

# A Computer Algorithm to Estimate Leaf Area Removal (LAR) by Insects

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A computer algorithm is described which can be used with a magnetic planimeter board to produce a rapid and accurate digital planimeter. A version for the measurement of percentage of leaf area removal (LAR) by chewing phytophagous insects is given using the Hewlett-Packard\* HP 9825A computer system as an example, although the algorithm has wide ecological applicability and is compatible with many small computer systems. An area algorithm using polar rather than rectangular coordinates economizes on the storage of intermediate points, allowing measurement of closed areas of any size or shape. Sensitive areas are set up on the digitizer surface to allow the user to concentrate on measurements instead of switching attention between digitizer and keyboard. Correction routines allow for removal of errors and preservation of statistical intermediates. Data collection, transformation, storage and initial statistical analysis are performed during the measurement step. Estimation error is less than 1.2% when measuring actual areas of 25 cm<sup>2</sup> or less.

## Introduction

Estimation of catchment area, river drainage, crop acreage, growth rate, particle size and leaf area all involve the measurement of planar area. Classical methods of planar measurement include simple graph paper integration [1], weighing silhouettes cut from uniform-density paper, regression of area on linear dimensions [2], mechanical planimetry [2] and various photometric techniques [3,4,5].

We describe a computer program used with a magnetic planimeter board to produce a rapid and accurate digital planimeter. Since it involves a small computer, this method has the advantage of performing data collection, transformation, storage and initial statistical analysis during the measurement step. The labor intensity of

interactive digitizing is comparable with other techniques for measurement of planar areas, but enjoys some increase in accuracy over most other methods [6]. Unlike optical methods, there are no problems with calibration or color sensitivity and the digital planimeter can be used in cases where regression methods are inadequate or inapplicable.

This program (Listing 1) was created specifically for the measurement of percentage leaf area removal (LAR) by chewing phytophagous insects as a tool for the quantification of insect herbivory and was intended for use with the Hewlett-Packard HP 9825A desk-top computer system equipped with the 9864A digitizer peripheral. A typical paper-tape printout from this machine is given in Figure 1. The same algorithm can easily be adapted for use on other systems and other planimetry problems.

The program computes an area estimate from points sampled successively along the perimeter of a closed area of any shape using a gunsight type magnetic cursor puck. The cursor puck can sample single points from the board surface or can be used in a continuous-sampling mode to collect a number of points around the perimeter. Although the HP digitizer board returns rectangular Cartesian coordinates ( $x_i, y_i$ ), an internal conversion is made to polar coordinates ( $r_i, \sin \theta_i$ ), where:

$$r_i = (x_i^2 + y_i^2)^{1/2} \text{ and} \\ \theta_i = \arctan (y_i / x_i)$$

The area of the traced outline is estimated by the area of the n-sided polygon formed by connecting n successively sampled points, given by the absolute value of:

$$1/2[r_1 r_2 \sin (\theta_2 - \theta_1) + r_2 r_3 \sin (\theta_3 - \theta_2) + \dots \\ \dots + r_{n-1} r_n \sin (\theta_n - \theta_{n-1}) = r_n r_1 \sin (\theta_1 - \theta_n)]$$

where ( $r_1, \sin \theta_1$ ) are the coordinates of the first sampled point and ( $r_n, \sin \theta_n$ ) are the coordinates of the last sampled point [7].

The use of a polar rather than a Cartesian area algorithm economizes on the number of intermediate points which must be stored in machine memory as the area is calculated. The initial/closure point, the last sampled point, and the currently sampled point are all that

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*****
* Hargrove's *
Leaf consumption
* program *
* version 2.6 *
* 3 March 82 *
*****

trk0:file 32

area in cm2

Leaf Hole %
area area eaten
-----
6.05 1.30 21.5
4.08 1.13 27.7
9.16 1.99 21.7
9.18 2.25 24.5
6.23 2.36 37.9
10.31 0.61 5.9
9.83 0.04 0.4
8.84 0.52 5.9
6.42 0.51 7.9
7.13 0.67 9.4
6.74 0.36 5.3
5.86 0.85 14.5
7.85 0.80 10.2
5.86 0.53 9.0
4.84 0.41 8.5
7.52 0.99 13.2
9.39 1.85 19.7
****
8.74 1.05 12.0
7.44 1.15 15.5
8.38 0.38 4.5
5.52 0.75 13.6
6.33 0.82 13.0
7.27 0.89 12.2

3.89 1.46 37.5
7.19 1.14 15.9
3.74 1.42 38.0
0.42 4.36 51.8
9.17 0.50 5.5
6.48 0.63 9.7
****
6.56 0.93 14.2
8.44 0.37 4.4
9.00 1.52 16.9
7.41 0.73 9.9
4.79 0.39 8.1
7.48 3.39 45.3
7.22 0.62 8.6
5.27 0.80 15.2
5.47 0.34 6.2
5.20 1.49 28.7
12.54 0.47 3.7
-----
ΣLeaf 287.240
x̄Leaf 7.181
S.D. 1.901
S.E. 0.301
n 40
-----
Σhole 42.770
x̄hole 1.069
S.D. 0.852
S.E. 0.135
n 40
-----
% leaf eaten
avg. 14.890
x̄% 14.737
*arcsine trans.*
* (degrees) *
x̄% 22.1679
S.D. 9.1672
S.E. 1.4495
n FC942 40
*****

```

Figure 1 Sample paper-tape printout from the digital planimeter program. This printout was obtained by digitizing the leaf photocopy sheet shown in Figure 2.

must be stored as the running series is summed. There is no upper limit on the number of points which can be sampled around the periphery of the measured object, allowing measurement of very large and complex closed areas. A magnification factor can be included to accommodate reductions or enlargements and the program output can be converted to yield measurements in the desired units of area.

Board error with the HP system is 0.0254 cm (0.01 inches) and is probably eclipsed by operator error in most cases. Table 1 indicates accuracy and precision which can be expected when repeatedly measuring actual areas of graph paper squares in the range of 1 to 25 cm<sup>2</sup>, although these may vary for different systems, planar shapes and operators. Measurements below 0.0005 cm<sup>2</sup> are rounded to zero.

#### User Instructions

For the insect consumption application, leaves are collected from trees and placed in a plant press. After drying, the leaves are photocopied on a standard office

Table 1 Accuracy of planar measurement using the polar polygon estimation program.

True Area (cm <sup>2</sup> )	Estimated Area <sup>a</sup> (cm <sup>2</sup> ± 95% C.I.)
1	1.000 ± 0.017
4	4.010 ± 0.035
9	8.999 ± 0.073
16	15.999 ± 0.099
25	25.055 ± 0.151

a. Values shown represent means of ten measurements and include both machine and operator error.

copier. A magnification factor may be included in the program to compensate for alteration in image size during the photocopying process. By extrapolating leaf margins, the original, undamaged outline of each leaflet is reconstructed. Leaf images are sequentially numbered and sheets identified as to tree number and experimental treatment.

To streamline data acquisition and minimize changing between keyboard and digitizer pad, special regions are set up on the digitizer board surface above and to the left of the photocopy sheet to signify to the machine the type of area being traced next (gray areas in Figure 2). After the leaf photocopy sheet is taped to the digitizer board the machine origin is fixed at the lower left corner of the sheet using the cursor puck. This origin establishes Cartesian coordinates across the board surface. The cursor puck is then used to mark a single point somewhere along the upper edge of the sheet. This point establishes an imaginary horizontal leaf-or-hole reference line across the top of the photocopy sheet (Figure 2). A single point sampled anywhere above this horizontal reference signifies to the machine that a leaf area follows and a new leaf input cycle is beginning.

An initial/closure point is selected on the outline of the first leaf image (the leaf apex is convenient) and a series of points are collected around the reconstructed leaf perimeter using the continuous point sampling mode of the cursor puck. The coordinates of the initial/closure point are retained in machine memory. When the machine samples a point whose rectangular coordinates are within 0.0254 cm of the initial/closure point in both the x and y directions, it beeps and pauses briefly (2 seconds). During this pause the machine closes the n-sided polygon and computes its area, and the continuous sampling mode must be terminated by the operator.

The same tracing technique is then used to digitize all holes present in the first leaf. As long as the initial/closure point for each of these holes is below the reference line at the top of the sheet the machine will identify all areas measured subsequent to the first area to be holes in the first leaf. To estimate the consumption on a per leaf basis the areas of all holes in the same leaf are summed. This program can measure leaves with any

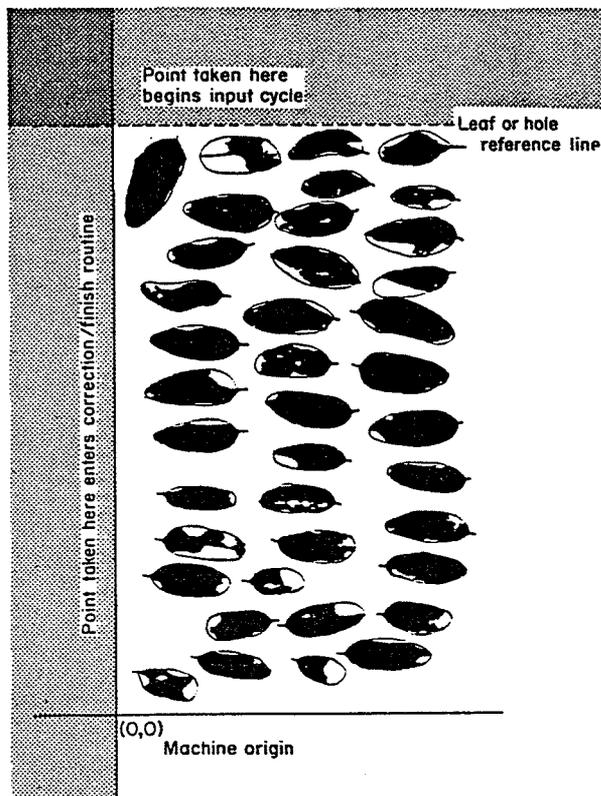


Figure 2 Digitizer board with a leaf photocopy sheet showing imaginary areas which allow the operator to control the computer without switching attention from the digitizing tablet to the keyboard.

number of holes, but if hole area exceeds leaf area, the machine will reset and a warning is issued.

When all holes in that leaf have been measured a single point is read with the cursor puck anywhere above the reference line at the top of the sheet. This causes the machine to print the leaf area, hole area and percentage consumption for that leaf. The next area traced with the puck is assumed by the machine to be the next reconstructed leaf area and the input cycle is repeated.

If an error is made or the initial/closure point is lost, it can be corrected by reading a single point anywhere to the left of the origin past the left edge of the sheet (Figure 2). When the Cartesian x-coordinate of a sampled point is less than zero the machine enters a correction routine and issues a user prompt asking if the last area is to be corrected. If a "yes" response is received via a special function key, the machine asks if the area to be corrected is a leaf or hole; the location of the next sampled point relative to the horizontal reference line determines whether the area to be corrected is a leaf or hole area. For correcting a leaf area, a single point must be read anywhere above the leaf-or-hole reference line before the leaf can be retraced. Hole areas can be redone immediately following entry into the correction routine, since the initial/closure point will be below the leaf-or-hole reference line.

If several errors are made while measuring a given leaf or if an error is not discovered until the leaf totals are printed, it may be desired to completely erase the last leaf and its holes. Another special function key can be used to delete the last entire leaf input cycle, repair running statistical totals and cause the program to print a "deleted" message. Various combinations of the correction routines can be used to preserve the accuracy of the sheet totals and summary statistics kept by the machine.

To print sheet summary statistics when the sheet is finished, a single point is taken anywhere to the left of the y-axis at the left edge of the sheet. Rather than entering the correction routine, a "no" answer is given via the appropriate special function key. The machine responds with prompt "Finished?" and a "yes" reply will initiate printing of summary statistics for leaf area, hole area and percentage of leaf area missing (LAR) on that sheet. LAR is expressed both as an arithmetic average and an arcsine-square root transformation [8]. Re-running the program initializes all variables to zero and resets the machine for the next leaf photocopy sheet.

In addition to the digitizer program, a listing has been supplied for a "companion file" program (Listing 2) which serves as a method for rapid verification of the sheet summary statistics. When individual values for reconstructed leaf area and total hole area are entered via the keyboard, the companion file program generates a summary statistics output tape in the same format as the original digitizer program. Additions or deletions of leaf areas or hole areas from sheet statistics can be made using the companion file and it is helpful in dealing with power interruptions, data pooling, aberrant samples and operator fatigue.

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Listing 1 Leaf and hole measurement program.

```

0: 1→M→W;dim H[25]
1: trk 0;ldk 0
2: fmt 5,16"*"
3: wrt 16.5;prt "*" Hargrove's *","Leaf consumption"
4: prt "*" program *","* version 2.6 *","* 3 March 82 *"
5: wrt 16.5;spc;prt "trk0;file 34";spc
6: fmt 1," area in cm",b,2/
7: wrt 16.1,29
8: fmt 1,"Leaf Hole % ",/,,"area area eaten",/,16"-
9: wrt 16.1
10: fmt 2,b,c4,f11.3
11: fmt 3,c4,f12.3
12: fmt 4,"n",10x,f5.0
13: fmt 6,"Leaf #",x,f3.0,x,"area",f7.2,x,"#holes",x,f2.0
14: fmt 8,16"-
15: fmt 9,f5.2,x,f5.2,x,f4.1
16: "Read":dsp "Read reference point for leaves";red 4,F,H
17: "2":beep;dsp"dig.above(leaf) or below (holes)";red
    4,K,L;beep
18: if K<0;gto 46
19: gto "3";if not flg1 or L-H>0;gto +1
20: for I=1 to W;P+H[I]→P;prnd (P,-2)→P;next I
21: gto +3;if P>V;gto+1
22: beep;dsp "Something's wrong:Do leaf again!;wait 2000
23: for I=1 to 25:0→H[I];next I;cfg 1;0→P→V;1→W;r0-1→r0; gto
    "2"
24: if V=0;gto +6
25: prnd(V,-2)→V;wrt 16.9,V,P,100P/V
26: V+E→E;r1+V→r1;G+P→G;r2+P→r2;V→r9;P→r10;P/V→r11
27: if P=0;1/400V→r11
28: if V-P<.0005;1-1/400V→r11
29: r3+asn(√r11)→r3;r4+asn(√r11)↑2→r4
30: for I=1 to 25;0→H[I];next I;cfg 1;0→P→V;1→W
31: "3":0→S→T→U→X→Y→Z
32: if flg1;K→X;L→Y;gto +3
33: wrt .6,r0,V,W-1
34: red 4,X,Y
35: if X<0;gto 46
36: X→A;Y→B;√(XX+YY)→Q;atn(Y/X)→T
37: 0→I
38: I+1→I
39: red 4,C,D;if I>50 and abs(A-C)<=.01 and abs(B-D)<=.01 or
    C<0;beep;gto 42
40: wrt .6,r0,V,W-1
41: √(CC+DD)→R;atn(D/C)→U;QRsin(U-T)/2+S→S;R→Q;U→T;gto -3
42: √(XX+YY)→R;atn(Y/X)→U;QRsin(U-T)/2+S→S
43: abs(6.4516*S/M↑2)→S
44: if flg1;S→H[W];W+1→W;wait 2000;gto "2"
45: S→V;sfg 1;0→r9→r10;r0+1→r0;wait 2000;gto "2"
46: 0→Z;ent "CORRECT LAST AREA?",Z;gto +4;if Z;gto +1
47: if Z>1;0→Z;prt "*" deleted*" ;gto "again"
48: if V#0 and W=1;0→V;prt "****";r0-1→r0;cfg 1;0→Z;gto "2"
49: if W>1;W-1→W;0→H[W];prt "****";0→Z;gto "2"
50: 0→Z;ent "Finished?",Z;gto "2";if Z;gto +1
51: 0→S→T→U
52: wrt 16.8;wrt 16.2,126, "Leaf",E;wrt 16.2,2, "Leaf",E/r0
53: √((r0r1-EE)/r0(r0-1))→S;wrt 16.3,"S.D.",S
54: wrt 16.3, "S.E.",S/√r0;wrt 16.4,r0;wrt 16.8
55: wrt 16.2, 126,"hole",G;wrt 16.2,2,"hole",G/r0
56: √((r0r2-GG)/r0(r0-1))→T;wrt 16.3,"S.D.",T
57: wrt 16.3,"S.E.",T/√r0;wrt 16.4,r0;wrt 16.8
58: prt " % leaf eaten ";wrt 16.3,"avg.",100G/E
59: wrt 16.2,2,"% ",100sin(r3/r0)↑2+.5cos((2r3/r0)(1-exp(-
    2UU)))
60: prt "*arcsine trans.*";prt"* (degrees) *"
61: fmt 2,b,c4,f11.4
62: fmt 3,c4,f12.4
63: wrt 16.2,2,"% ",r3/r0
64: √((r0r4-r3r3)/r0(r0-1))→U;wrt 16.3,"S.D.",U
65: wrt 16.3,"S.E.",U/√r0;wrt 16.4,r0;wrt 16.5;spc 2;end
66: "again":if r9=0;gto "2"
67: G-r10→G;E-r9→E;r1-r9r9→r1;r2-r10r10→r2
68: r3-asn(√r11)→r3;r4-asn(√r11)↑2→r4
69: beep;dsp "Do leaf over! (press cont.)";stp
70: cfg 1;0→P→V→r9→r10→r11;1→W;r0-1→r0;for i=1 to
    25;0→H[I];next I;gto "2"

```

Listing 2 Leaf and hole companion file program.

```

0:  fmt 1,16"-
1:  fmt 2,"Leaf",f7.2,x,"Hole",f7.2
2:  fmt 3,f5.2,x,f5.2,x,f4.1
3:  fmt 4,b,c4,f11.3
4:  fmt 5,c4,f12.3
5:  fmt 6,b,b,b,f13.4
6:  fmt 7,c4,f12.4
7:  fmt 8,c1,10x,f5.0
8:  fmt 9," area in cm",b
9:  trk 0;ldk 0
10: prt "*****          Hargrove's * Leaf
consumption* program *"
11: prt "** version 2.6 **companion file** 6 March 82
*****"
12: spc ;prt "trk 0;file 35";spc
13: wrt 16.9,29;spc
14: prt "Leaf Hole % area area eaten"
15: wrt 16.1
16: ent "Number of leaves on this sheet",N
17: dim X[N,3]
18: for I=1 to N
19: ent "Leaf Area",X[I,1];gto +3;if X[I,1]=9999;gto +1
20: prt "* ↑deleted↑ *";I-1=I;0→X[I,1]→X[I,2]→X[I,3];gto -1
21: ent "Leaf Area",X[I,1]
22: ent "Hole Area",X[I,2]
23: wrt .2,X[I,1],X[I,2];stp
24: cfg 13;ent "if correct, push continue",Z;if not flg
13;0→Z;gto 19
25: X[I,2]/X[I,1]→X[I,3]
26: wrt 16.3, X[I,1],X[I,2],100X[I,3]
27: next I
28: cfg 13;ent "last area correct? push 'Yes' key",Z;gto +4;if
flg13;gto +1
29: prt "* ↑deleted↑ *";I-1→I;ent "Leaf Area",X[I,1]
30: ent "Hole Area",X[I,2];X[I,2]/X[I,1]→X[I,3]
31: wrt 16.3,X[I,1],X[I,2],100X[I,3]
32: for I=1 to N
33: X[I,2]→r11;X[I,3]→r12
34: if r11=0;1/400r10→r12
35: if r10-r11<.0005;1-1/4r10→r12
36: r0+r10→r0;r1+r10r10→r1;r2+r11→r2;r3+r11r11→r3
37: asn(√r12)→r12
38: r4+r12→r4;r5+r12r12→r5
39: next I
40: wrt 16.1
41: wrt 16.4,126,"Leaf",r0
42: wrt 16.4,2,"Leaf",r0/N
43: √((Nr1-r0r0)/N(N-1))→S
44: wrt 16.5,"S.D.",S;wrt 16.5,"S.E.",S/√N
45: wrt 16.8,"n",N
46: wrt 16.1
47: wrt 16.4,126,"hole",r2;wrt 16.4,2,"hole",r2/N
48: √((Nr3-r2r2)/N(N-1))→S
49: wrt 16.5,"S.D.",S;wrt 16.5,"S.E.",S/√N
50: wrt 16.8,"n",N;wrt 16.1
51: prt " % leaf eaten";wrt 16.5,"avg.",100r2/r0
52: √((Nr5-r4r4)/N(N-1))→S
53: wrt 16.4,2," % ",100sin(r4/N)↑2+.5cos((2r4/N)(1-exp(-
2SS)))
54: prt "*arcsine trans.** (degrees) *"
55: wrt 16.6,2,32,16,r4/N;wrt 16.7,"S.D.",S;wrt
16.7,"S.E.",S/√N
56: wrt 16.8,"n",N;wrt 16.1
57: spc 2
58: end
59: for I=0 to 100;0→rI;next I

```