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Micropenetrometer for In Situ Measurement of Soil Surface Strength

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ABSTRACT

Soil surface characteristics greatly influence seedling emergence, water infiltration, and soil erosion. A portable micropenetrometer was designed to measure the strength of the soil surface (or crust) as an indirect measure of soil surface characteristics in the field. The penetrometer is designed to operate on a 12 V DC battery and is controlled by a portable microcomputer. Penetrometer measurements can be made a few millimeters apart along 1-m long transects with a small (1.6 mm) probe in order to evaluate spatial patterns of crust strength. Laboratory and field measurements show that the penetrometer is capable of detecting detailed differences in the near-surface soil (0–4 mm depth) that result from different physical, chemical, and management-related conditions. Penetration measurements from 0 to 30-mm depth at 0.1-mm depth increments reflected differences in the structure of the surface soil layer due to irrigation method by detecting sequences of aggregates and pores as the probe penetrated the soil. These results indicate that the micropenetrometer is capable of detecting and quantifying differences in soil surface characteristics influencing physical processes at the soil surface.

SOIL CRUSTING has long been known for its detrimental effects on seedling emergence (Hanks and Thorp, 1956, Parker and Taylor, 1965), water infiltration (Duley, 1939; Morin et al., 1981), and soil erosion (Epstein and Grant, 1967). Crusts are characterized by greater bulk density, smaller macroporosity, and greater mechanical strength in the dry stage (Hillel, 1959).

Soil strength is often implied from measurements of the force or resistance of the soil matrix to deformation from a penetrating metal probe or penetrometer (Bradford, 1986). Small probes to simulate root penetration in soil have been used by Taylor and Gardner (1963), Barley et al. (1965), Waldron and Constantin (1970), Bradford et al. (1971), Voorhees et al. (1975), Bradford (1980), and Groenevelt et al. (1984). Grant et al. (1985) used a micropenetrometer to characterize soil structure in laboratory soil cores. Larney et al. (1989) developed a portable computer-controlled constant rate, cone penetrometer as a means of characterizing tillage effects on soil strength and soil compaction. This device was designed to measure strength throughout the rooting depth of annual crops.

Measurements of crust strength were made using a laboratory penetrometer by Taylor et al. (1966). Callebaut et al. (1985) developed an electrically-operated needle type penetrometer to measure soil surface strength in the laboratory in order to evaluate factors affecting seedling emergence. Most field conditions that influence strength measurements, such as cracks, living organisms, plant cover, and residues, are difficult to duplicate in laboratory experiments. Therefore, it is desirable to measure and characterize the physical and mechanical features of the soil surface in the field. It is expected that the potentially large areal variability of in situ crust strength may have a significant influence on physical properties controlling such processes as infiltration, gas diffusion, evaporation, and seedling emergence.

The objectives of this article are to (i) describe an instrument to measure strength of soil surfaces (or crusts) at a small enough spacing both on the soil surface and with depth for detection of spatial patterns and the microfabric of soil in the field; and (ii) evaluate the capabilities of the instrument in detecting differences in surface characteristics associated with soil physical properties and irrigation management.

MATERIALS AND METHODS

Micropenetrometer

A photograph of the micropenetrometer is shown in Fig. 1. The unit is small enough (1.62 m long, by 0.61 m wide by 0.61 m high) to be transported for field measurements. It weighs 60 kg and operates from a 12-V DC gel-cell battery, a battery in a vehicle, or any 12-V battery that can supply a minimum of 5 A.

The penetrometer consists of a rectangular steel frame supported by three adjustable legs to allow levelling the penetrometer. Running the length of the frame are two stainless steel guide rods and a stainless steel lead screw. A transverse steel plate slides on the guide rods by means of three ball bearing pillow blocks. The plate is attached to the ball bearing follower of the lead screw allowing it to move back and forth by a horizontal stepper motor.

The transverse steel plate supports two vertical guide rods and a lead screw. These are attached to the load cell carriage and allow it to move up and down with a vertical stepper motor. On the bottom of the load cell is a contact sensor and a chuck, which holds the penetrometer probe. A flat-tipped, 1.59-mm diam. probe was used for crust measurements.

The penetrometer has two electronic components, the stepper motor circuitry and the computer-based controller. The controller is built around an Intel 8748 microcomputer (Intel Corp., Santa Clara, CA). The controller is able to communicate with an external computer by means of an RS-232C serial interface for purposes of data transfer to a more powerful computer for statistical analysis and data presentation. The controller can respond to commands that cause the penetrometer probe to move horizontally or vertically and to initiate a penetration sequence. The penetration sequence causes the probe to move down until it contacts the

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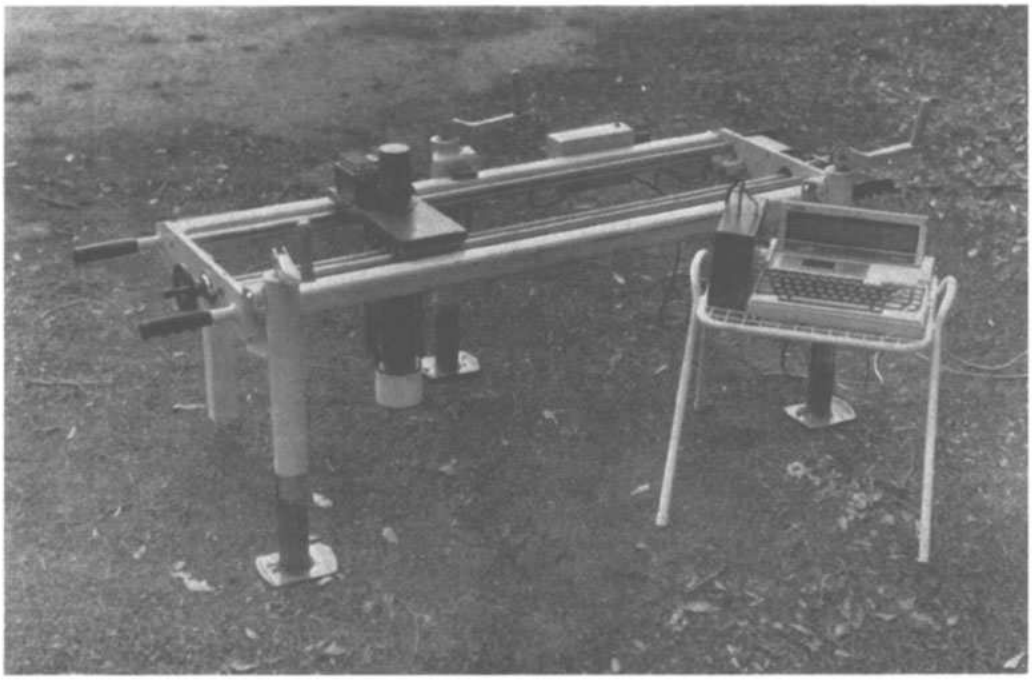

Fig. 1. Photograph of the micropenetrometer and computer.

soil, and then the controller begins sending force data to the computer across the serial line. Penetration continues until a predetermined depth is reached and the probe retracts and moves to the next spatial position. Some specifications of the micropenetrometer are given by Table 1.

Laboratory and Field Measurements

Laboratory measurements were made to examine soil behavior with the penetrometer probe and to determine operational settings such as depth and speed of penetration and the probe size and shape. Air-dry Zamora soil (fine-silty, mixed, thermic Mollic Haploxeralf; Wyo loam soil, May 1968 soil survey of Glenn County, California) was ground, sieved (4 mm), packed into a 0.9 by 0.45 by 0.2 m box to a bulk density of 1.32 Mg/m^3, saturated, left to drain, and then to dry at room temperature. To test reproducibility, a series of readings were taken across a range of water contents from 0.027 to 0.346 g g^{-1}, with six replicates at each water content taken within an area of 40 by 40 mm.

Field strength measurements were made to investigate effects of soil surface changes induced mainly by management alterations. Four field plots located within an area of 2 ha of Yolo loam soil (fine-silty, mixed, nonacid, thermic Typic Xerorthent) consisted of the following treatments: (i) soil crusted under rainfall, (ii) soil with 10 mm scraped from the surface, (iii) soil with a densified surface after furrow irrigation, and (iv) compacted soil from tractor traffic. All measurements were made when the upper 30 mm of the soil surface was considered to be air dry.

Table 1. Mechanical and electronic specifications of the micropenetrometer.

Horizontal		Vertical	
Maximum travel	1.5 m	Maximum travel	0.20 m
Resolution	0.025 mm	Resolution	0.016 mm
Maximum speed	10 mm/s	Maximum speed	6.7 mm/s
Force measurements		**Computer interface**	
Maximum force	23 kg	Interface	RS-232C
Resolution	5.5 gm	Rate	9600 baud
Load cell	SM-50†	Data format	16-bit binary

† Interface, Inc., Scottsdale, AZ.

At an additional field site, three types of surface amendments had been applied to Hanford sandy loam soil (coarse-loamy, mixed, nonacid, thermic Typic Xerorthent) a year before strength measurements were taken. These included gypsum ($CaSO_4 \cdot 2H_2O$), almond (*Prunus amygdalus* Batsch) hulls, and a surface stabilizer of poly vinyl alcohol (PVA). Sixty penetrometer measurements were obtained from each plot. Both the maximum force and the total work of penetration of the top 4 mm, determined by integrating the area under the force-depth curves, were calculated.

To evaluate soil strength as affected by different water quality levels and irrigation methods, two water qualities, electrical conductivity (EC) = 0.33 dS/m (sodium absorption ratio [SAR] < 0.3) and EC = 2.7 dS/m (mainly Na, SAR = 8.4) were applied by sprinkler and flood irrigation to Yolo loam soil. After drying, at least 60 strength measurements of the upper 4 mm of soil were made in each of the four treatments. In addition, measurements to the 30-mm depth were made at five locations in each plot.

RESULTS AND DISCUSSION

A 1.59-mm-diam, flat-tipped, cylindrical probe was found to provide enough support against hard soil surfaces and yet resulted in minimal disturbance to the surface. The small size of the probe allows for measurements to be generally made as close as 3 mm without causing surface cracking or chipping. Thus, slightly >300 locations along a 1.0-m transect can potentially be sampled without moving the penetrometer frame. Measurements along extended depths in uniform, packed soil showed that most of the changes in force occurred in the very top few mm. For near-surface soil strength characterization, a measurement depth of 4 mm was selected with measurements taken every 0.1 mm with depth.

A penetration rate of 8 mm min^{-1} was used. Although a range of penetration rates resulted in similar force or work values, higher rates caused cracking in some cases or caused the soil edges near cracks to chip and break more readily.

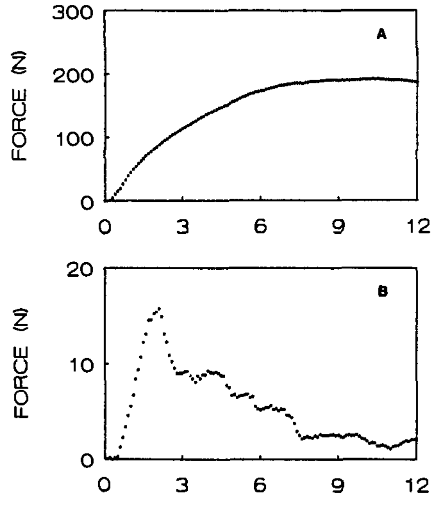

Fig. 2. (A) A typical force-depth curve for a homogeneous surface soil. (B) A force-depth curve for a shallow crust over loose soil.

A typical force–depth curve in uniform soil is presented in Fig. 2A. If the probe enters a crack or is in very loose soil, very small values of force will be measured. For a case where the probe is very near a soil crack, the probe may cause chipping of the soil with a resultant decrease in force after chipping occurs. Barley et al. (1965), using a pointed probe of 1.5-mm diameter, found that the constant-force segment began at about 9 mm. The depth is shallower for blunt probes than it is for pointed ones (Waldron and Constantin, 1970), which agrees with our observations (Fig 2A). Thus, in order to evaluate crust strength, a blunt probe appears more desirable than a pointed probe. Figure 2B shows an example of a force-depth curve for a shallow surface crust over loose, unsettled soil. The shallow crust was formed by a light sprinkler irrigation of freshly tilled soil. A curve like Fig. 2B allows the crust thickness to be determined.

Very consistent measurements were attained between six different replications at five different water contents of a crust (0–5 mm) in a packed box. The mean coefficient of variation (CV) of the five measurements was 3.84%. Due to the strong dependance of strength on crust water content, measurement presented in the following sections were made when the soil surface was air dry.

Management Practices

A goal in designing the micropenetrometer was to be able to sample strength at many locations along a transect in order to evaluate spatial patterns. Figure 3 shows differences in strength patterns along transects of ≈60 locations for different treatments. These patterns show that the strength of the surface soil can be quite variable even across spatial scales <1 m. Table 2 presents summary statistics of maximum force for the four transects of Fig. 3, as well as, other measurements to follow. Maximum force occurred at different depths for different treatments. Standard deviations were relatively high due to cracks and other variations encountered in the field soil. Transects with high CVs, such as the compacted and scraped, tended to have frequency distributions best described by natural log

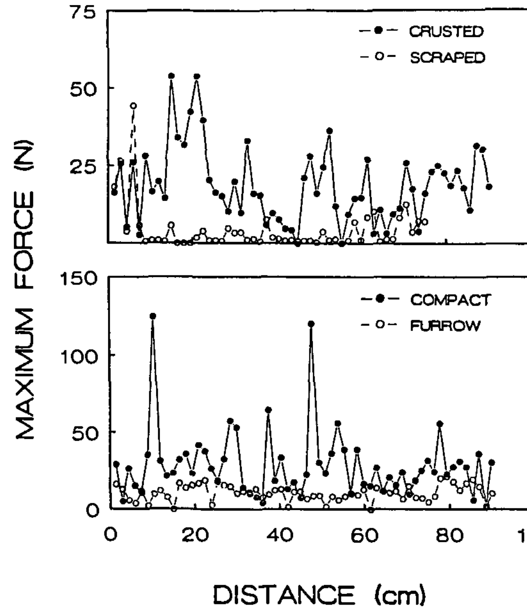

Fig. 3. Maximum force within the top 4 mm of 60 locations (50 scraped) along transects in Yolo soil for four surface conditions.

normal or some highly skewed distribution (Table 2). The compacted field had the highest overall force, followed by the crusted soil (due to rainfall), and the furrow irrigated, then last by the scraped field. It is important to note that the soil-water content (0.047 g g^{-1}) in the furrow-irrigated plot for the 0- to 4-mm depth was higher than the other treatments (0.02 g g^{-1}) at the time of measurement; otherwise, the strength values would have probably been larger. Statistical *t*-tests showed that the maximum force was significantly different ($\alpha = 0.05$) between every pair of treatments. The action of water, either as rain or irrigation, resulted in greater strength values in the surface than in the underlying soil (scraped case). A strong correlation was observed between the total work (force integrated for depth of 0–4 mm) and the maximum force, reflected in correlation coefficients that ranged between 0.83 and 0.94 for the different treatments.

The ability of the micropenetrometer to measure penetration force at many locations along a transect allows an evaluation of spatial patterns and variability using several statistical measures such as the variance,

Table 2. Summary statistics of strength measurements for various soil conditions and treatments.

Treatment	Sample size	Mean maximum force	Standard deviation	CV	Frequency distribution
		N		%	
Furrow	60	10.66	5.15	48.38	Normal
Crusted	60	18.69	11.97	64.03	Normal
Compacted	60	28.63	22.21	77.58	Ln Normal
Scraped	50	4.49	7.56	168.27	Ln Normal†
Control	60	20.45	10.83	52.96	Normal
Gypsum	60	7.62	6.88	90.29	Ln Normal
Almond	60	11.07	6.72	60.70	Ln Normal
PVA	60	5.86	4.10	69.97	Ln Normal
Sprinkle Hi Na	60	11.49	7.61	66.23	Ln Normal
Sprinkle Lo Na	60	11.58	6.15	53.11	Normal
Flood Hi Na	60	28.64	9.47	33.07	Normal
Flood Lo Na	60	21.98	8.68	39.49	Normal

† Skewed more than ln normal.

the frequency distribution, and the autocorrelation function. Autocorrelations for the four transects of 60 locations showed spatial correlation only in the crusted field. A high correlation was obtained at the first lag, reflecting the influence of neighboring points on one another. The crusted field had a high frequency of medium-sized cracks. It was observed that penetrometer readings taken near a crack usually resulted in cracking or chipping of the soil, thus causing a significant number of neighboring points having small force values to be spatially correlated. Autocorrelation and other spatial techniques provide opportunities to obtain additional information on crust strength patterns for various soils.

Visual inspection of spatial patterns of surface soil or crust strength can also be useful in interpreting results from soil management treatments. As an example, Fig. 4 shows two transects of surface soil strength within two, 1-m^2 plots of differing cover crops in an orchard. Inspection of the strength patterns indicate an area of very low surface strength indicating a weak crust or no crust at all in a portion of one of the plots. Infiltration measurements made across the entire area of the 1-m^2 plots gave cumulative infiltration during a 120-minute period of 3.3 cm in the plot represented by open circles and 6.7 cm in the plot represented by closed circles (Fig. 4). Differences in infiltration between the plots were probably due to differences in soil surface characteristics due to soil spatial variability rather than differences in cover crop effects.

Surface conditioners and organic amendments have been known to improve permeability-related characteristics of the soil and influence crust strength (Wischmeier and Mannering, 1969; Callebaut et al., 1985). Gypsum addition has also been shown to improve soil aggregation and decrease the susceptibility of the soil to form a hard seal. Organic materials have a similar effect.

Statistical analysis of the different surface treatments on Hanford soil showed significant differences in strength between the control and all other treatments (t-test at $\alpha = 0.05$) 1 yr after applying amendments (Fig. 5 and Table 2). No significant differences were detected between the gypsum treatment and the almond hulls or the PVA stabilizer treatments. The almond hulls treatment showed significantly higher strength than the PVA stabilizer treatment (Fig. 5). Different treatments had a clear impact on soil surface characteristics, which could be detected with the penetrometer. The average work was highest in the control plot (0.039 J), followed by that for the plots treated with almond hulls (0.017 J), followed by the gypsum treatment (0.012 J). The lowest average work was in the plots with PVA surface stabilizer (0.009 J). Lower strength is apparently due to aggregation or to a less dense surface soil. The CVs of the mean force were quite high for all but one of the four treatments, indicating large variability. Correspondingly, frequency distributions were best described by natural log normal distributions.

As shown in Fig. 5, relative magnitudes of the penetration resistance had the same trend whether expressed as the average of the total work or the maximum force with high correlation between the two.

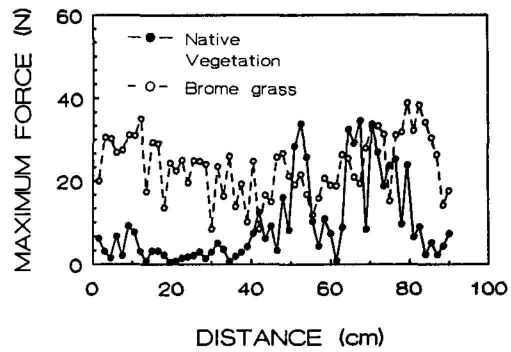

Fig. 4. Maximum force along transects (60 locations) in 1-m^2 plots of different cover-crop treatments. The growth of native vegetation was controlled by light applications of herbicides.

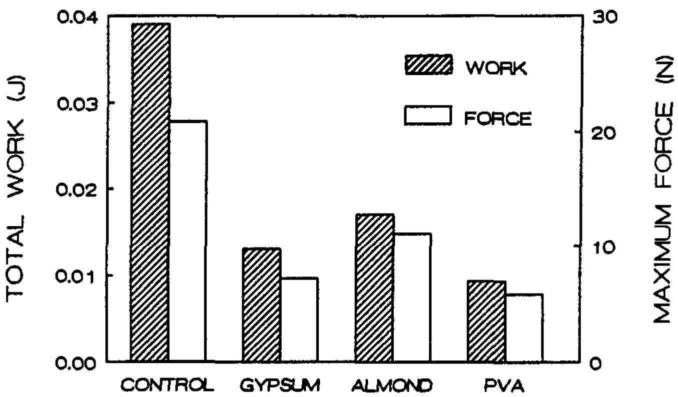

Fig. 5. Average maximum force and total work for three soil surface treatments and a control on Hanford soil. Each mean was calculated from 60 measurements. Surface cracks were not visible for any of the treatments.

The advantage of this conclusion is the convenience of using a single integrated value or a single maximum force value rather than a string of values as a measure of surface strength.

Water Quality and Irrigation Method

Average strength measurements calculated for locations not affected by cracking for different treatments of water quality and irrigation method treatments are shown in Fig. 6. Soil surface strength was higher for flood- than for sprinkle-irrigated plots. Also, flood-irrigated plots with high-Na water showed higher penetration resistance than those irrigated with low-Na water (Fig. 6 and Table 2). The CVs of mean force were not exceptionally high for these treatments except for the sprinkle-irrigated, high-Na plot and could be described generally by normal frequency distributions. Flooding of the soil surface and the settling and reorganization of soil particles under saturated conditions promote the development of a densified layer at the soil surface that can extend several cm deep (Bedaiwy, 1988). This densified layer existed for both water types, ranging from $\approx$30 to 50 mm, and had high bulk density and mechanical resistance. The bulk densities of the sprinkle- and flood-irrigated plots were 1.54 and 1.62 Mg m^{-3}, respectively. Water quality did not significantly affect bulk density values. A crust, on the other hand, 8 to 12 mm thick, developed in sprinkle-irrigated plots.

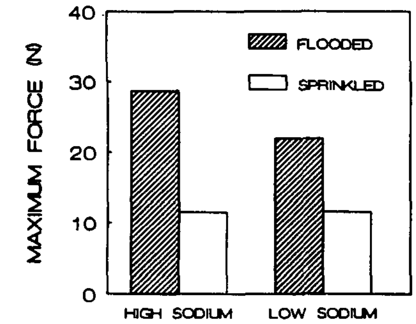

Fig. 6. Average maximum force for Yolo soil irrigated by high- and low-Na water with flood and sprinkler irrigation. Each mean was calculated from 60 measurements in noncracked areas.

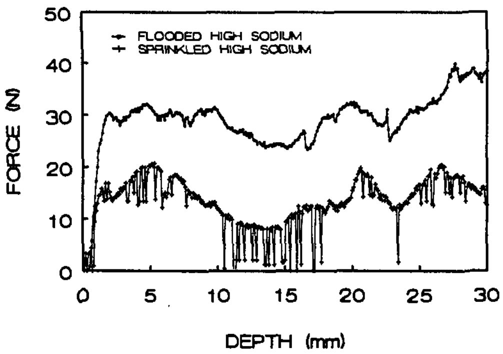

Fig. 7. Force-depth curves to the 30-mm depth for the flood- and sprinkler-irrigated treatments on Yolo soil.

Force-depth curves for deep (30 mm) penetrations in soil irrigated by the two methods revealed that the soil surface under flood and sprinkle irrigation (the densified layer and the crust, respectively) were clearly different for the two methods. Densification under flooding and saturation resulted in settling and reorganization of particles into a closely-packed system. This is indicated by the solid, smooth force curve in Fig. 7. Sprinkle irrigation, on the other hand, is known to lead to the formation of a surface crust. A crust is characterized by a skin of well-oriented clay particles on top of a washed-in zone (McIntyre, 1958; Tackett and Pearson, 1965). The soil under the crust typically had an open system with more and larger pores as reflected in the force curve (Fig. 7). The soil surface was air dry and at the same water content for both irrigation methods. Force curves at four other locations of both irrigation treatments showed similar behavior. The oscillating trend across the 300 measurements with depth, which corresponds to a penetration depth of 30 mm, reflects this open system, particularly at depths >5 to 10 mm, which agrees well with crust thickness as visually observed in the field. This capability to measure changes in penetration force at distances as small as 0.1 mm may be quite useful, since it provides information about the microfabric of the surface layer, as well as, the depth of a crust by defining the zones of dense and open packing.

SUMMARY AND CONCLUSIONS

The micropenetrometer is capable of detecting and quantitatively determining differences in soil surface strength as influenced by various factors. Differences due to management practices, surface additives, irrigation water quality, and irrigation method were reflected in differences in surface penetration resistance whether expressed as maximum force or integrated work of penetration. The detection of the detailed microfabric of the soil surface reflecting its particle packing and the thickness of the surface crust appears to be possible due to the capability of making measurements at 0.1-mm depth intervals. The capability to make many measurements along a 1.0-m transect of the soil surface without moving the penetrometer frame allows an evaluation of spatial patterns and variability.

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