Chapter 2

MATERIALS AND METHODS

Three distinct field experiments were conducted at the University of Arizona's Marana Agricultural Center (626 m elevation above MSL, 32.5 degrees north latitude) about 30 miles NW of Tucson. A 1 ha area was used in Field E-2 under the second span of a lateral move sprinkler with low pressure circular spray nozzles. The soil is a Pima clay loam, fine-silty, mixed, thermic family of Typic Torrifluvents. A uniform clay loam surface layer extends to about 90 cm depth and grades into fine sandy loam. Clay lenses occur discontinously. The surface clay loam is somewhat thicker in the NW corner of the plot than in the SE corner. Particle size distribution is 36% sand, 33% silt and 31% clay. The soil contains about 1% organic matter (Post et al. 1978)

Experiments 1 and 2 were conducted concurrently in March and April 1985. Experiment 1 compared the infra-red temperature based method of evaporation estimation from a bare soil (energy balance model of Ben-Asher et al. 1983) to the microlysimeter method on a small scale, while also investigating the effects of length and wall material on microlysimeter performance. Using data from this experiment the energy balance model was modified and improved in preparation for its use in experiments 2 and 3.

Experiment 2 was an attempt to determine the soil water balance at 57 locations in the field using the infra-red method to estimate evaporation and neutron scattering to measure soil water content. Also, the uniformity of irrigation as measured with catch cans was compared with that measured by neutron scattering at the same locations.

Experiment 3 was conducted in October and November, 1986 in the same area with the same irrigation system. Comparisons of the infra-red method were made with the microlysimeter method at the 57 locations used previously. There were two experimental runs, the second of which was used to validate the energy balance model.

Experiment 1, Microlysimeter Performance

The first experiment compared the temperature-based and microlysimeter methods of estimating evaporation from bare soil. Sub-experiments compared the performance of steel versus plastic microlysimeters (ML's), the performance of ML's of 3 different lengths, and the effect of capped vs. uncapped ML bottoms. Microlysimeters were installed in a two factor experimental design using 3 replicates and 2 blocks (Figure 2-1). The factors were length (3 levels; 10, 20 and 30 cm) and wall material (2 levels; PVC plastic and steel). Plastic ML's were 8.15 cm in inside diameter with 0.35 cm wall

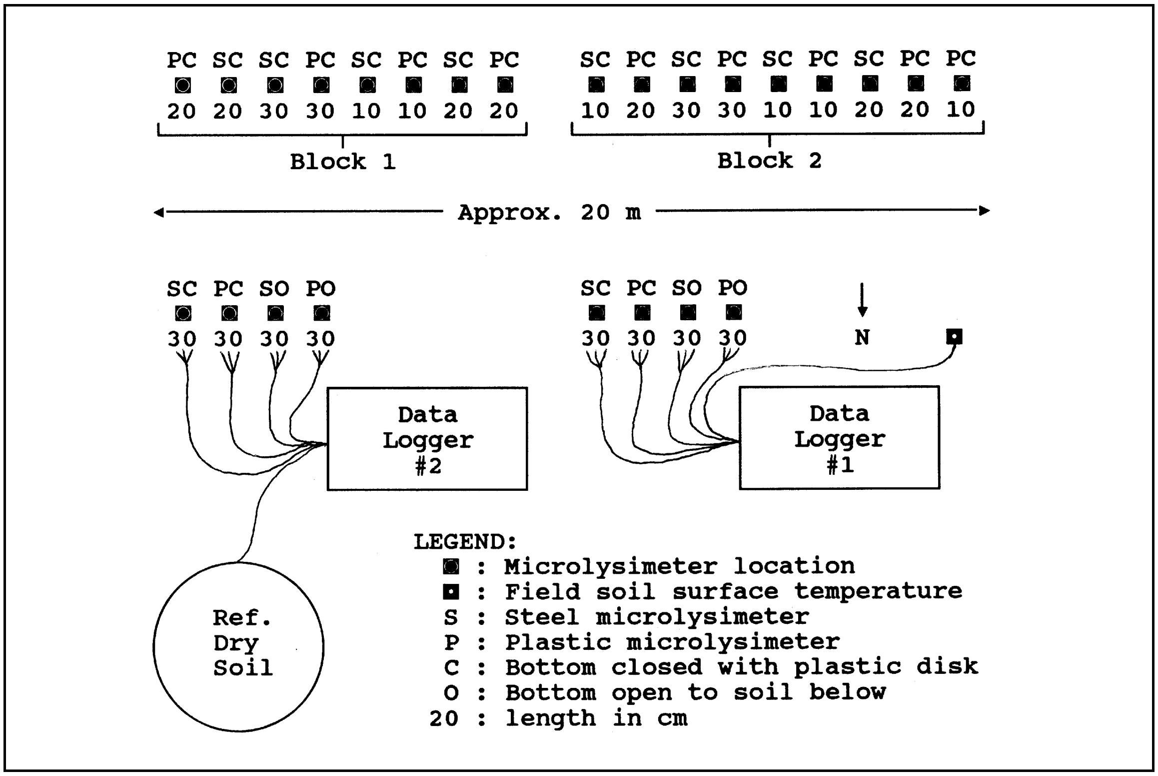

Figure 2-1. Field layout schematic for Experiment 1. Top row of ML's was weighed daily. Bottom row was instrumented with thermistors and weighed at experiment's end.

thickness and were of white polyvinyl chloride plastic (nominal 3 inch diameter, schedule 40 water pipe). Actual lengths were 10.5, 20.5 and 30.5 cm. Steel ML's were 8.5 cm inside diameter with 0.15 cm wall thickness and were made of nominal 3 inch diameter electrical conduit (EMT tubing). Actual lengths were 11.1, 21.1 and 31.1 cm. Since the lengths of steel and plastic ML's were not the same, the length factor was treated as a covariate in later statistical analysis. Normally ML's were capped on the bottom (after extraction) using a 6 mm thick disc of PVC plastic secured with non-stretching tape. Figure 2-2 shows an installed microlysimeter.

Only 8 ML's contained thermistors (4 plastic and 4 steel, 2 of each with bottoms capped, 2 of each in direct contact with underlying soil). This arrangement provided a comparison of the thermal regimes of steel vs. plastic ML's and of open vs. capped bottoms. Sixteen thermistors were calibrated ensemble by placing in ice water and letting the bath warm to room temperature and then placing in boiling water and letting the bath warm to room temperature. All thermistors read to within 0.5 °C of each other.

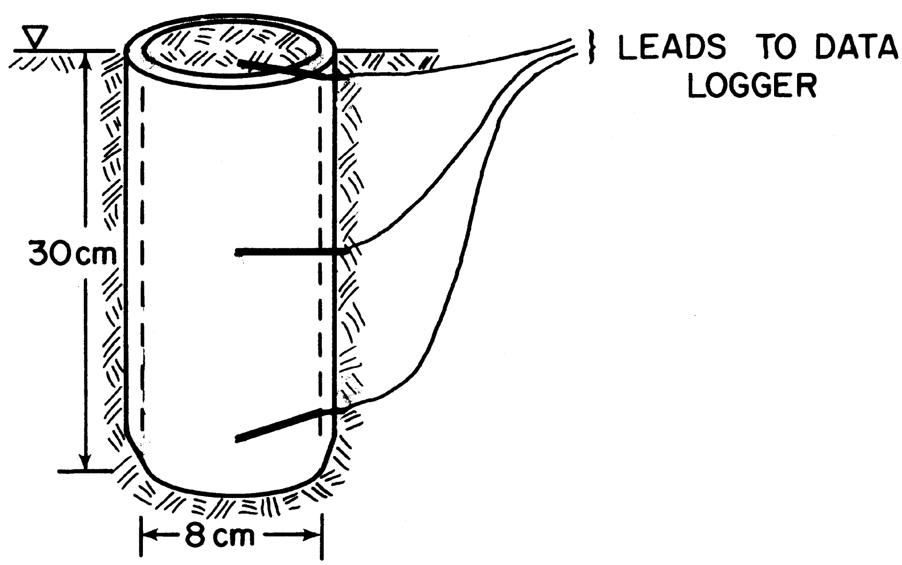

Figure 2-2. An installed microlysimeter. Thermistors shown were not installed in all ML's.

During the first and second experiments the field was planted to barley as a green manure crop. The barley was cleared to bare soil in a 3 m diameter area surrounding all measurement locations. Also the barley was cut in a wider area to the east and west of each location so that early morning and late afternoon sun could reach the sites unimpeded.

Due to the plasticity and stickiness of the soil, installation of the ML's immediately after irrigation was not possible. Installation was done on the 4th day after a preliminary irrigation when the soil was more cohesive. The maximum compaction observed during installation occurred with the 30 cm ML's and was less than 1 cm. After an additional 4 days of drying an irrigation of 2.1 cm was applied with a low pressure lateral move sprinkler. The silty soil surface was immediately puddled and sealed by the large drops from the sprinkler and no preferential channeling of water along the ML's walls was expected. Measurements on the ML's started on the day after irrigation and continued for 9 days. The timing of events is shown in Table 2-1.

Microlysimeters were extracted, cleaned, capped on the bottom and weighed between 8:30 AM and 3:15 PM on the day after irrigation. Weighing was done with a large triple beam balance installed in a wooden box as protection against wind. Evaporation was measured by weighing ML's on subsequent days

Table 2-1.

Schedule of events for Experiment 1, March and April 1985.

Date	Day	ML's Weighed[1]	IR[1] AM	IR[1] PM	Rain	Comments
31-3	90	no	no	no	no	---
1-4	91	Irrigation, 2.08 cm. King tube samples taken before irrigation.				
2-4	92	15:03	no[2]	13:12	no	3
3-4	93	8:00	6:20	12:55	no	---
4-4	94	8:58	6:20	13:00	no	4
5-4	95	7:34	6:20	13:05	no	5
6-4	96	6:55	6:10	13:00	no	---
7-4	97	6:59	6:00	13:00	no	---
8-4	98	7:17	6:07	13:06	no	---
9-4	99	6:41	6:00	13:05	no	6
10-4	100	7:18	6:10	13:05	no	---
11-4	101	7:18	no	no	no	---
		King tube samples taken. Experiment ended.				

1 Times when weighing and IR thermometry were completed.
2 IR readings done by 6:20 in field around access tubes.
3 Thermistors installed in ML's by 15:00.
Thermistors were installed in 2 field soil locations on 22 March at surface, 15 and 30 cm.
4 Replaced CR21 data logger on weather station.
Lost wind speed data for most of this day.
5 Replaced anemometer at 6:30, calibrated vs. previous one.
6 Thunderheads appeared in east in afternoon.

within a half-hour after sunrise. The lengthiness of the extraction and cleaning process precluded accurate measurement of evaporation on the first day after irrigation. Because of this disadvantage, special extraction tools were built for later experiments to speed up the process. Tools for installation and extraction of ML's are shown in Figure 2-3.

Soil surface temperatures were taken daily with the infrared thermometer (Everest Interscience Infrared Thermometer model no. 110 with 3 degree field of view) and recorded automatically on a polycorder (Omnidata Polycorder, model 516-32, serial no. 0587). The average and standard deviation were calculated for 10 readings of soil surface temperature taken for each ML, once just before dawn and again between 1:00 and 1:30 PM. If the standard deviation was more than 0.1 °C, the measurement was made again. The infrared thermometer was calibrated against a blackbody at ambient temperatures of 14.5, 20.0, 31.5 and 41 °C. Over the range from 0 to 50 °C, the largest deviation from blackbody temperature was +1.6 °C at a blackbody temperature of 50 °C.

Two reference dry soils were established by packing plastic buckets (29 cm inside diameter, 34 cm deep) with air dry soil (sieved to 2 mm) to a bulk density of 1.62 Mg m^{-3} and burying them in the field so that the soil surfaces in the buckets were at the same elevation as the field surface. Burial occurred 2 weeks before irrigation in order to allow the reference soils to equilibrate thermally. The buckets were sealed during irrigation to prevent wetting. Surface temperatures of the reference dry soils were obtained in the same manner as for the ML's both before and after readings on the ML's.

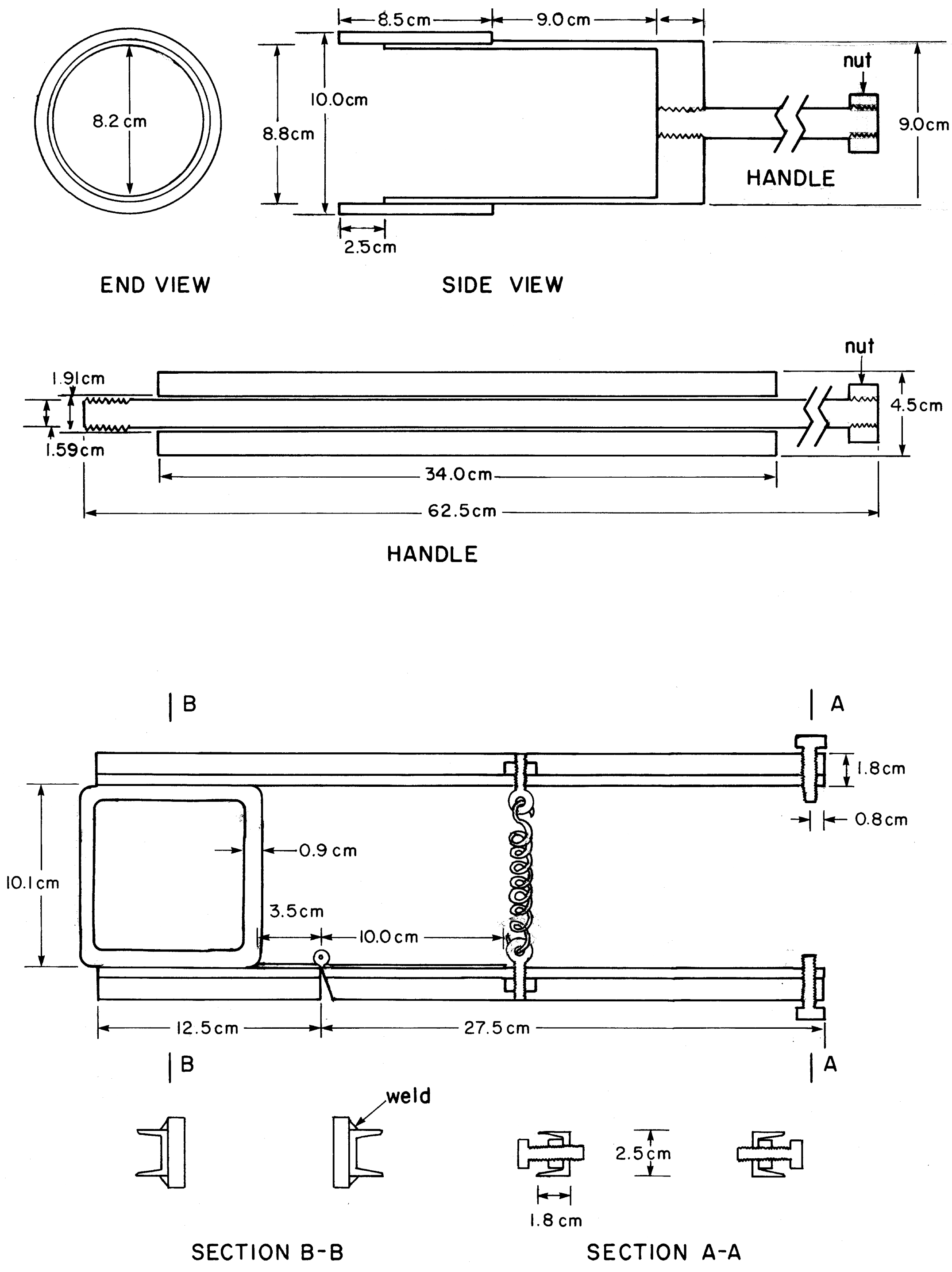

Figure 2-3. Microlysimeter driver (top) and extraction (bottom) tools.

Table 2-2.

Instrumentation.

<u>Weather Station</u>

Campbell Scientific Inc., model 21X micrologger,
serial no. 2066.
Campbell Scientific Inc., model 107 thermistor probe
Li-Cor Inc., model LI200S, pyranometer, serial no. 3879.
Campbell Scientific Inc., model 207 relative humidity and
temperature sensor, serial no. 1049.
Met One, Inc., model 014A, windspeed sensor, Part 014
Micromet Instruments net radiometer, serial no. 760.
Sierra-Misco, model RG2501, tipping bucket raingage.

<u>Other Instruments</u>

Campbell Pacific Nuclear model DR503, neutron depth gage,
serial no. H34115766.
Everest Interscience Infrared Thermometer, model no. 110,
serial no. 10134.
Omnidata Polycorder, model 516-32, serial no. 0578.

Soil temperatures were also measured at 3 depths in 8 ML's in a sub-experiment comparing the thermal regime of plastic to steel ML's (Figure 2-1). All 8 ML's were 30 cm long, 4 were of steel and 4 of plastic. Holes for insertion of thermistors were drilled in the sides of the ML's at 3 depths, at 1 cm, at 15 cm and at 30 cm. Thermistors were placed so as to be centered at the vertical axis of the ML's. The thermistors at 15 and 30 cm depths were inserted horizontally into the soil. The surface thermistor was pushed through the soil from 1 cm below the surface until the tip of the thermistor had just begun to disturb the surface. This technique was an attempt to measure as close to the surface as possible without exposing the thermistor to direct solar radiation. The thermistors used were Campbell Scientific model 107 thermistors modified to be water resistant. The thermistors were scanned every 15 minutes by 2 Campbell Scientific model 21X microloggers which recorded the average of 6 readings taken at 10 s intervals. Thermistors were installed on day 92 1985, the day after irrigation. One thermistor was installed just beneath the surface in the reference dry soil.

A weather station was set up in the SW corner of the field to measure wind speed (at 3 m), relative humidity (at 2 m), air temperature (at 2 m), net and solar radiation (at 2 m). Data were recorded on magnetic tape at 15 minute intervals around the clock. Table 2-2 shows the manufacturer and model of sensors used.

Experiment 2, Field Water Balance

Experiment 2 required the installation and calibration of neutron scattering access tubes at 57 locations for the determination of soil water content (the storage component of the field water balance) (Figure 2-4). A random number generator was used to choose the x- and y-coordinates of 42 locations on a finite, 1 m square grid. Fifteen additional locations were chosen by the author on a 0.5 m square grid so as to have a reasonable number of sampling locations within 1 to 2 m of each other. This non-random choice of sample locations was dictated by the desire to calculate the variogram for lags of 2 m with about the same precision as those calculated for larger lags. When locations were chosen on a completely random basis, the shorter lags (around 2 to 10 m) had a much lower number of sample pairs than did the longer lags (around 20 m and above). The lag classes (class number) and number of sample pairs per class are shown for different class widths in Table 2-3. Sampling locations were flagged in the field using a surveying instrument and tape measure to a precision of +/- 5 cm.

Table 2-3.

Number of data pairs per class for different class widths.

Maximum separation distance allowed was 100 m. Location coordinates were those for the 57 access tube locations (Figure 2-4). Number of pairs were not computed for class numbers greater than 24.

Class No.	Class width (m) 2.5	5	10	15	20	25	30
1	27	45	92	156	228	312	405
2	18	47	136	249	318	386	447
3	23	64	177	218	306	325	355
4	24	72	141	229	231	273	
5	21	84	152	171	213		
6	43	93	154	184			
7	38	65	121				
8	34	76	110				
9	35	77	124				
10	49	75	89				
11	45	78					
12	48	76					
13	31	53					
14	34	68					
15	41	50					
16	35	60					
17	43	74					
18	34	50					
19	34	51					
20	41	45					
21	33	47					
22	45	64					
23	38	72					
24	38	84					
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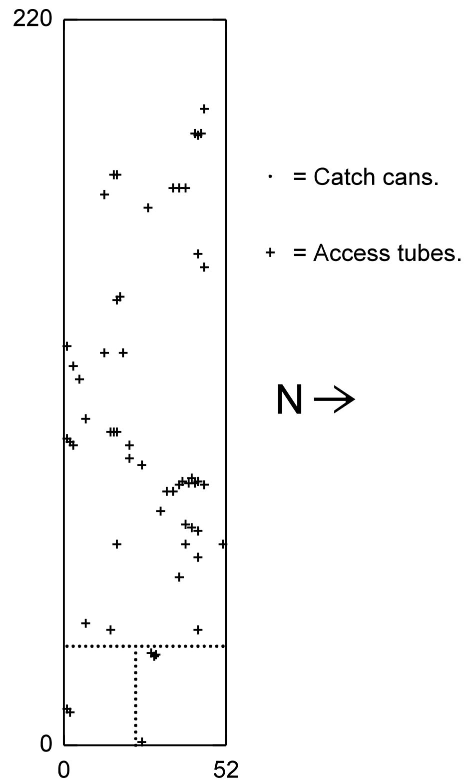

Figure 2-4. Sampling locations for Experiments 2 and 3. Catch cans were also placed at access tubes. Dimensions are in meters.

Irrigations of 4.16, 2.08 and 1.60 cm were applied on March 21, April 2 and April 12, 1985, respectively. Neutron probe readings were taken at all 57 locations just before irrigation and on every day after irrigation (Table 2-4).

The neutron probe (Campbell Pacific Nuclear model DR 503) was field calibrated concurrent with the installation of 57 access tubes (2 inch nominal diameter steel electro-mechanical tubing) to a depth of 152 cm. Access holes were bored with a 4.4 cm diameter auger and undisturbed cores of 60 cm^3 volume were taken with a Madera probe (Figure 2-5) centered at depths

Table 2-4.

Schedule of events for Experiment 2, March and April 1985.

			IR			
Date	Day	NP	AM	PM	Rain	
18-3	77	yes	no	no	no	
19-3	78	--	--	--	--	
20-3	79	Irrigation, 4.16 cm. Catch can measurements at neutron access holes, parallel to lateral and perpendicular to lateral.				
21-3	80	yes	7:13	14:00	no	
22-3	81	yes	7:07	13:32	no	
23-3	82	yes	6:45	13:08	no	
24-3	83	yes	6:35	13:08	no	
25-3	84	no	6:21	13:17	no	No wet soil visible today.
26-3	85	yes	6:31	13:06	no	Added NP reading at 90 cm.
27-3	86	no	6:30	13:06	no	
28-3	87	no	6:18	13:10	no	
29-3	88	no	no	no	yes	Rain ended experiment.
31-3	90	yes	no	no	no	
1-4	91	Irrigation, 2.08 cm. Catch can readings at neutron access holes and parallel to lateral. King tube samples before irrigation.				
2-4	92	yes	6:20	13:01	no	
3-4	93	yes	6:20	12:37	no	
4-4	94	yes	6:20	12:45	no	
5-4	95	yes	6:20	12:49	no	
6-4	96	yes	6:10	12:50	no	
7-4	97	no	6:00	12:47	no	
8-4	98	yes	6:07	12:51	no	
9-4	99	no	6:00	12:50	no	
10-4	100	yes	6:10	12:51	no	
11-4	101	Irrigation, 1.60 cm. Catch can readings at neutron access holes and parallel to lateral. King tube samples before irrigation.				
12-4	102	yes	6:10	13:05	no	
13-4	103	yes	6:04	12:57	no	
14-4	104	no	6:10	13:00	no	
15-4	105	yes	none	none	no	Experiment ended.

of 15, 30, 45, 60, 75 and 105 cm. Immediately after each hole was bored the access tube was installed and neutron scattering was measured at the same 6 depths.

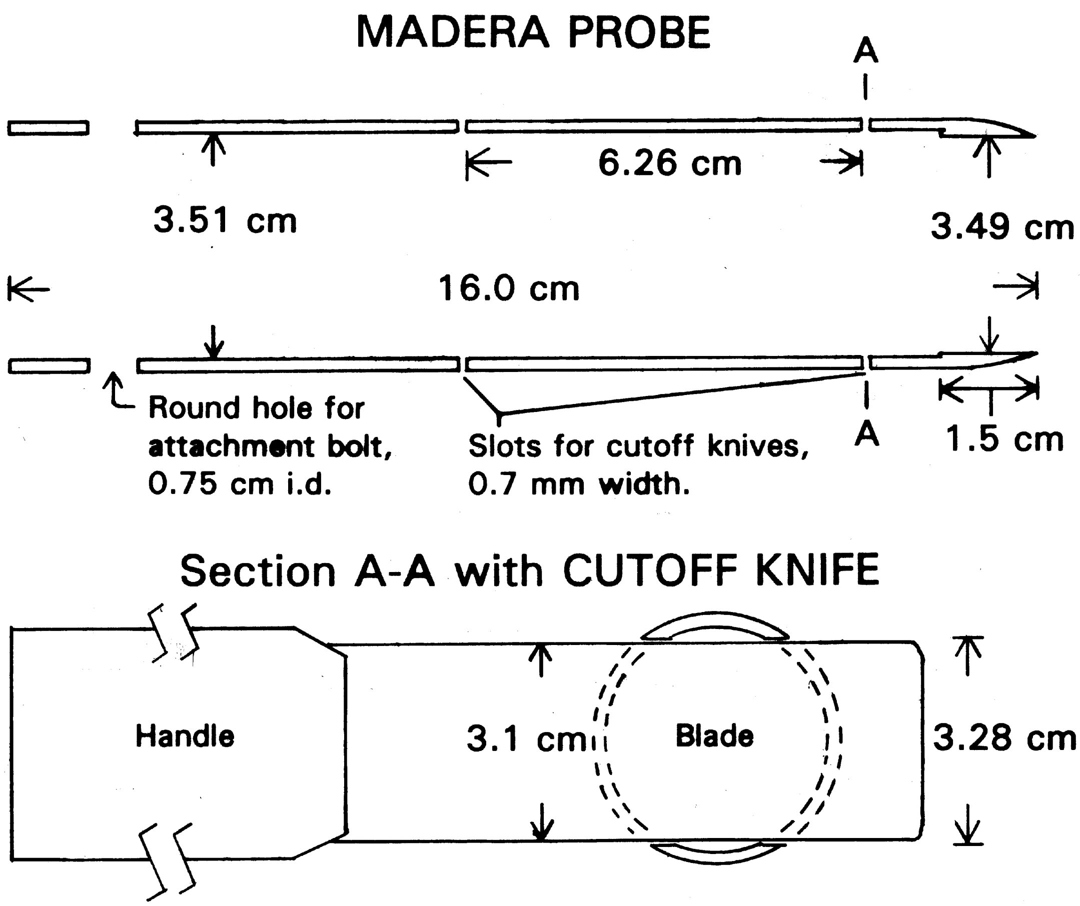

Figure 2-5. Schematic of Madera probe used for volumetric soil sampling.

The Madera probe (Figure 2-5) is no longer available from the original manufacturer. It is a cylindrical probe with a beveled tip for easy soil penetration. Above the cutting edge the probe is bored slightly larger to eliminate friction, between the probe and soil core, which might compress the core. The probe attaches to a driving tube which allows it to be used inside an auger hole. After augering to a few centimeters above the depth to be sampled the auger is removed and the probe is inserted into the hole and pushed or driven into the bottom of the hole until it is centered at the depth to be sampled. Twisting the driving tube shears the soil at the bottom of the probe allowing the probe to be withdrawn with a soil core inside. Two sets of slots in the probe allow the insertion of knives for cutting the soil core into a solid cylinder with a volume of 60 cm^3.

Linear regression analysis of volumetric water content, θ, versus neutron probe count resulted in 4 regression equations (Table 2-5). The equations were for the surface layer (samples at 15 cm), and 3 subsurface layers corresponding to samples taken at 30 and 45 cm depth, those taken at 60 and 75 cm depth, and those taken at 105 cm depth, respectively. Equation slopes for the 3 subsurface layers were significantly different at the 95% confidence level. The surface layer equation was probably influenced by the proximity of the surface which would have intersected the neutron probe's sampling volume resulting in some neutrons being lost. The other 3 equations probably reflect the change in soil texture with depth - the soil became sandier in texture as depth increased.

Table 2-5.

Neutron probe calibration equations.

Campbell Pacific Nuclear model DR503, serial no. H34115766, Marana Agricultural Center, Field E-2. Count was for 1 minute. Water content, Θ (m^3/m^3), ranged from 0.38 to 0.07.

Depth	Equation	R^2	N
15 cm	Θ = 0.114 + 2.98E-05(count)	0.86	34
30 & 45 cm	Θ = -0.127 + 2.94E-05(count)	0.95	89
60 & 75 cm	Θ = -0.170 + 3.59E-05(count)	0.92	85
105 cm	Θ = -0.109 + 3.19E-05(count)	0.97	48

Soil surface temperatures were taken twice daily as noted above. The infra-red gun was pointed at about a 45 degree angle at the soil surface within 30 cm of each access tube and slowly rotated to scan an area around the tube while 50 measurements were taken. If the standard deviation was more than 1.0 degree C the temperature was measured again.

Catch cans were constructed of 3 inch nominal diameter white PVC plastic pipe (8.15 cm inside diameter). The cans were 15 cm high with a beveled upper edge as shown in Figure

2-6. The plastic material was chosen because Kohl (1972) has shown that metal catch cans may loose excessive amounts of water to evaporation due to heat conduction by the walls. The 15 cm height was chosen to minimize splash out of the can and the beveled upper edge provided accurate knowledge of the horizontal surface area of the cans.

During the initial irrigation the cans were deployed in two transects, one perpendicular and one parallel to the sprinkler lateral, at a spacing of 2 m (Figure 2-4). If cans placed to the east of the lateral in the perpendicular transect were disregarded (due to edge effects) the irrigation uniformity measured by the 2 transects was virtually identical so only one transect parallel to the lateral and with 1 m spacing was used thereafter. Water collected in the cans was measured to the nearest ml (equivalent to 0.19 mm depth of water) immediately after the sprinkler had passed, using a graduated cylinder. Catch cans were also placed on top of each access tube so that the irrigation uniformity as measured by catch cans could be compared to that measured by neutron scattering. The neutron scattering method involved measurement of the soil water content of the profile both before and after irrigation. The soil moisture stored in the profile was then used as data for the uniformity calculations.

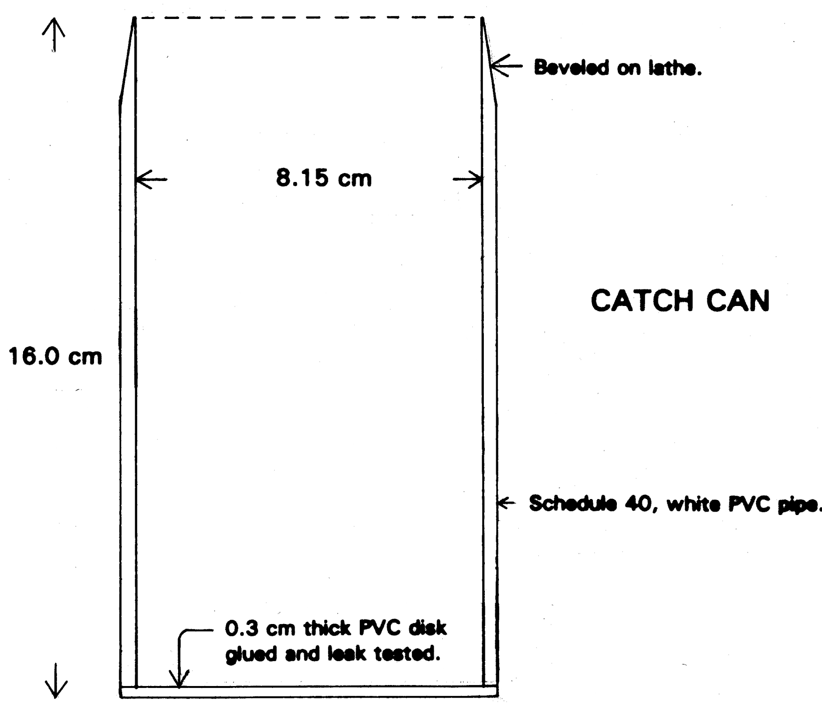

Figure 2-6. Catch can schematic.

Experiment 3, Field Scale Evaporation Measurements

Experiment 3 involved the installation of ML's at the same 57 sample locations and under the same sprinkler system as were used in Experiment 2. The purpose of this experiment was to compare the estimates of evaporation from bare soil provided by the microlysimeters to those estimates calculated from the energy balance method, on a field scale. The spatial variability of estimates from the two methods was also investigated.

The 30 cm high, white PVC ML's were driven into the ground the day before irrigation and were removed, capped on their bottoms and weighed as early as possible on the day after irrigation. On all subsequent days ML's were weighed during the first hour after sunrise (between 7:00 and 8:00 AM). For the second run the ML bottoms were closed with thin non-stretching plastic tape in order to eliminate much of the interference with soil heat flux that was caused by the 6 mm thick plastic disks used previously.

Two irrigations and subsequent measurement runs were accomplished. The first irrigation of 2.3 cm took place on October 29, 1986 (day 302) and measurements were taken until the run ended on November 17 (day 321). The second irrigation of 2.4 cm occured on 24 November (day 328) and the run ended on day 338. It took until 11:30 AM on the day after the first irrigation to remove and weigh all of the microlysimeters. This delay meant that appreciable evaporation took place before some of the ML's were weighed. For this reason soil surface temperature measurements were not made that day. Subsequently it rained on 2 days during the first run. The schedules for both runs are shown in Table 2-6. Improvements in the equipment and procedure for the initial extraction of ML's allowed weighing to to be finished by 9:14 AM on the first day of the second run and soil surface temperatures were measured that day. The entire field soil surface was bare.

Table 2-6.

Schedules for Runs 1 and 2 of Experiment 3, 1986.

Schedule for Run 1.

Calendar day	Julian day	Rain	Infra-red finished	MC's weighed
29 Oct.	302	Irrigation, 2.3 cm.		
30 Oct.	303	no	none	11:27
31 Oct.	304	no	7:08	8:32
1 Nov.	305	no	6:44	7:46
2 Nov.	306	yes	6:52	8:08
3 Nov.	307	yes	none	none
4 Nov.	308	no	6:44	8:45
5 Nov.	309	no	6:50	8:00
6 Nov.	310	yes	6:44	7:43
7 Nov.	311	no	6:45	9:40
8 Nov.	312	no	6:43	7:54
9 Nov.	313	no	6:41	7:55
10 Nov.	314	no	6:42	7:29
11 Nov.	315	no	6:44	7:29
12 Nov.	316	no	6:51	7:36
13 Nov.	317	no	6:39	7:25
14 Nov.	318	trace	6:38	7:26
15 Nov.	319	no	6:42	7:35
16 Nov.	320	no	6:34	7:54
17 Nov.	321	no	6:40	7:44

Schedule for Run 2.

Calendar day	Julian day	Rain	Infra-red finished	MC's weighed
24 Nov.	328	Irrigation, 2.4 cm.		
25 Nov.	329	no	none in AM	09:14
26 Nov.	330	no	06:42	08:13
27 Nov.	331	no	06:50	08:02
28 Nov.	332	no	06:58	07:54
29 Nov.	333	no	07:00	07:55
30 Nov.	334	no	06:58	08:12
1 Dec.	335	no	06:58	08:20
2 Dec.	336	no	06:55	08:10
3 Dec.	337	no	06:40	08:05

Soil surface temperatures were taken daily before dawn and between 1:00 and 1:30 PM at all locations by pointing the infra-red thermometer directly at the tops of the ML's and the reference dry soils. The average and standard deviation were recorded for 10 measurements at each location. If the standard deviation was more than 0.1 °C the measurement was repeated. Reference dry soils were established as for the first experiment. Soil temperatures at 0, 15 and 30 cm depths were measured by thermistors at a mid-field location and recorded every 15 minutes on tape. Unfortunately the thermistor data were lost for the first run. Net radiation was also measured at mid-field.

Since the beam balance had proved too imprecise during the first experiment, ML weights were measured to a precision of 1 g (equivalent to 0.19 mm depth of water) with a portable electronic scale (Yamato, model LZ-5000). The balance was fit into the bottom of a modified 5 gallon bucket which served both to transport the balance around the field and as a wind shield during weighing. With this system all 57 ML's spread over a 1 ha field could be extracted, weighed and returned to their holes in a 1 hr period.

Two weather stations were set up, one each at the SE and NW corners of the field. Each station measured the parameters described for the first experiment.