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STUDYING HERBICIDE RESISTANCE USING TREATMENT AREA DYNAMICS MODEL

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Abstract

Repeated use of a herbicide or herbicides with the same mode
of action on a particular crop over a number of years may
cause the selection of herbicide resistant weed populations.
As a result effective weed control is lost which can
seriously affect crop yield and quality. The selection of
herbicide resistant weed populations is a concern not only
for crop-growers, but also the manufacturers of the affected
herbicides. In the present paper a two-step procedure is
developed to identify the herbicide resistant activity in a
particular crop growing region by estimating the resistant
areas (in acres/hectares) in a given year of herbicide
continued treatment along with percent risk of detecting
herbicide resistance. A computer aided treatment area
dynamics model (TADM) for estimating resistant areas, and a
multistage model for estimating risk of herbicide resistance
are discussed. An example is presented at the end to
illustrate the two-step procedure.

Keywords: treatment area dynamics, rotational pattern, risk,
multistage model.

1.   INTRODUCTION

Repeated use of a herbicide or herbicides with the same mode
of action on a particular crop over a number of years has
caused resistant weed populations. Some of these
populations developed resistance to newer herbicides soon
after their introduction (LeBaron, 1991). Chlorsulfuron was
introduced for weed control in cereals in 1982 in the
western United States. In 1987 Thill, et. al. (1991)
discovered prickly lettuce populations near Lewiston, Idaho
which were resistant to the sulfonylureas. Since then other
sulfonylurea resistant populations including kochia (Kochia
scoparia L. Schrad # KOCSC), common chickweed (Stellaria
media L. Vill # STEME), and russian thistle (Salsola iberica
Sennan & Pau # SALIB) have developed (Thill,et. al., 1991).
Powles, et. al. (1990) reported that there are populations

of rigid ryegrass (Lolium rigidium L. # LOLRI) in Australia which are resistant to several different classes of herbicides. One population reportedly developed resistance to diclofop after only 4 applications.

The relatively rapid selection of resistant weed populations to new, highly efficacious herbicides indicate the need for establishing strategies early in the development of a new herbicide to prevent the selection for resistant weed biotypes. Although certain strategies, such as crop rotation with a concomitant rotation in weed control practices, tank mixes or sequential applications of herbicides with different modes of action, and integration of chemical weed control with mechanical, cultural and biological weed control practices are well understood, it has been difficult to know how effective these strategies will be before a herbicide is introduced into the market.

To try to predict how rapidly a new herbicide will select resistant weed populations, several biological models have been developed (Gressel, 1991; Maxwell,et. al., 1990). These models use different biological genetic and ecological data (i.e., the initial frequency of the resistant trait within the population, the fitness of the resistant biotypes, the reproductive capacity of the species and selective pressure of the herbicide) to estimate how rapidly the herbicide resistant trait will increase in a population. Although these models are very useful, their application is limited due to the lack of basic information on weed biology and ecology. Another limitation of these models is that they only predict which weeds might develop resistance, but not where those resistant populations are most likely to arise.

The location where a resistant population develops depends on the use pattern of the herbicide including the area treated with a herbicide, the crops on which a herbicide is used, and the rotation or tank mixing of a herbicide with other herbicides with different or similar modes of action. The objective of the present paper is to present a computer aided dynamic model to estimate the cumulative area at a given time (or year) which would have received a certain number of herbicide applications over a designated period of time (years), and then to estimate the associated risk of herbicide resistance. The mechanism of the model which is labeled here Treatment Area Dynamics is discussed in section 2. Section 3 describes the procedure for evaluating the risk of herbicide resistance, and an example is given in section 4.

2. TREATMENT AREA DYNAMICS

Treatment area dynamics (TAD) pertains to the dynamic
allocation of areas in a two-way decision model to herbicide
application in a region based on herbicide rotational
pattern and the herbicide market share in that region. The
basic assumptions of TAD are as follows:

    1. The initial allocation of area (in acres/hectares) to
       the herbicide is always known;

and

    2. The rotational pattern for subsequent herbicide
       applications are known for the region.

The rotational pattern in the two-way (with or without the
herbicide) decision tree model is a quadruplet of
proportions, namely, P_{11}, P_{12}, P_{21}, and P_{22}, where P_{ij} is
the proportion of area going from herbicide i to herbicide
j, and it is assumed that

$$P_{ij} \text{ (for } i \neq j) = 1 - P_{ii}.$$

The subscript i,j in the following discussions can have two
values as follow:

i,j=1 means that the allocation is to herbicide "A" of
       interest;

    =2 means that the allocation is either to no herbicide or
       some other herbicide, other than "A".

These proportions may vary from one application time to
another, or may be constant over a given period of herbicide
application (for example say, 3 or 5 years). It should be
noted that if the herbicide "A" is efficient and shows no
adverse effect, the rotational pattern will remain constant
at each subsequent application. On the other hand, if the
herbicide "A" starts showing problems after a few repeated
application, the proportional allocation of area to the
herbicide "A" will decrease over the subsequent applications
of the herbicide. In the next section, method of multistage
modelling will be described to evaluate risk (in %)
associated with a specified number of applications of the
herbicide "A" over a specified period of time.

2.1 DISTRIBUTION OF AREA UNDER HERBICIDE TREATMENT BY APPLICATION NUMBER

Let A denote the herbicide of interest and B denote some other herbicide (other than A) or no herbicide. Also let

Y_{ij} = Area under herbicide treatment at the jth application coming from the ith application

The diagram given in figure 1 illustrates the flow of areas in subsequent applications of the herbicide based on the rotational pattern, P_{ij}'s. It is assumed that after the first application, an area equal to Y_{ii} is added as a result of some efficient marketing strategies adopted by the maker of the herbicide, where Y_{11} is the starting area.

The distribution of area at different applications is given in Table 1.

2.2 AREA UNDER EXPOSURE OF HERBICIDE WITH "a" OR MORE APPLICATIONS OVER A PERIOD OF "n" YEARS

Generally the herbicides are used for major crops like corn, wheat, soybean, cotton, etc... These crops may be grown every year or may be rotated every year. The herbicide treatment therefore is conducted in the field annually. With the herbicide treatment repeated over "n" years, we shall obtain expressions for area receiving just "a" number of herbicide applications, where $a \leq n(>1)$.

Consider the layout in figure 1. The starting area receiving herbicide application, i.e. in year 1 is Y_{11}, and the new area additions starting from year 2 are Y_{22}, Y_{33}, Y_{44}, etc... in the 2nd, 3rd, 4th, etc.. year respectively. From figure 1 we create Table 2. Computation of areas with a given number of herbicide applications over a given number of years thus becomes lengthy after year 4; however the logic is simple to understand. The computer has been used at this point to compute the areas with user specified input on "a", "n", and P_{ij}'s. The computer program HRMODEL written in FORTRAN on VAX compute these areas at user's specification. An example is given in section 4.

3. RISK ASSESSMENT USING MULTISTAGE MODEL

Risk of selection of weed populations resistant to a herbicide increases with repeated use of the herbicide in a region. How much a herbicide is creating resistance in weed populations in a particular crop in a region is also reflected in the rotational pattern (P_{ij}'s) over the years. A slight decrease in the values of P_{11} and/or P_{21} used in that region over subsequent years may result in significant decreased in the area exposed to "a" or more number of herbicide treatments over a period of "n" years compared to a constant values of P_{11} and P_{21} over the years, where $a \leq n$ is a positive integer greater than 1. The intent of this section is to assess the risk of herbicide resistance in a quantifiable term associated with a region which would have received or has received "a" or more herbicide applications over a period of "n" years. It is assumed here (as is the practice) that an application of a herbicide is made on a yearly basis.

It can be assumed without any loss of generality that rates of occurrence of resistance brought in by "m" changes (m=a-1), 'a' being the number of herbicide applications (or treatments), is directly proportional to the number of applications (or years) of the herbicide. The cumulative incidence of area with resistance after a continuous usage can be given by the multistage model

$$P(y) = 1 - \exp\left(-\sum_{j=1}^{k} \beta_j y^j\right) \qquad (1)$$

where y is the number of years of application with the herbicide, and $k \leq m$ is a known positive integer and $\beta_j \geq 0$ for all j. The model in (1) does not assume any background effect which is reasonable because unless treated with the herbicide, selection of a herbicide resistant weed population is unrealistic. Method of maximum likelihood is used to fit the multistage model (1) which is discussed in Guess, H., et. al. (1977). Reference may also be made to Crump, K. (1982) and Portier, C. and Hoel, D. (1984). In (1) when y=0, P(y)=0 which means there is no risk of resistance, P(y) ranges between 0 and 1. As will be seen in section 4, the area with resistance which has received a specified number of herbicide treatments increases over the years in approximately a straight line. A computer program HRISK written in FORTRAN on VAX fits the model to input data on exposed and resistant areas which has received a user-specified number "a" or more of herbicide treatments with user-specified value of "k", the degree of the polynomial in the model.

4. AN EXAMPLE

The example refers to data on areas under use of a herbicide
called "triazine" on corn field in Wisconsin. The herbicide
use was first started by farmers in Wisconsin corn growing
areas in 1961. The rotational pattern (P_{ij}'s) and areas (in
millions of acres) treated with the herbicide for 19 years
(1961-1979) are shown in Table 3.

The first complaint on triazine resistance was registered in
1975, that is, after 14 years of repeated use. It will be
of interest to examine here the risk associated with a=10 or
more of triazine applications over n=19 years of continued
use. The computer program HRMODEL was run on the data given
in Table 3, and the triazine resistant area (in acres) at
year 10 (i.e. 1970) of application and after obtained from
the program are shown in Table 4.

Detailed computer output is shown in the Appendix. The
computer program HRISK was then run on data of Table 4 and
the 95% upper confidence limits on risk of resistance at
year 10 and after are given in Table 5.

Although a risk of 20% or more is more visible, a warning to
the manufacturer of a herbicide producing resistant weed
population in a crop should be signalled at a stage when the
risk is 10% or more. At this stage then, farmers can be
cautioned to take appropriate measures for protecting their
crop yield and quality. Also the manufacturers can protect
themselves against unnecessary massive expenses in legal
complications.

5. CONCLUSION

In this manuscript, an effort has been made to study
herbicide resistance problems facing the crop-growers and
the herbicide manufacturers through a two-step procedure.
In the first step treatment area dynamics modelling is used
empirically to arrive at the estimates of areas which have
received a certain specified number of herbicide treatment
over a specified period of time. A computer program HRMODEL
is used for carrying out this step. The data used by
HRMODEL are the rotational pattern (P_{ij}'s) and the areas
treated with the herbicide for a given number of years.
HRMODEL generates input data for the next step which uses
the computer program HRISK to evaluate the risk associated
with the herbicide used repeatedly for a specified number of
times.

It is the authors' view that treatment area dynamics
modelling is not the final solution to the detection of
herbicide resistance in various classes of weed population,
but an effort to study the resistance in the field. The
information obtained through this effort can be utilized to
develop effective weed-control management.

[Executable computer program can be obtained from the author
by request.]

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Application No.

1   2   3   4 . . . .

[Figure 1: probability tree diagram with branches labelled P_{11}, P_{12}, P_{21}, P_{22} leading to nodes A and B across applications 1–4]
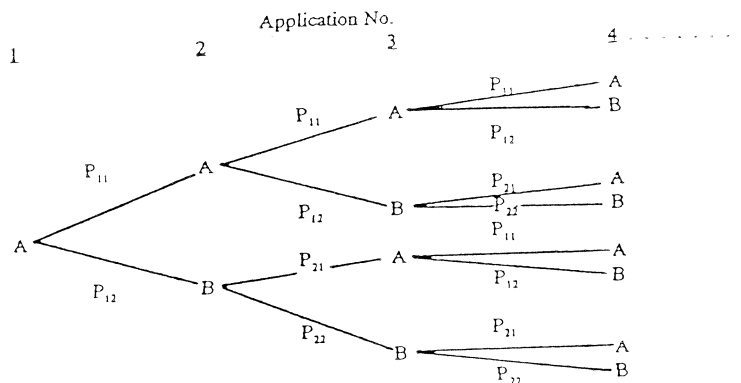
Figure 1

Area:

Y_{11};

$Y_{12} = P_{11}Y_{11}$;

$Y_{13} = P_{11}^{2}Y_{11} + P_{12}P_{21}Y_{11}$;

$Y_{14} = P_{11}^{3}Y_{11} + 2P_{11}P_{12}P_{21}Y_{11} + P_{12}P_{22}P_{21}Y_{11}$;

$Y_{23} = P_{11}Y_{22}$;

$Y_{24} = P_{11}^{2}Y_{22} + P_{12}P_{21}Y_{22}$;

$Y_{34} = P_{11}Y_{33}$;

Addition:

— Y_{22}; Y_{33}; Y_{44};

Total Area:

Y_{11}; $Y_{12}+Y_{22}$; $Y_{13}+Y_{23}+Y_{33}$; $Y_{14}+Y_{24}+Y_{34}+Y_{44}$

Table 1

Distribution of area under herbicide treatment by application number

Application	Starting Area	New Area Added	Total Area Under Herbicide Treatment
1	Y_{11}	0	Y_{11}
2	Y_{12}	Y_{22}	$Y_{12} + Y_{22}$
3	$Y_{13} + Y_{23}$	Y_{33}	$Y_{13} + Y_{23} + Y_{33}$
4	$Y_{14} + Y_{24} + Y_{34}$	Y_{44}	$Y_{14} + Y_{24} + Y_{34} + Y_{44}$
–	–	–	–

Table 2

Area Receiving "a" Herbicide Applications in "n' Years

Years (n)	Starting or Year 1 Area	Addition	a	Total area with 1,2,etc... of herbicide applications
1	Y_{11}	0	1	Total area with $1A = Y_{11}$
2	Y_{11}	Y_{22}	2	Total area with $2A's = P_{11}Y_{11}$
			1	Total area with $1A = P_{12}Y_{11} + Y_{22}$
3	Y_{11}	Y_{33}	3	Total area with $3A's = P_{11}{}^2 Y_{11}$
			2	Total area with $2A's = P_{11}P_{12}Y_{11} + P_{12}P_{21}Y_{11} + P_{11}Y_{22}$
			1	Total area with $1A = P_{12}P_{22}Y_{11} + P_{12}Y_{22} + Y_{33}$
4	Y_{11}	Y_{44}	4	Total area with $4A's = P_{11}{}^3 Y_{11}$
			3	Total area with $3A's = P_{11}{}^2 P_{12}Y_{11} + P_{11}P_{12}P_{21}Y_{11} + P_{11}{}^2 Y_{22}$
			2	Total area with $2A's = P_{11}P_{12}P_{22}Y_{11} + P_{12}P_{21}P_{12}Y_{11} + P_{12}P_{22}P_{21}Y_{11} + P_{11}P_{12}Y_{22} + P_{12}P_{21}Y_{22} + P_{11}Y_{33}$
			1	Total area with $1A = P_{12}P_{22}{}^2 Y_{11} + P_{12}P_{22}Y_{22} + P_{12}Y_{33} + Y_{44}$
5	--	--	--	--

Table 3

Rotational Pattern and Area (in millions of acres)
Treated with Triazine

(1961-1979, Wisconsin Data)

Year	Year of Application	Rotational Pattern				Area (in Millions of Acres) Treated With Triazine
		P_{11}	P_{12}	P_{21}	P_{22}	
1	1961	0.38	0.62	0.54	0.46	0.14
2	1962	0.38	0.62	0.54	0.46	0.28
3	1963	0.38	0.62	0.54	0.46	0.46
4	1964	0.38	0.62	0.54	0.46	0.64
5	1965	0.38	0.62	0.54	0.46	0.89
6	1966	0.30	0.70	0.54	0.46	1.10
7	1967	0.30	0.70	0.54	0.46	1.40
8	1968	0.30	0.70	0.54	0.46	1.60
9	1969	0.30	0.70	0.54	0.46	1.70
10	1970	0.30	0.70	0.54	0.46	1.80
11	1971	0.28	0.72	0.60	0.40	2.00
12	1972	0.28	0.72	0.60	0.40	2.10
13	1973	0.28	0.72	0.60	0.40	2.10
14	1974	0.28	0.72	0.60	0.40	2.10
15	1975	0.28	0.72	0.60	0.40	2.10
16	1976	0.28	0.72	0.60	0.40	2.10
17	1977	0.28	0.72	0.60	0.40	2.10
18	1978	0.28	0.72	0.60	0.40	2.10
19	1979	0.28	0.72	0.60	0.40	2.10

Table 4

Exposure with 10 or More of Triazine Treatment (in acres)

Year (1)	With Constant Rotational Pattern as in Year 1 (2)	With Actual Rotational Pattern (3)	Resistant Area (in acres) (2)-(3)
10	23	9	14
11	244	102	142
12	1323	588	735
13	4928	2375	2553
14	14527	7487	6770
15	34268	19570	14698
16	71474	44121	27353
17	133315	88258	45057
18	227262	159992	67270
19	359738	267176	92562

Table 5

Risk Associated with 10 or More Triazine Treatments at Year 10 and After

Year	95% Upper Confidence Limit on Risk of Resistance
10	0.1834 (or 18% approximately)
11	0.1998 (or 20% approximately)
12	0.2159 (or 22% approximately)
13	0.2316 (or 23% approximately)

APPENDIX

Computer Output from HRMODEL

Constant Rotational Pattern

DESIRED MAXIMUM NO. OF YEARS, NM = 19

ACRES (in million unit) TREATED WITH HERBICIDE
FOR YEAR 1 TO NM :
  0.1400   0.2800   0.4600   0.6400   0.8900   1.1000   1.4000   1.6000   1.7000   1.8000
  2.0000   2.1000   2.1000   2.1000   2.1000   2.1000   2.1000   2.1000   2.1000

DESIRED STARTING NO. OF HERBICIDE TRTMTS. = 10

PROPORTIONS OF ACRES GOING TO DIFFERENT ROTATIONS :
P11,P12,P21,P22 =
    0.3800 0.6200 0.5400 0.4600
    0.3800 0.6200 0.5400 0.4600
    0.3800 0.6200 0.5400 0.4600
    0.3800 0.6200 0.5400 0.4600
    0.3800 0.6200 0.5400 0.4600
    0.3800 0.6200 0.5400 0.4600
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    0.3800 0.6200 0.5400 0.4600
    0.3800 0.6200 0.5400 0.4600
    0.3800 0.6200 0.5400 0.4600
    0.3800 0.6200 0.5400 0.4600
    0.3800 0.6200 0.5400 0.4600

AREA RECEIVING DESIRED NO. OF TRTMTS. >=10

NO. OF TRT.	YEARS: 10 / 18	11 / 19	12	13	14	15	16	17
10	23. / 146202.	235. / 214761.	1222.	4340.	11903.	26979.	52817.	92091.
11	0. / 57037.	9. / 96895.	97.	547.	2096.	6182.	15000.	31287.
12	0. / 18031.	0. / 35279.	3.	40.	242.	995.	3142.	8135.
13	0. / 4315.	0. / 10139.	0.	1.	16.	106.	465.	1567.
14	0. / 769.	0. / 2244.	0.	0.	0.	7.	46.	215.
15	0. / 98.	0. / 372.	0.	0.	0.	0.	3.	20.
16	0. / 8.	0. / 44.	0.	0.	0.	0.	0.	1.
17	0. / 0.	0. / 4.	0.	0.	0.	0.	0.	0.
18	0. / 0.	0. / 0.	0.	0.	0.	0.	0.	0.
19	0. / 0.	0. / 0.	0.	0.	0.	0.	0.	0.
TOTAL:	23. / 227262.	244. / 359738.	1323.	4920.	14257.	34268.	71474.	133315.

APPENDIX

Computer Output from HRMODEL

Actual Rotational Pattern

DESIRED MAXIMUM NO. OF YEARS, NM = 19

ACRES (in million unit) TREATED WITH HERBICIDE
FOR YEAR 1 TO NM :
  0.1400   0.2800   0.4600   0.6400   0.8900   1.1000   1.4000   1.6000   1.7000   1.8000
  2.0000   2.1000   2.1000   2.1000   2.1000   2.1000   2.1000   2.1000   2.1000

DESIRED STARTING NO. OF HERBICIDE TRTMTS. = 10

PROPORTIONS OF ACRES GOING TO DIFFERENT ROTATIONS :
P11,P12,P21,P22 =
    0.3800 0.6200 0.5400 0.4600
    0.3800 0.6200 0.5400 0.4600
    0.3800 0.6200 0.5400 0.4600
    0.3800 0.6200 0.5400 0.4600
    0.3800 0.6200 0.5400 0.4600
    0.3000 0.7000 0.5400 0.4600
    0.3000 0.7000 0.5400 0.4600
    0.3000 0.7000 0.5400 0.4600
    0.3000 0.7000 0.5400 0.4600
    0.3000 0.7000 0.5400 0.4600
    0.2800 0.7200 0.6000 0.4000
    0.2800 0.7200 0.6000 0.4000
    0.2800 0.7200 0.6000 0.4000
    0.2800 0.7200 0.6000 0.4000
    0.2800 0.7200 0.6000 0.4000
    0.2800 0.7200 0.6000 0.4000
    0.2800 0.7200 0.6000 0.4000
    0.2800 0.7200 0.6000 0.4000
    0.2800 0.7200 0.6000 0.4000

AREA RECEIVING DESIRED NO. OF TRTMTS. >=10

NO. OF TRT.	YEARS : 10 18	11 19	12	13	14	15	16	17
10	9. 117246.	99. 175037.	555.	2164.	6549.	16338.	34953.	65974.
11	0. 36916.	3. 67307.	32.	200.	864.	2873.	7820.	18144.
12	0. 9020.	0. 19750.	1.	10.	70.	334.	1215.	3595.
13	0. 1594.	0. 4314.	0.	0.	3.	24.	126.	497.
14	0. 198.	0. 685.	0.	0.	0.	1.	8.	46.
15	0. 17.	0. 77.	0.	0.	0.	0.	0.	3.
16	0. 1.	0. 6.	0.	0.	0.	0.	0.	0.
17	0. 0.	0. 0.	0.	0.	0.	0.	0.	0.
18	0. 0.	0. 0.	0.	0.	0.	0.	0.	0.
19	0. 0.	0. 0.	0.	0.	0.	0.	0.	0.
TOTAL:	9. 159992.	102. 267176.	588.	2375.	7487.	19570.	44121.	88258.

APPENDIX

Computer Output from HRISK

Risk Assessment

UPPER CONFIDENCE LIMITS ON RISK FOR FIXED YEAR

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CONFIDENCE LIMITS FOR A YEAR OF 10.0000     . THE MLE ESTIMATE OF RISK IS0.182897
THE 95.0     PERCENT UPPER LIMIT ON RISK IS0.183436
THE COEFFICIENTS CORRESPONDING TO THE 95.0     PERCENT UPPER BOUND ARE:
Q( 0)=.000000000000E+00
Q( 1)=.202649632611E-01
```
****

```
CONFIDENCE LIMITS FOR A YEAR OF 11.0000     . THE MLE ESTIMATE OF RISK IS0.199236
THE 95.0     PERCENT UPPER LIMIT ON RISK IS0.199817
THE COEFFICIENTS CORRESPONDING TO THE 95.0     PERCENT UPPER BOUND ARE:
Q( 0)=.000000000000E+00
Q( 1)=.202649632611E-01
```
****

```
CONFIDENCE LIMITS FOR A YEAR OF 12.0000     . THE MLE ESTIMATE OF RISK IS0.215249
THE 95.0     PERCENT UPPER LIMIT ON RISK IS0.215869
THE COEFFICIENTS CORRESPONDING TO THE 95.0     PERCENT UPPER BOUND ARE:
Q( 0)=.000000000000E+00
Q( 1)=.202649632611E-01
```
****

```
CONFIDENCE LIMITS FOR A YEAR OF 13.0000     . THE MLE ESTIMATE OF RISK IS0.230941
THE 95.0     PERCENT UPPER LIMIT ON RISK IS0.231600
THE COEFFICIENTS CORRESPONDING TO THE 95.0     PERCENT UPPER BOUND ARE:
Q( 0)=.000000000000E+00
Q( 1)=.202649632611E-01
```
****

```
CONFIDENCE LIMITS FOR A YEAR OF 14.0000     . THE MLE ESTIMATE OF RISK IS0.246319
THE 95.0     PERCENT UPPER LIMIT ON RISK IS0.247015
THE COEFFICIENTS CORRESPONDING TO THE 95.0     PERCENT UPPER BOUND ARE:
Q( 0)=.000000000000E+00
Q( 1)=.202649632611E-01
```