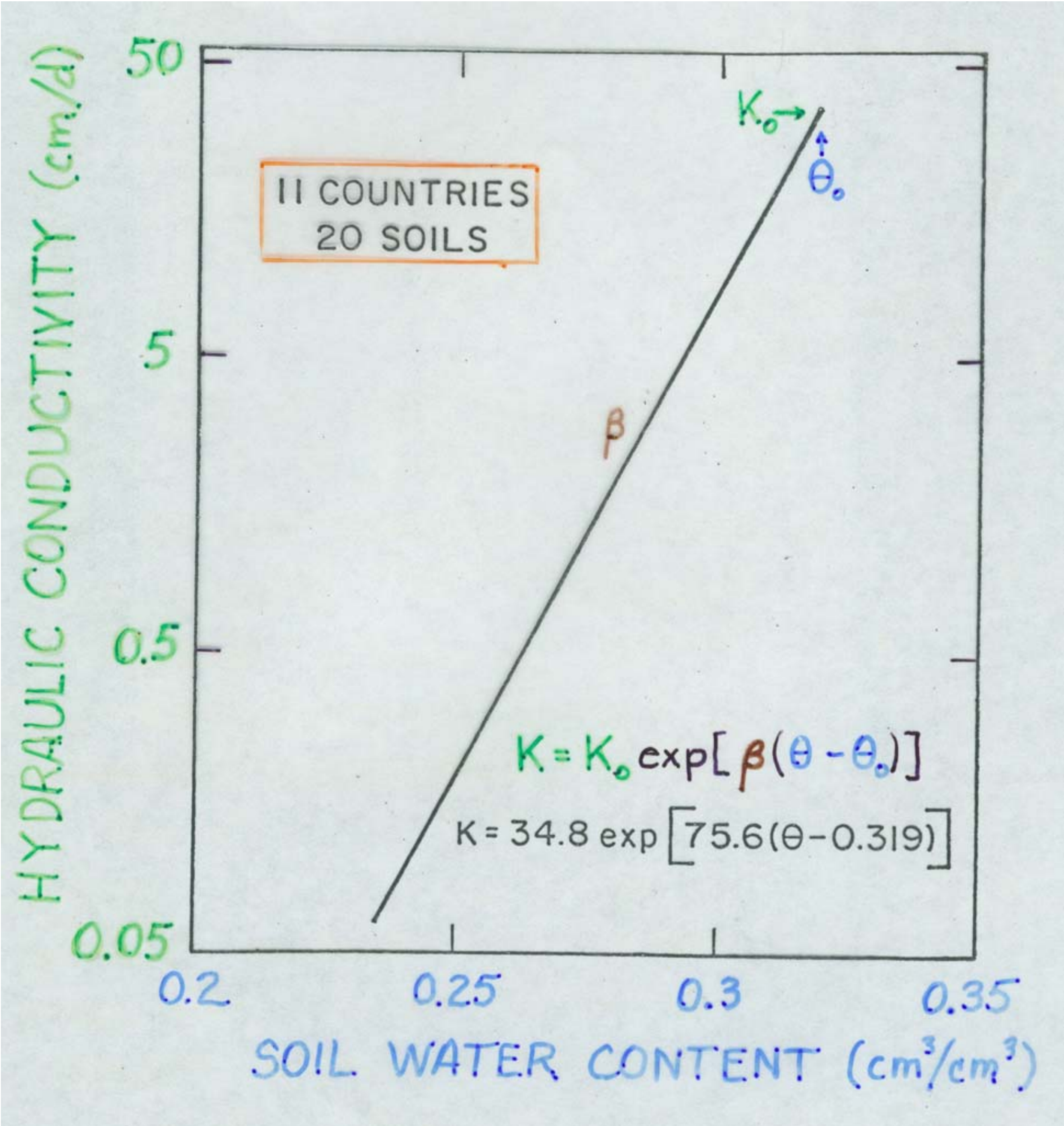


Int' cooperation 1970's

$$K = K_0 \exp[\beta(\theta - \theta_0)] \quad (cm/d)$$

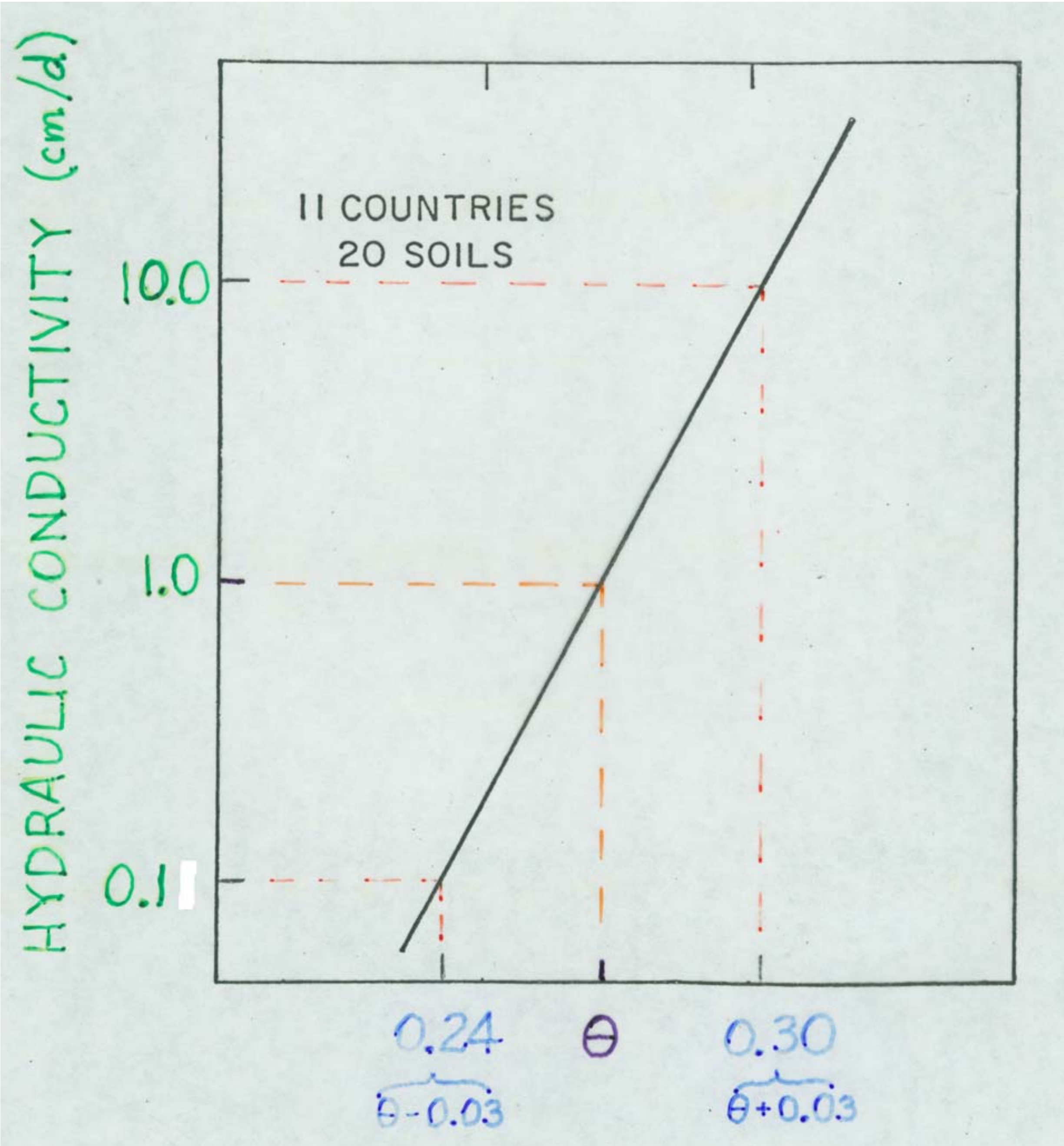
	θ_0	s_{θ_0}	K_0	s_{K_0}	β	s_β
ISRAEL	0.178	0.019	90.7	44.8	43.3	6.12
BRAZIL	0.355	0.026	8.57	17.1	110.	53.9
BRAZIL	0.387	0.012	253.	175.	44.6	7.78
CYPRUS	0.459	0.016	21.2	46.9	70.5	50.0
JAPAN	0.268	0.018	653.	343.	11.4	1.22
SYRIA	0.338	0.034	11.2	11.1	160.	122.
MADAGASCAR	0.271	0.014	32.4	22.8	59.7	9.61
BELGIUM	0.295	0.037	59.5	75.9	90.2	56.2
THAILAND	0.510	0.029	228.	295.	75.1	17.0
CHILE	0.452	0.010	6.30	9.21	42.7	26.8
SENEGAL	0.193	0.024	55.3	13.5	14.5	2.17
SENEGAL	0.206	0.026	1.63	0.52	37.3	11.6
NIGERIA	0.260	0.018	12.3	11.6	110.	54.0

World ave. K



HYDRAULIC CONDUCTIVITY (cm/d)
50
5
0.5
0.05
0.2
0.25
0.3
0.35
SOIL WATER CONTENT (cm³/cm³)
11 COUNTRIES
20 SOILS
K₀
θ₀
β
K = K₀ exp[β(θ - θ₀)]
K = 34.8 exp [75.6(θ-0.319)]

K uncertainty

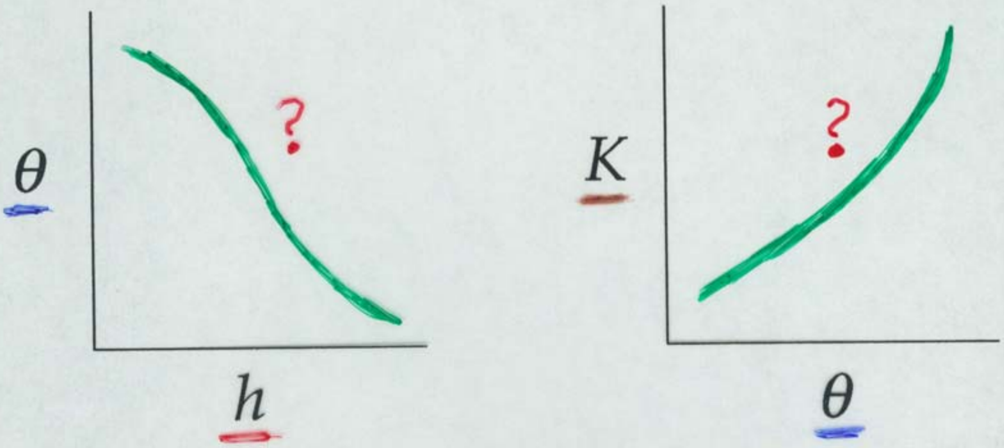


Dates of known K

SOIL WATER PROPERTIES

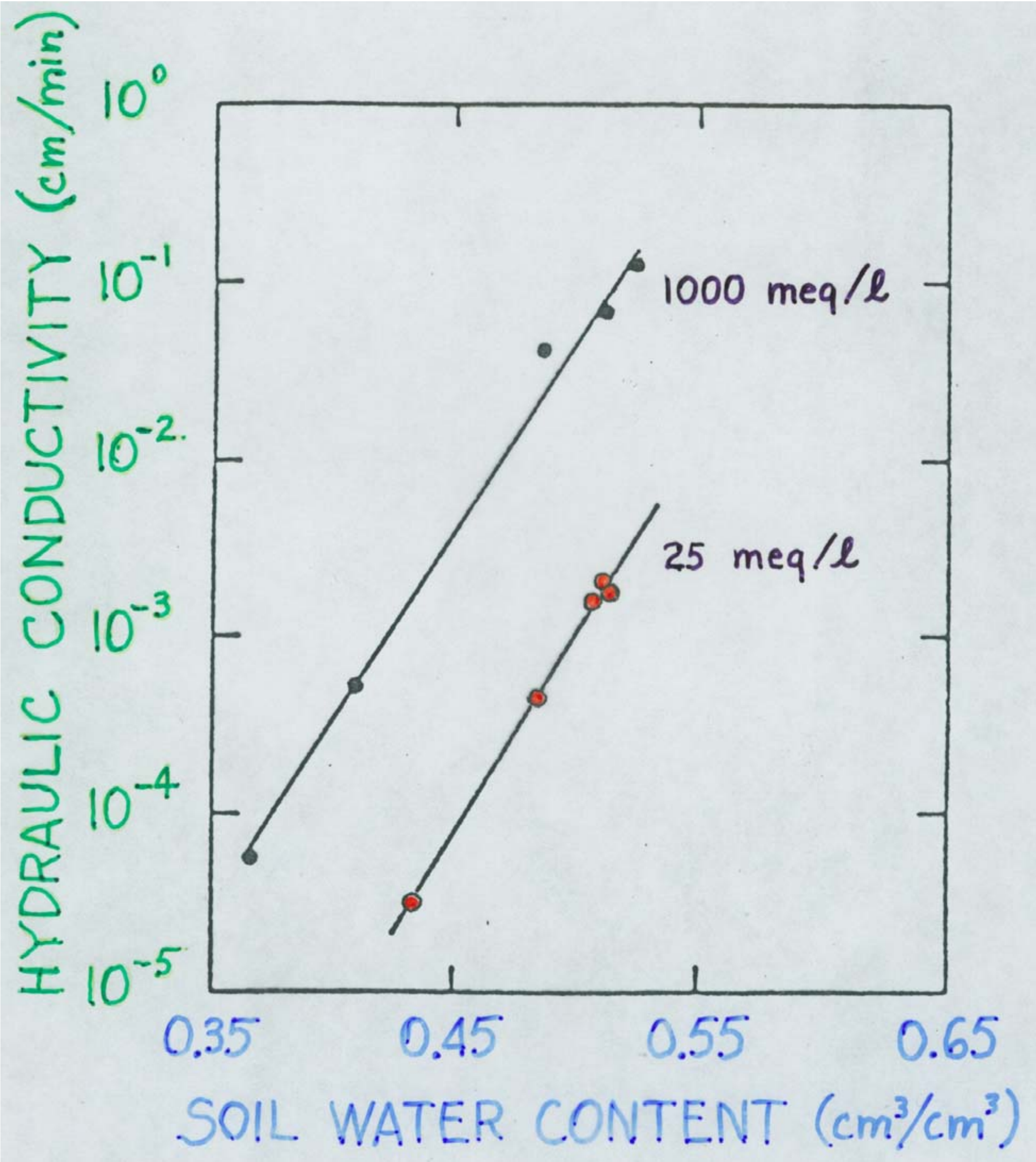
$$\frac{\partial \theta(h)}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\frac{\partial H}{\partial z}\right] - \phi$$

PLANT ABSORPTION

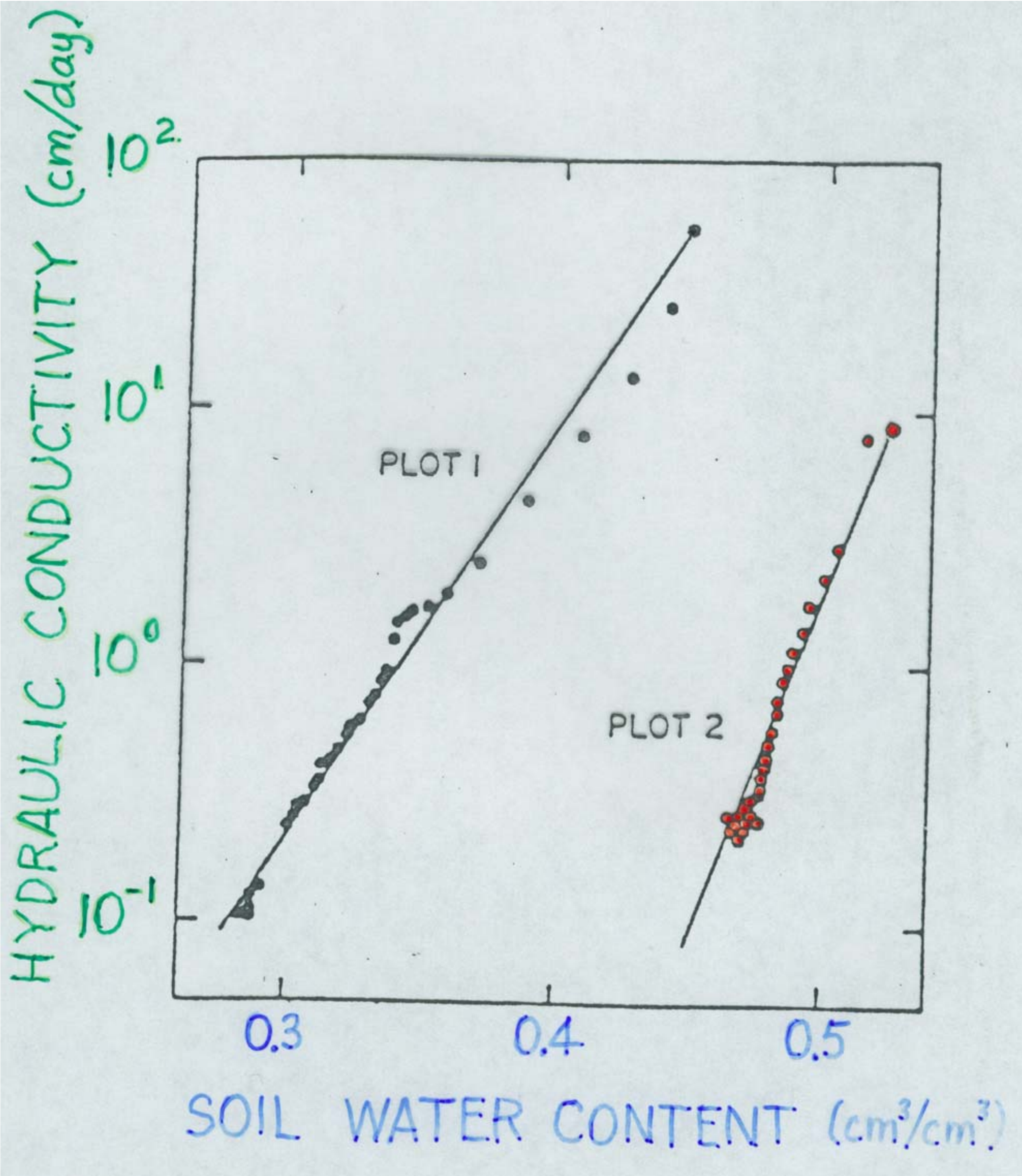


BEFORE 1960's	CURVES NOT MEASURED IN FIELD
BEFORE 1970's	SHAPES OF CURVES NOT KNOWN
AFTER P.C.'s	CURVES ASSUMED TO BE KNOWN
TODAY, 2005	FIELD TECHNOLOGY NOT DEVELOPED TO ASCERTAIN FUNCTIONS WITHIN PRESCRIBED LIMITS OF ACCURACY AND PRECISION ! !

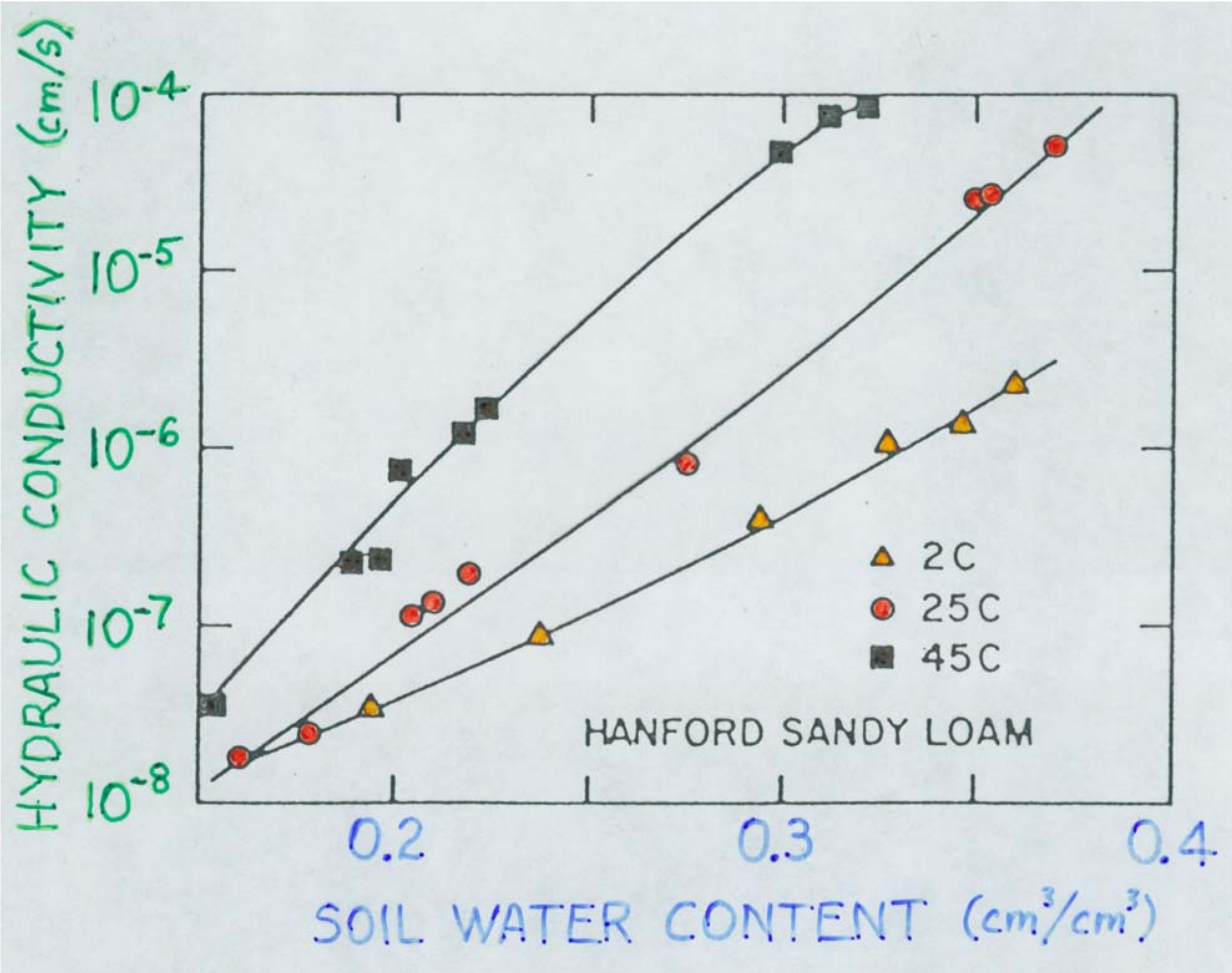
Water quality on K



Two field plots

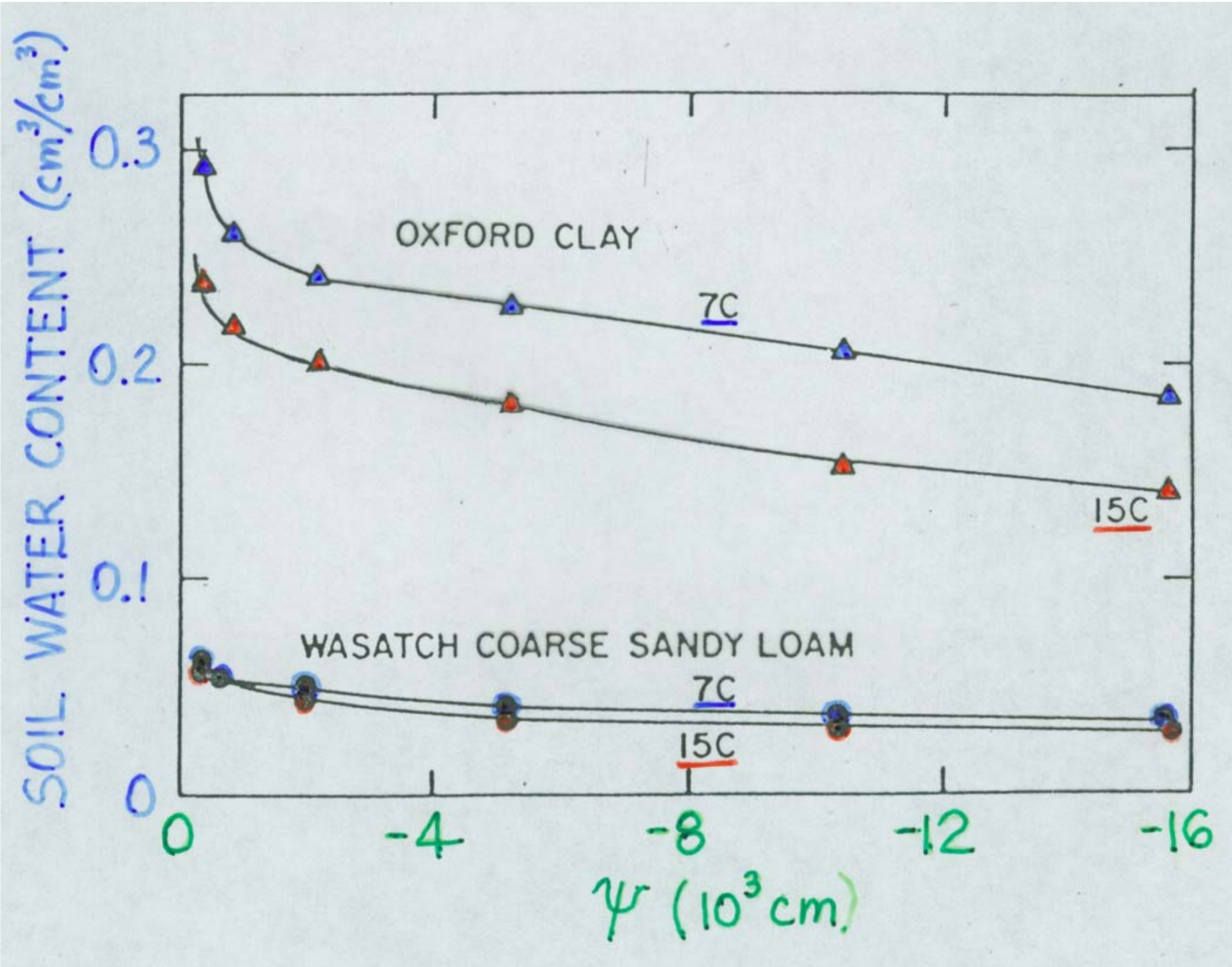


Temp. on K

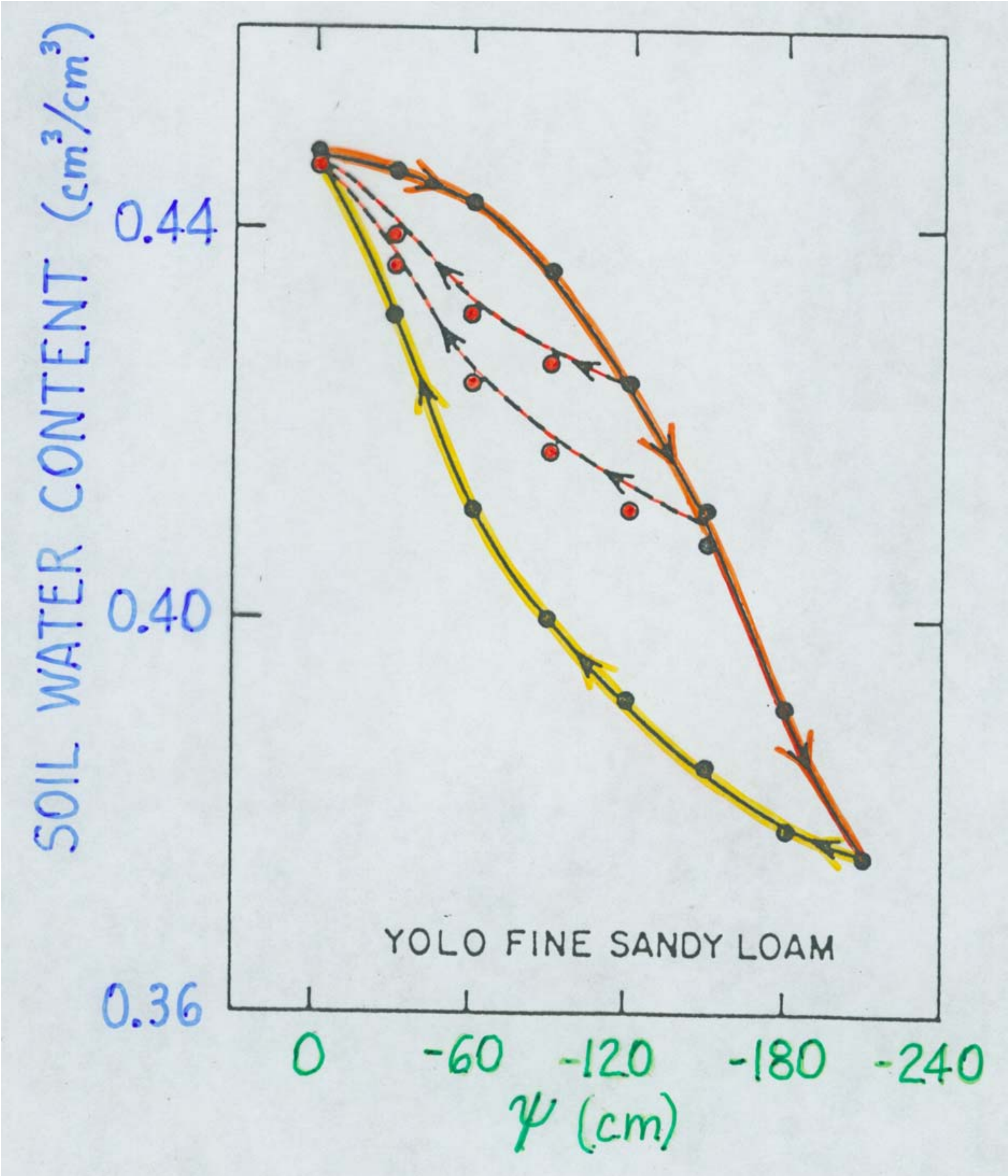


HYDRAULIC CONDUCTIVITY (cm/s)
10-4
10-5
10-6
10-7
10-8
0.2
0.3
0.4
SOIL WATER CONTENT (cm3/cm3)
2C
25C
45C
HANFORD SANDY LOAM

Temp. on theta

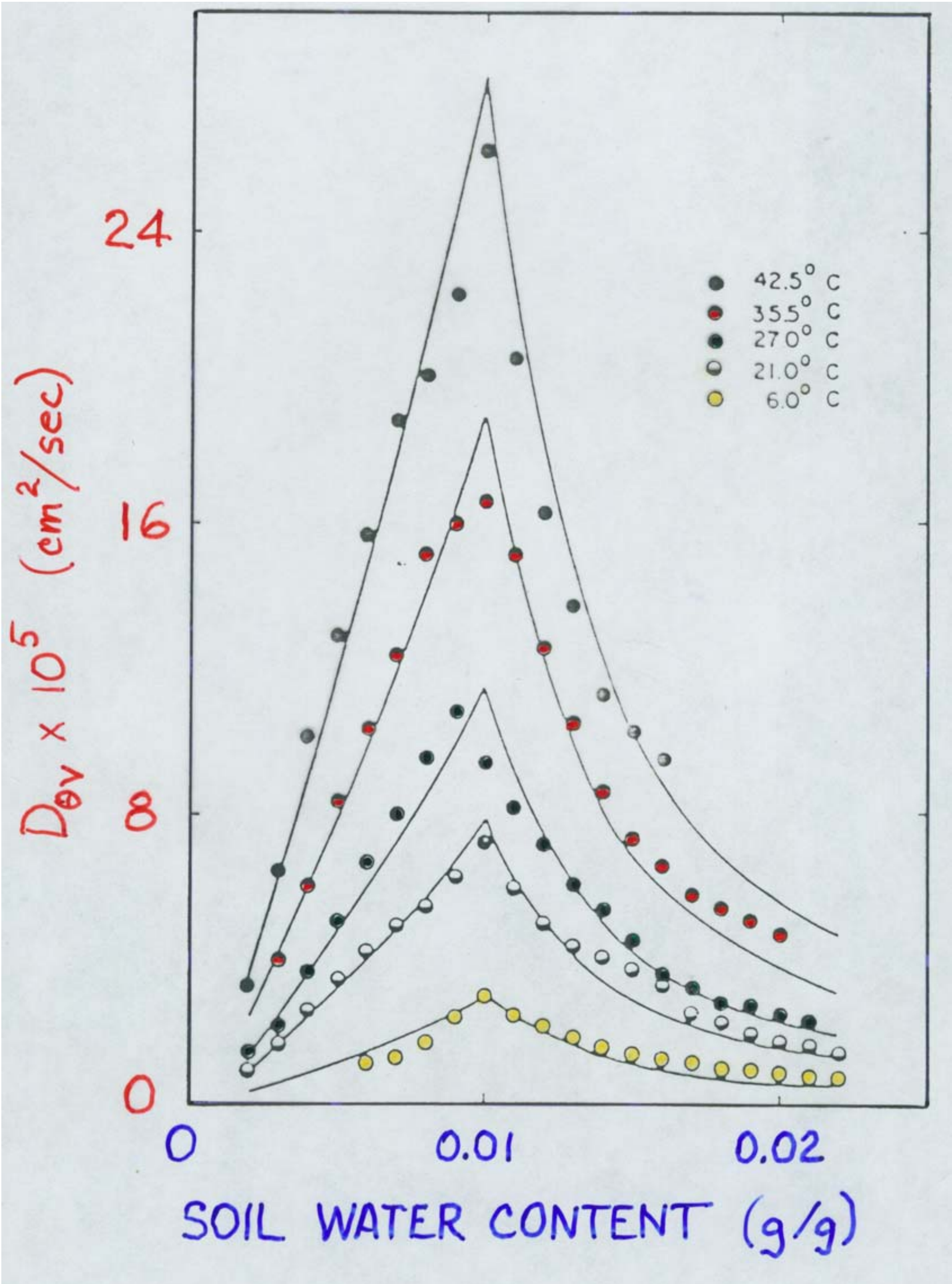


Hysteresis



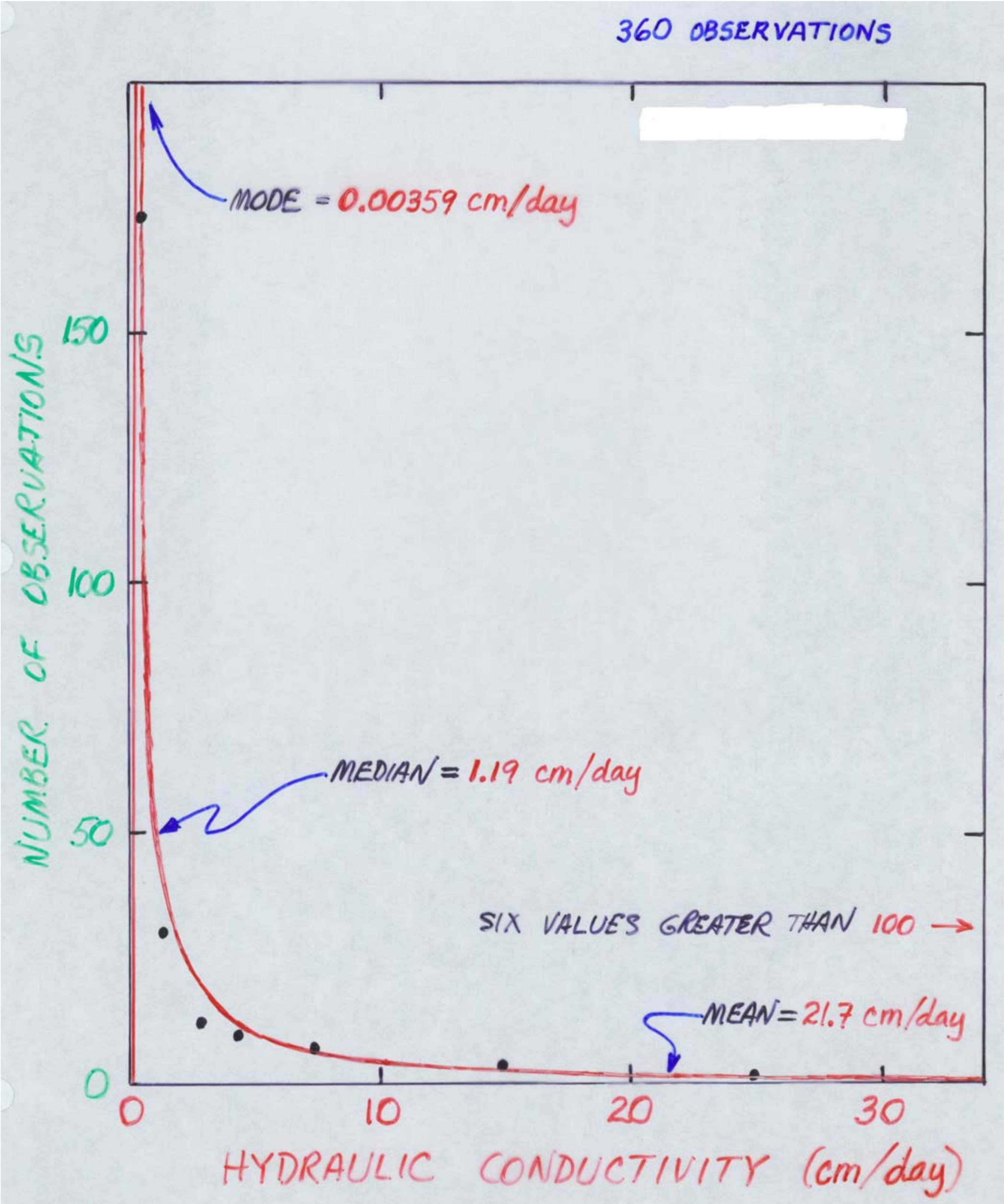
SOIL WATER CONTENT (cm³/cm³)
0.44
0.40
0.36
YOLO FINE SANDY LOAM
0
-60
-120
-180
-240
ψ (cm)

Temp. on D



42.5° C
35.5° C
27.0° C
21.0° C
6.0° C
24
16
8
0
$D_{\theta v} \times 10^5$ (cm²/sec)
0
0.01
0.02
SOIL WATER CONTENT (g/g)

Mode,med, mean



Present-day instrument

PRESENT-DAY METHODS FOR MEASURING SOIL PROPERTIES

MICROSCALE

- Radiography
- Computed Tomography
- Magnetic Resonance Microscopy
- Fiber Optic Systems
- Optical and Scanning Electron Microscopy
- Microscopic Pressure Probe

LABORATORY COLUMN OR SMALL FIELD PLOT SCALE

- Time Domain Reflectometry
- Soil-Water Potential Devices
- Soil Solution Extraction Devices
- Heat Pulse Probe

OBSERVATIONS IN LARGE FIELDS

- Lysimetry
- Invasive Techniques
- Isotope hydrology
- Electromagnetic Induction
- Electrical Resistivity
- Seismic Reflection & Refraction
- Ground Penetrating Radar
- Nuclear Magnetic Resonance
- Cross-Borehole Techniques

Title satellite

SATELLITE DEDICATED TO CONTINUOUSLY MONITOR THE WATER CONTENT OF THE EARTH'S SURFACE

Soil phys with sat.

SOIL PHYSICS

- Ascertain soil physical properties and conditions within soil profiles based upon surface soil water content distributions.

- Quantification of correlation lengths of soil water content in time and space relative to precipitation and evaporation events.

- Is there a useful covariance structure between soil water properties and those associated with water and heat fluxes at the land-atmosphere interface identifiable at a soil mapping unit scale?

- Can vertical and horizontal fluxes of energy and matter in gaseous and liquid phases below the soil surface be ascertained from surface soil water distributions?

Soil genesis with sat

SOIL GENESIS AND PEDOLOGY

- Development of criteria for soil mapping units based upon spatial and temporal variance structures of physical, chemical and biological state variables.

- Are covariance structures of soil water properties consistent with present-day soil mapping units?

- What are the most promising opportunities to quantify covariance structures of soil water properties with soil profile and landscape attributes?

- Identify scales of observation most useful or informative for different soil and land processes consistent with soil taxonomy and their application.

Soil microbio with sat

SOIL MICROBIOLOGY

- Identification of state variables of microbiological populations related to surface soil water distributions.

- Are rates of microbially induced transformations of organic materials linked with surface soil water distributions? Do they have a covariance structure according to soil taxonomy?

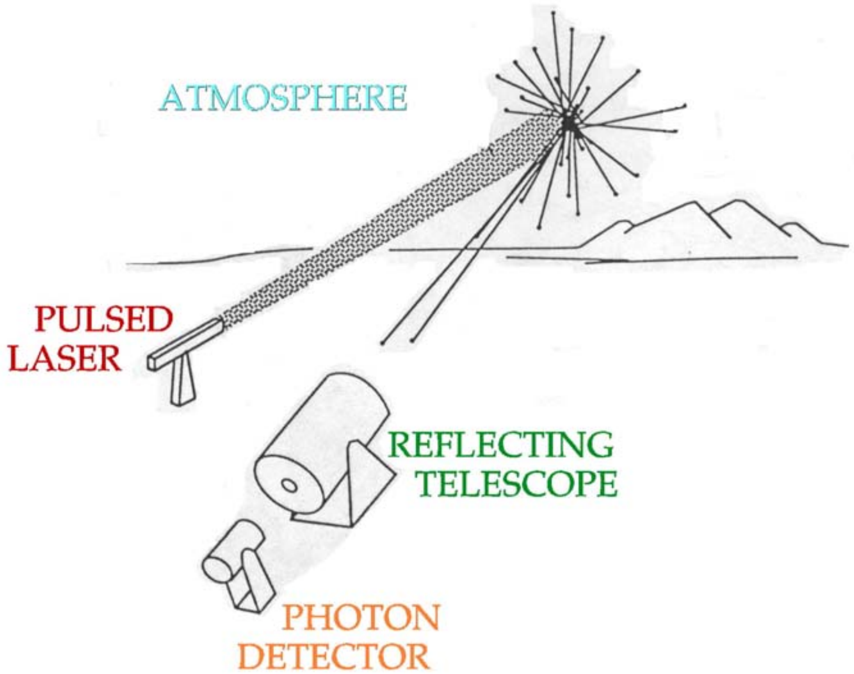
- Can changes of microbial growth, metabolism and death be associated with surface soil water distributions at different scales of time?

- Are the mobility and persistence of soil borne disease organisms related to surface soil water distributions?

Lidar system

LIDAR

LIGHT DETECTION & RANGING



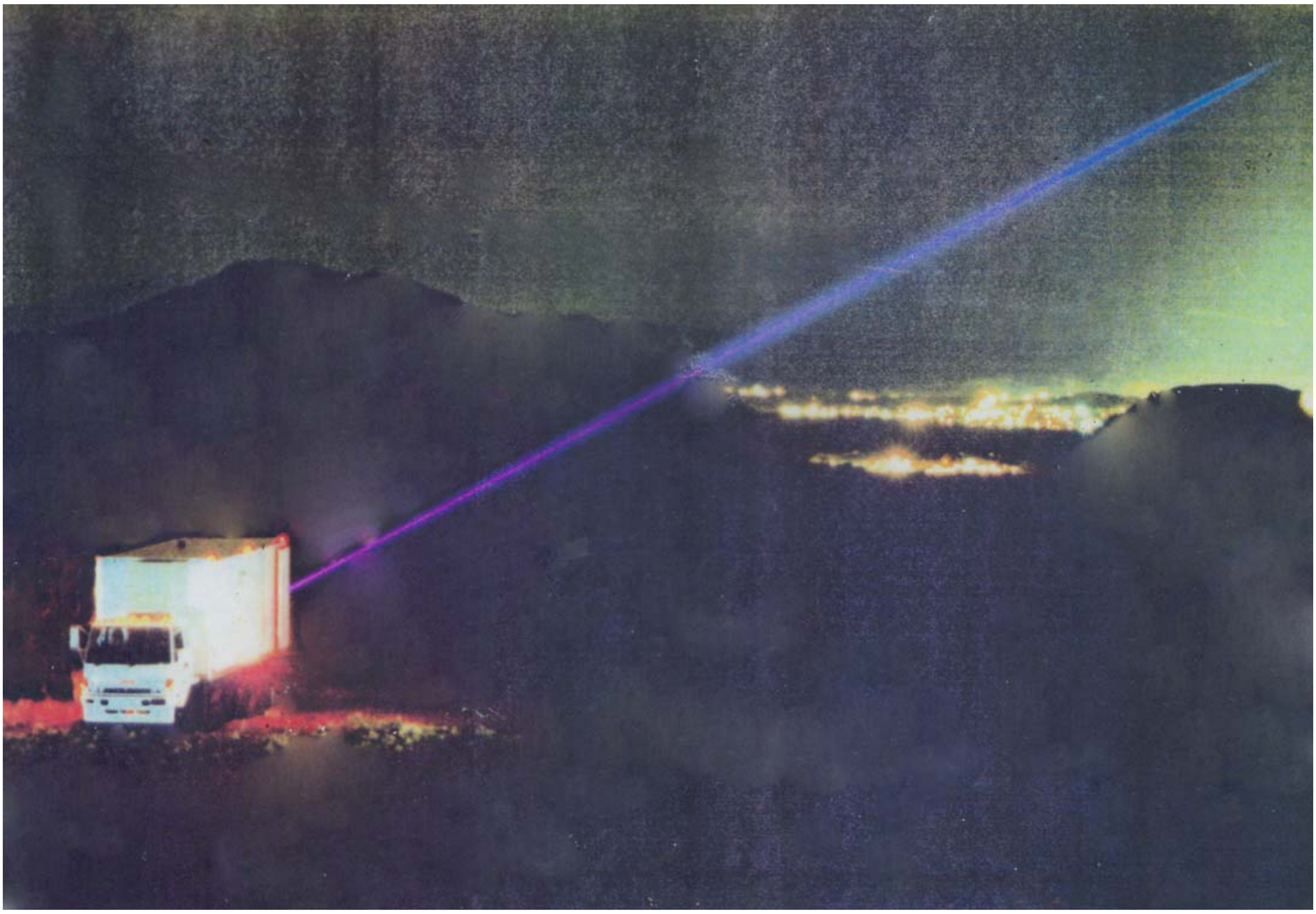
- SCATTERED LIGHT COLLECTED AT PHOTON DETECTOR
- CONVERTED TO AN ELECTRIC SIGNAL
- SAMPLED 100 MILLION TIMES PER SECOND
- CONVERTED TO A DIGITAL SIGNAL

DETECTS, IDENTIFIES & QUANTIFIES

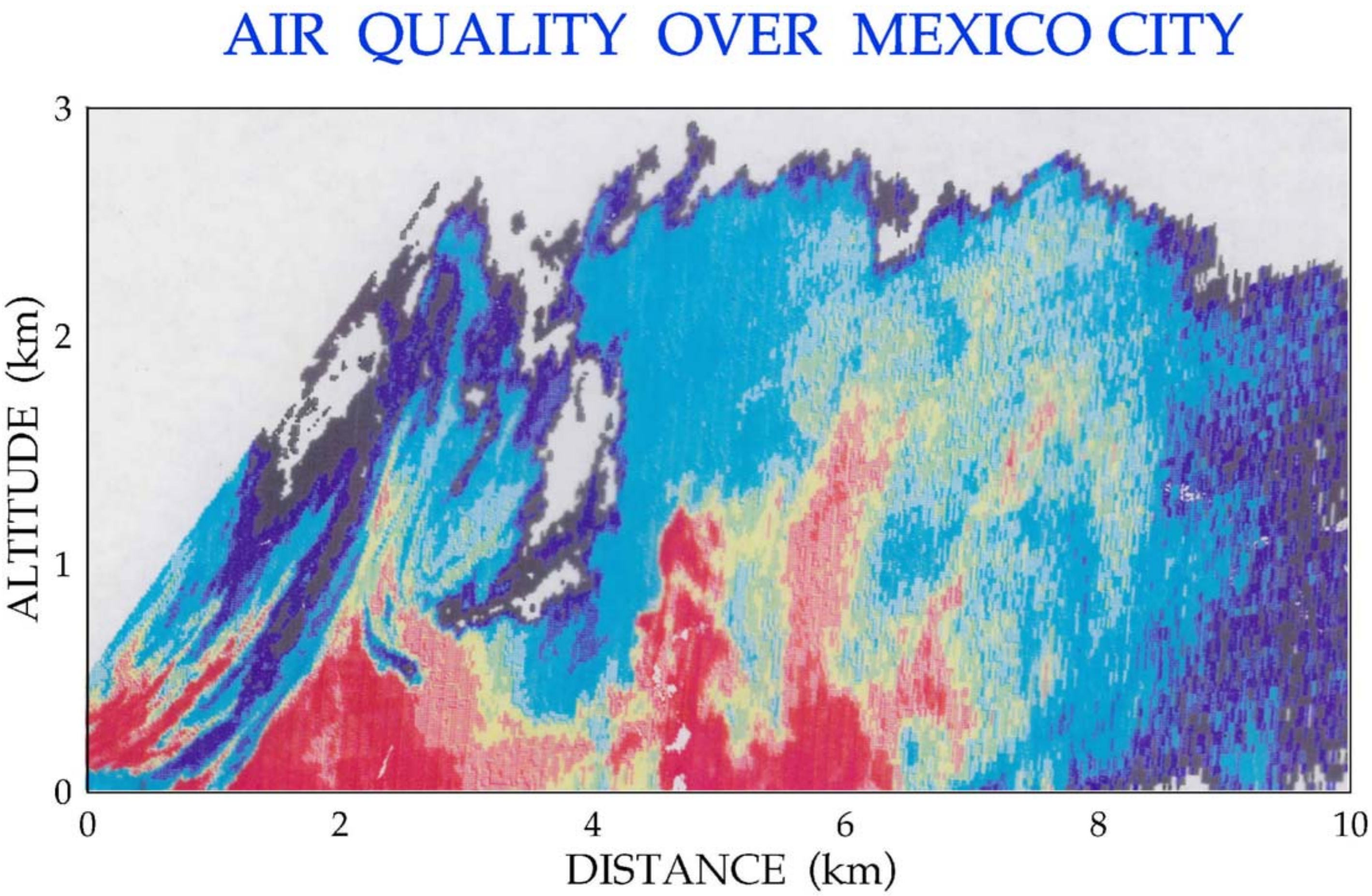
HYDROCARBONS, CHEMICALS, WATER VAPOR AND SPORES

Lidar in truck

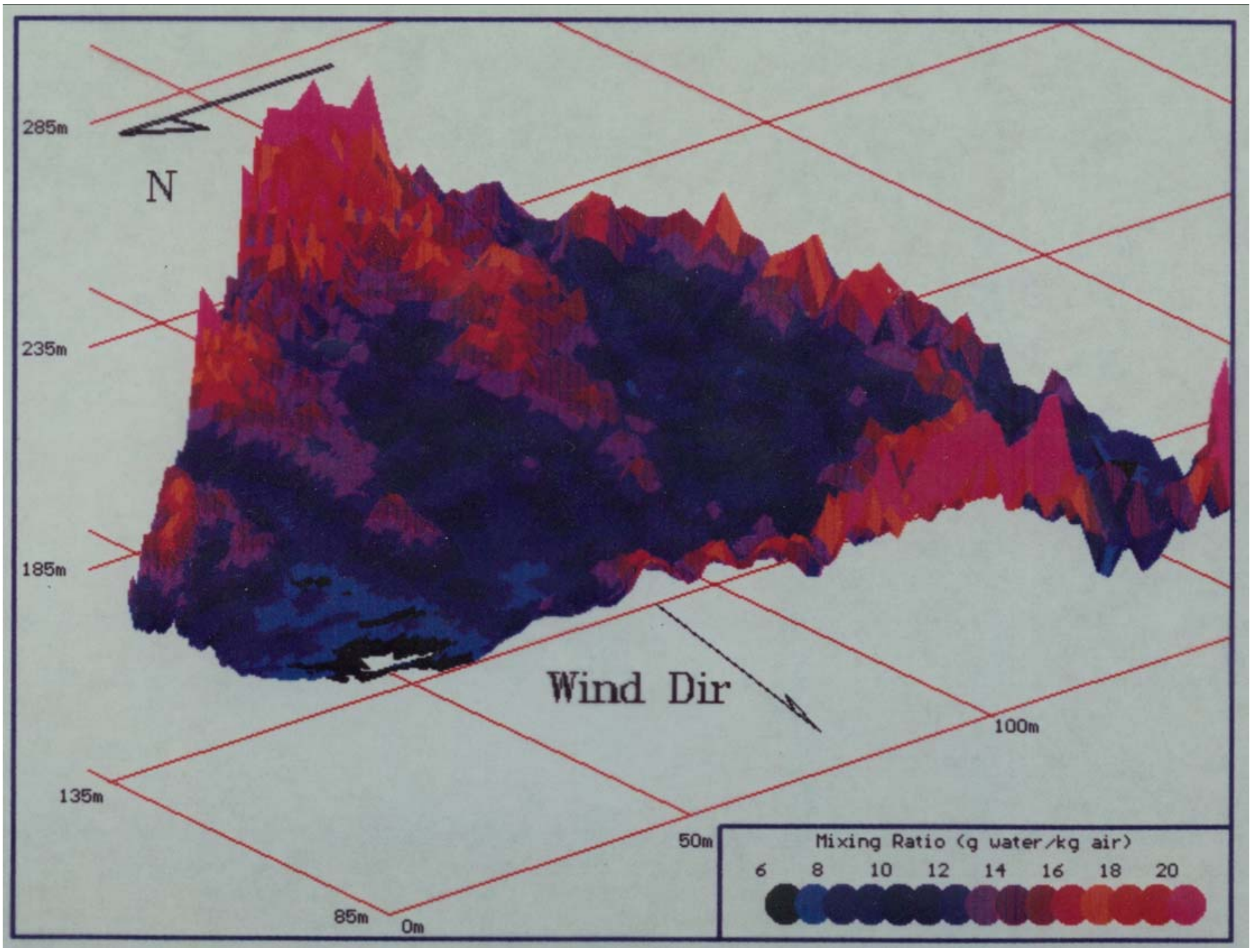
Lidar from truck



Mexico city air



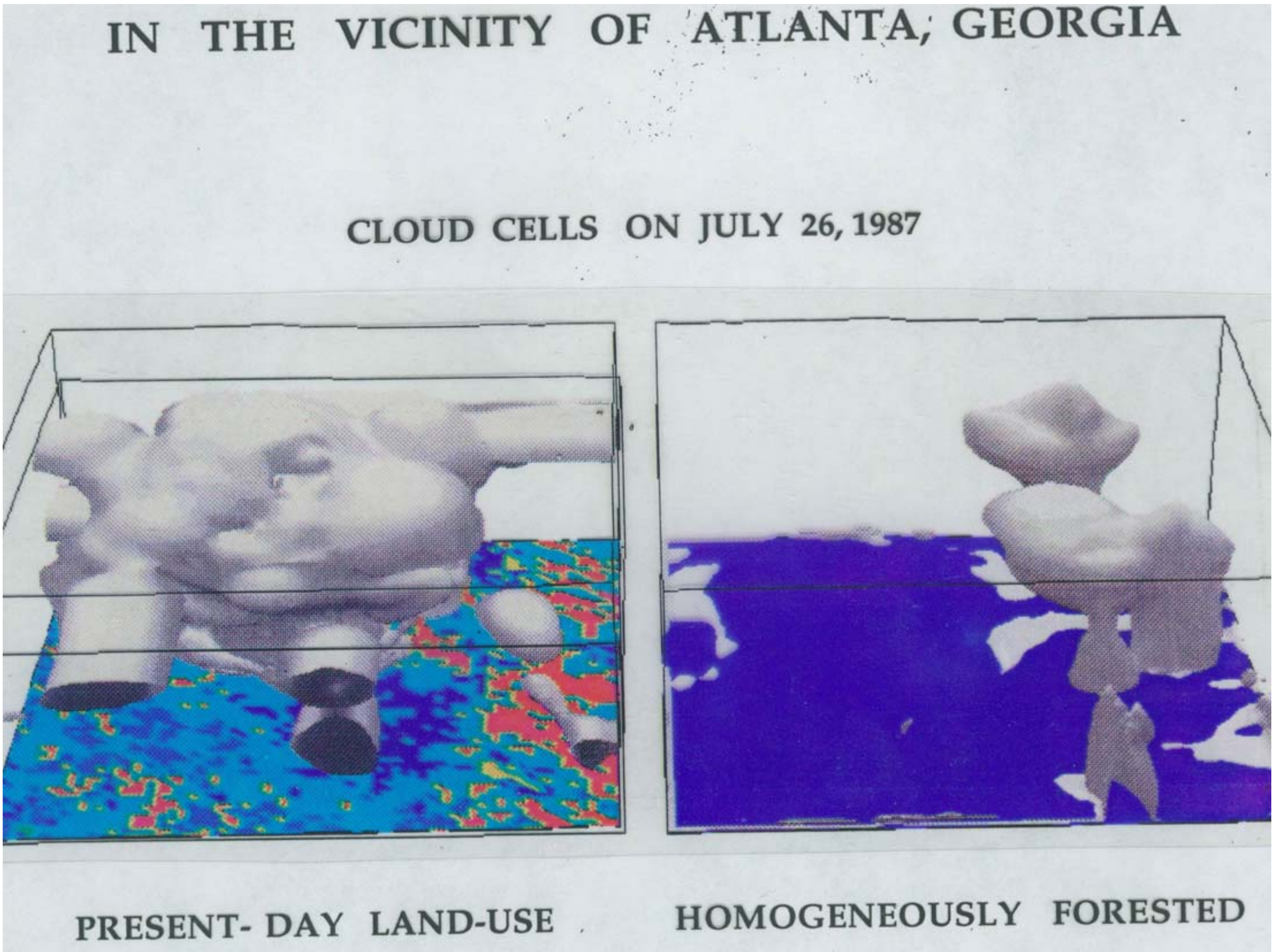
Alfalfa air water



Title regional models

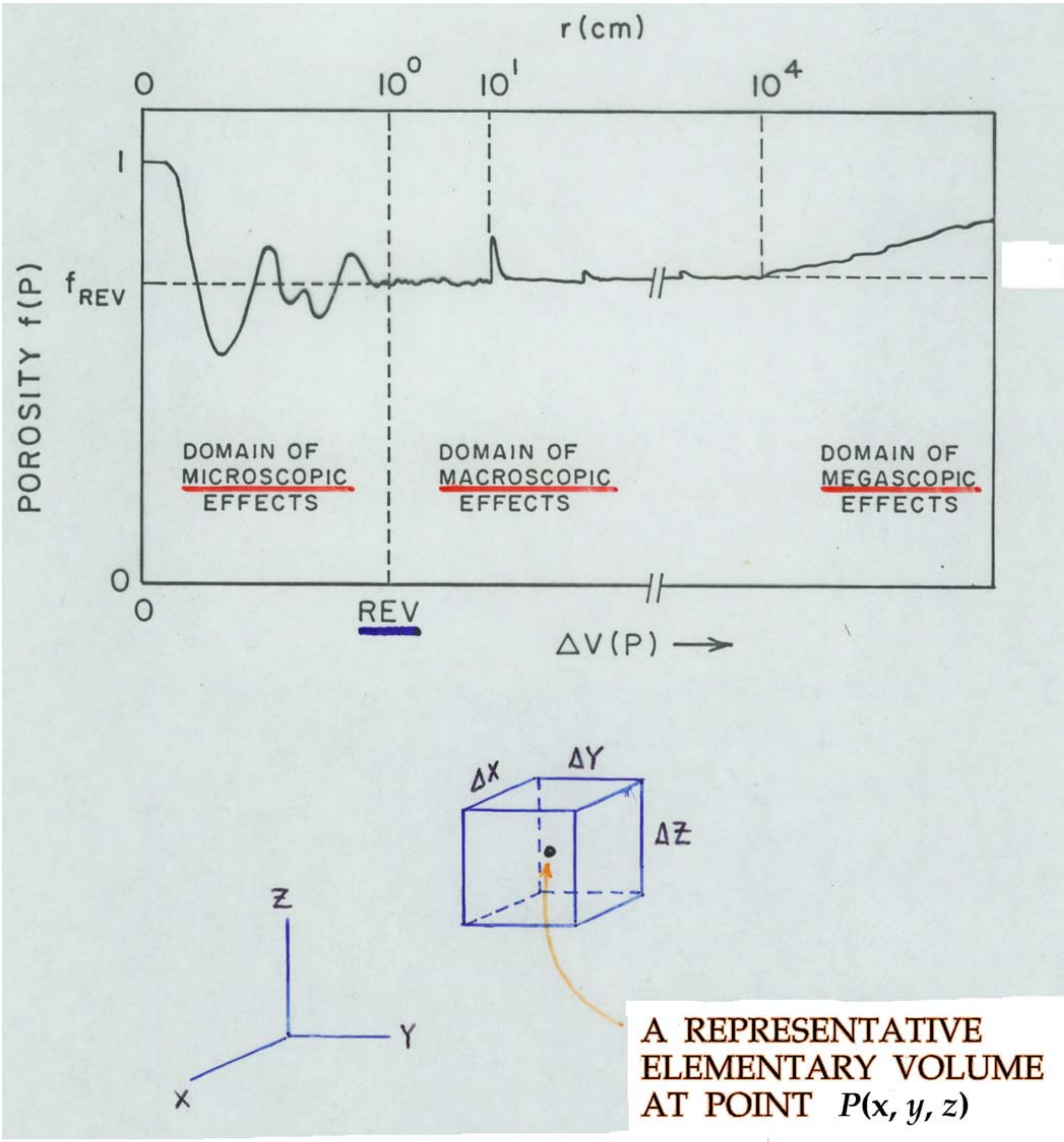
IMPROVED REGIONAL SCALE MODELS OF LAND-ATMOSPHERE EXCHANGE PROCESSES

Vicinity of Georgia

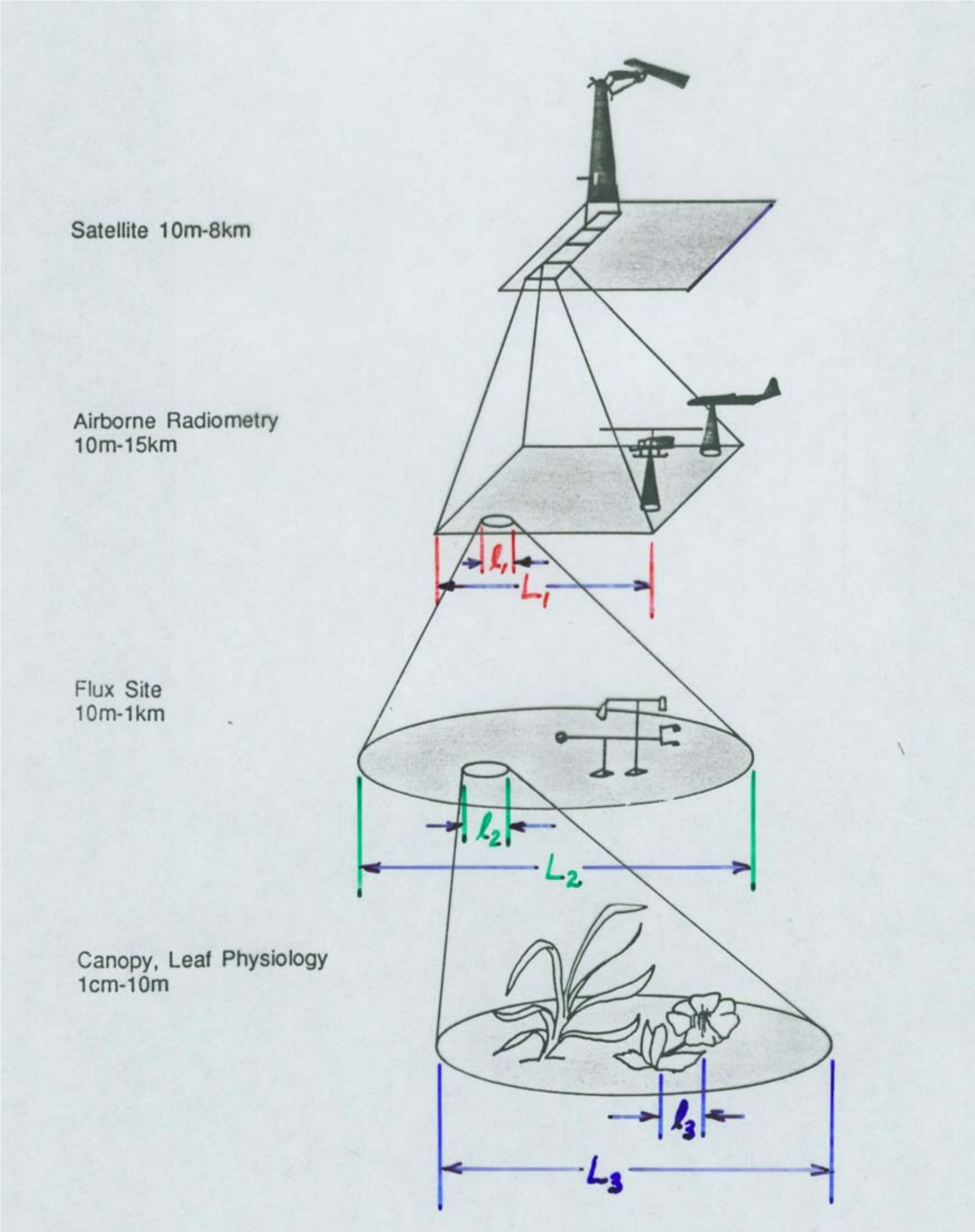


Still use REV

REPRESENTATIVE ELEMENTARY VOLUME



Measurem't scales



Special effort

A SPECIAL EFFORT MUST BE MADE TO EFFECTIVELY DEAL WITH TEMPORAL AND SPATIAL HETEROGENEITY OF FIELD SOILS IN RELATION TO ENVIRONMENTAL PROTECTION

- alternative formulations of differential equations to describe soil processes
- alternative functions for soil parameters contained in those equations
- alternative frequencies of temporal and spatial measurements to match theoretical considerations
- alternative criteria for accepting different levels of uncertainty always inherent in observation instruments and their calibration including human error

Changes past 50 yrs

1. Today, a thousand or more soil physicists
   - Teach many topics of basic soil physics
   - Research applied to agriculture, hydrology, & environmental sciences and engineering

2. Many more students studying soil physics
   - Interests in agriculture, global environment, natural resources, ecology and engineering

3. An abundance of scientific instruments for micro- to field-scale methods

   radiography, computed tomography, magnetic resonance microscopy, fiber optic systems, optical and scanning electron microscopy, microscopic pressure probes, time domain reflectometry, soil-water potential devices, soil solution extraction probes, heat pulse probes, lysimetry, invasive field techniques, isotope hydrology, electromagnetic induction, electrical resistivity, seismic reflection and refraction, ground penetrating radar, nuclear magnetic resonance, cross-borehole techniques, and more

More changes

4. Development of the first, and presently, only journal of vadose zone research

- **Soil physicists led its development.**
- **Soil physics, hydrogeology, geophysics, geochemistry, soil chemistry, microbiology, ecology, agric'l and environ'l engineering, civil, petroleum, and chemical engineering**

5. New data acquisition and processing systems

- **Simultaneous analysis of huge variety and number of distributed sensors in a soil column or landscape domain**

6. Scenarios developing for linking soil physics to other disciplines

- **Able to solve and better manage landscape processes**

7. Daily internet communication between soil physicists and other scholars

- **Inspired to apply their joint expertise to sustain food production and enhance the quality of our global environment.**

Where are opportunities

WHERE ARE THE OPPORTUNITIES
FOR
FUTURE SUCCESS IN SOIL PHYSICS ?

THERE ARE THREE OF THEM

First opporutnity

FIRST OPPORTUNITY

RE-VISIT BASIC, FUNDAMENTAL CONCEPTS

DARCY, BUCKINGHAM, RICHARDS, AND EDLEFSEN AND ANDERSON PROVIDED GUIDING PRINCIPLES FOR DESCRIBING BEHAVIOR AND ENERGY STATUS OF SOIL WATER.

- DURING THE PAST 75 YEARS, WE TAKE THEIR EQUATIONS FOR GRANTED
- WE TACITLY ACCEPT OUR SIMULATIONS OF SOIL WATER BEHAVIOR AS CORRECT WITHOUT ADEQUATE EXPERIMENTAL VERIFICATION
- WE ARE COASTING, APATHETIC, AND NOT ADEQUATELY EXPLORING THE UNKNOWN

Basic unknowns

UNKNOWN ISSUES ABOUT THE TRUE NATURE OF SOIL WATER

- Soil water content versus soil water energy based on first principles remains ambiguous
- A Buckingham-Darcy equation for non-isothermal conditions with or without solutes has yet to be fully developed and verified
- A useful theory for transient transport of soil water, heat and solutes has yet to explicitly include the simple, well-known concepts of electro-osmosis and streaming potential
- Limitations of Richards equation have not been quantitatively elucidated.
- Presence and metabolism of microbes and plant roots are not included in the nature of soil water.
- Paradigms for non-aqueous non-volatile and volatile liquids require considerations previously ignored in water-unsaturated soils

• • Need to explore crucial, yet-to-be understood physical, chemical and biological simultaneous soil processes and identify the degree of their dependency.

Simulations of soil water based upon empirical soil-water properties have not been adequately quantified across the landscape

Second opportunity

SECOND OPPORTUNITY

STUDY AND CONTRIBUTE TO PEDOLOGY

Soil physicists prefer mathematics, pedologists prefer subjective descriptions. Neither worked together until they attempted to develop pedotransfer functions.

- **Recently, Bouma popularized the name *pedotransfer function* – a mechanism to derive quantitative measures of soil properties from historical soil survey databases.**

How useful are pedotransfer functions?

- **Woefully less useful than initially expected**
- **Original, available databases are inadequate – must be supplemented with ancillary data, e.g. landscape slope and curvature**

A technology for ascertaining quantitative soil properties from routine soil survey data awaits development

- **Until then, successful integrated modeling of regional-scale processes will require intensive local monitoring that must be repeated for each domain or region**

Third opportunity

THIRD OPPORTUNITY

ELEVATE THE SCIENCE & IMPROVE UTILITY OF PEDOLOGY

As a discipline, soil science's only *raison d'etre* is its subdiscipline pedology

- **Pedology – soil genesis, soil morphology and soil classification – mapping soils according to their properties for their use and management by society.**

For the discipline of soil science to remain alive and appreciated into the next century, it must remain useful to others

- **Pedology's best contribution for civilization – delineated the surface of continents into soil domains of similar origins, properties and management potentials.**
- **They pride themselves for classifying soils and making soil maps to be used for various management purposes.**
- **From their work, soil maps now abundant at various spatial scales.**

How reliable are maps?

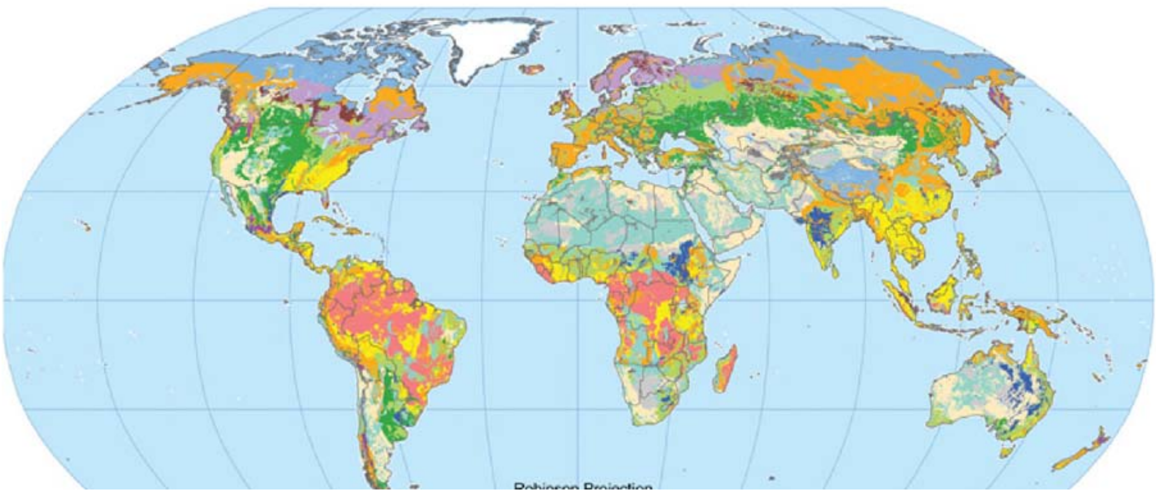
How reliable are these maps?

Are they accurate?

Are they dependable and useful?

Global maps

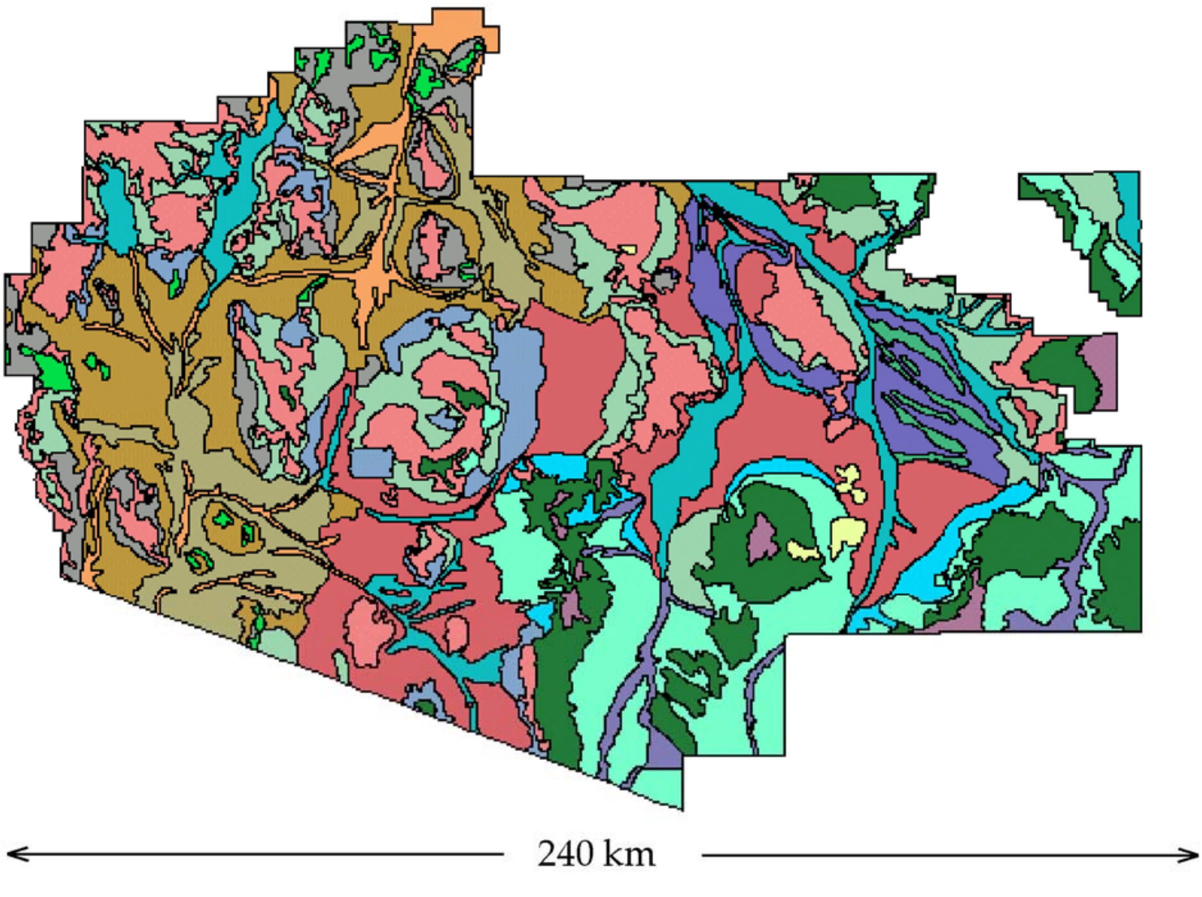
GLOBAL LOCATIONS OF SOIL ORDERS



More details

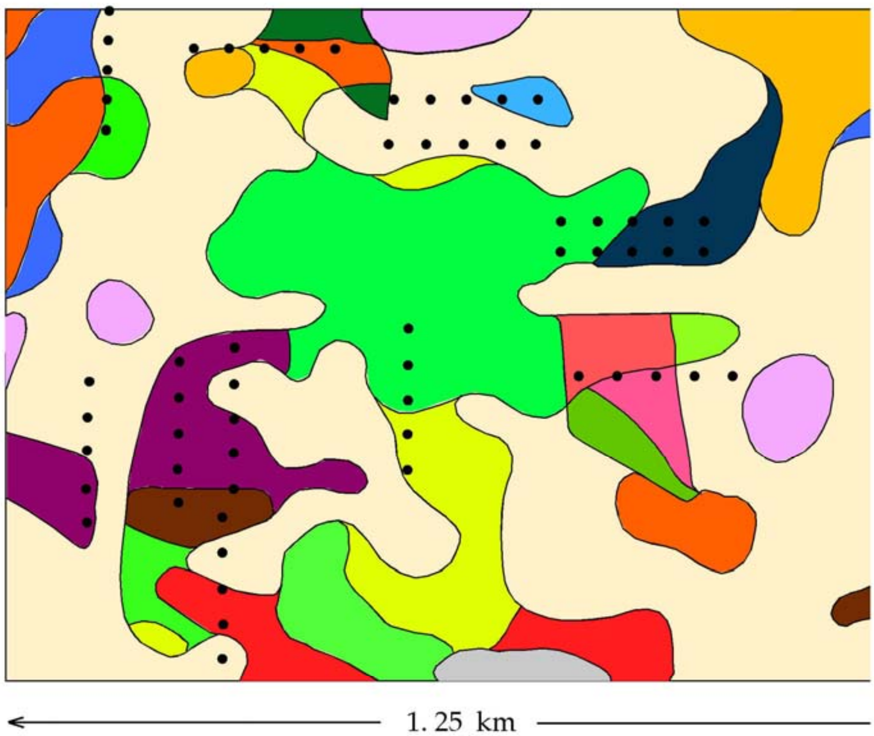
MORE DETAILED VIEW OF A LANDSCAPE SUBDIVIDED INTO SMALLER PARCELS

- **Based primarily on morphological parameters**
- **Each mapping unit of apparently different soil properties.**



Abrupt boundaries

A LANDSCAPE FURTHER SUBDIVIDED INTO STILL SMALLER MAPPING UNITS



Each mapping unit identified with clearly marked, abrupt boundaries

- **How uniform are soil properties within each mapping unit?**
- **How were boundaries ascertained?**

WHY ARE THESE QUESTIONS NOT ANSWERED?

Pedologists not done

BECAUSE PEDOLOGISTS HAVE NOT YET FINISHED THEIR JOB AS ORIGINALLY PERCEIVED

World Reference Base for Soil Resources (FAO), organization of soil exists at four scales of observation:

1. elementary organizations
2. assemblages
3. horizons
4. pedological systems

- Pedologists have focused on the first three, and ignored the fourth scale

What are pedological systems? They are the spatial distributions and relationships of horizons at the scale of the landscape

- Horizontal extent, continuity and uncertainty of soil properties has yet to be quantified
- No such information routinely available in soil survey databases
- That void explains why characteristics of a soil series are based on modal values expected within a soil-mapping unit with no explicit procedure to ascertain their spatial location

Needed information

INFORMATION NEEDED TO FILL THAT VOID

A conceptual framework to quantify and categorize that fourth scale of our soil landscape.

- **Measure auto- & cross-covariances between state variables of soil properties and processes at different scales of space and time**
- **Examine the need to aggregate or disaggregate data across one or several contemporary soil-mapping units for any particular application.**
- **Provide technology to stop the continual subdivision of the earth's soils into smaller and smaller differently classified domains.**
- **Quantitative description for studying soil dynamics in three dimensions**
- **Accurate information upon which monitoring systems (degradation, erosion, pollution, amelioration, etc.) could be developed and evaluated**

Who steps forward?

WHO STEPS FORWARD TO DEVELOP CONCEPTUAL FRAMEWORK?

Who converts framework into a normal routine for obtaining databases?

- Soil physicists lack appreciation of pedology
- Pedologists lack appreciation of physics and mathematics
- Soil microbiologists and chemists are busy with carbon
- Small group of eager, creative statisticians known as Pedometricians in the new Pedometrics Commission of IUSS
  - Somewhat aloof as were soil physicists
  - Understand statistics, but not adequately familiar with pedology and physics

Who steps forward?

- Soil physicists provide equations
- Pedometricians provide the statistics
- Pedologists provide sampling locations based on experience using first three scalesof morphological organization

When a reality?

WHAT HAPPENS WHEN THIS THIRD OPPORTUNITY BECOMES A REALITY?

- Soil science shall be elevated to a higher intellectual level with global appreciation
- Others shall not merely call upon, but actually depend more on soil scientists for technology to address and help solve issues associated with management of natural resources
- Senior soil scientists would no longer wrongly state that sustainable soil management is only a political and social issue, not a scientific issue.
- With the third opportunity in hand, a strong soil science basis for social and political policy for sustainable soil management would be a reality - not a futile, long-awaited dream as it is today
- And for me, my career wish would be realized - randomized treatments of small plots would not be the norm for agronomic & soil research!

Last and biggest

A MUCH MORE IMPORTANT OPPORTUNITY
IS UNIVERSALLY TREASURED BY
ALL SOIL PHYSICISTS

Respect, appreciation and personal friendship
amongst all of us throughout the world

Let us sustain the goals of this College of Soil Physics
and continue similar informal meetings everywhere
to enhance science as well as lasting friendships