# CHAPTER TWO

# COMPARISON OF TWO METHODS FOR ESTIMATING PESTICIDE VOLATILIZATION FROM TURF

## Abstract

Pesticide volatilization is a potential health hazard to turf users. Modeling pesticide volatilization can provide an effective tool for estimating environmental impact where complete information is unavailable. In the model developed (called Aero) the pesticide volatilization is directly related to the potential evapotranspiration, pesticide vapor pressure and the amount of pesticide left on the leaf surface. The latter was simulated as a first order pesticide degradation term and accounted for the rapid decrease in surface volatilization over time. The Aero model was tested against existing data from literature and compared to an existing model by Haith et al. (2002). The simulated volatilizations predictions were realistic and compared well with the observed data and the Haith model.

## 1. Introduction

Turfgrasses are plants that are used for a variety of purposes, including ornamentation, soil protection, and ground cover for recreational areas such as parks, golf courses, and athletic fields. Chemicals used for control of turfgrass pests may volatilize, resulting in potential health hazards for turf users (Clark *et al.*, 2000).

Pesticide volatilization is one of the dissipation processes affecting a wide variety of pesticides used in agriculture (Caro and Taylor, 1971; Cliath and Spencer, 1971; Farmer *et al.*, 1972; Farmer *et al.* 1974; Harper *et al.*, 1976; Spencer and

Farmer, 1980; Prueger *et al.*, 1999). Volatilization has been considered to be a major cause of pesticide loss from fields after application (Taylor *et al.*,1977; Cooper *et al.*, 1990; Prueger *et al.*, 1999). Field studies have confirmed that pesticides lost from volatilization could range from negligible to 54% of the mass applied (Murphy *et al.*, 1996a, 1996b; Taylor *et al.*, 1977; Turner *et al.*, 1977). Most of the volatilization losses occur within the first few days of application and follow a diurnal pattern, with largest losses corresponding to high mid-day temperatures and solar radiation (Cooper, *et al.* 1990; Haith *et al.*, 2002).

Due to the enormous number of pesticides currently in use, it is impractical to measure volatilization for each pesticide under different environmental conditions. Thus, effective mathematical models are needed that can predict the volatilization effects from pesticides where complete information on their impact on the environment is unavailable. Recently, Haith *et al.* (2002) presented such a model to predict pesticide volatilization from turf. Calibration using a specific pesticide was used as a method to develop the model to predict other independent data of different pesticides. The objective of this chapter was to develop a prediction model (Aero model) based upon a regression approach using the complete set of data used by Haith *et al.* (2002) to obtain pesticide degradation and absorption parameters in order to have a generalized prediction model of pesticide volatilization.

## 2. Model development

### 2.1 Aero model

A pesticide volatilization model is developed by drawing a parallel between water and pesticide vapor transport. The dispersal of residues into the atmosphere by vapor involves two distinct processes. The first is the volatilization of pesticide molecules into the air from the pesticide residue present on the soil or grass surfaces and represents a phase change into vapor from the liquid or solid state. The vapor pressure of pesticide is a direct function of the concentration either in the water or as solid matter and can be described with Henry's law:

$$d = h \cdot C_p \tag{1}$$

where

d = vapor concentration of pesticide, mole/$m^3$

$C_p$ = solute concentration, mole/$m^3$

h = Henry's law constant, dimensionless

Henry's law applies specifically to fluids but the same type of relationship holds for a solid when we assume that the rate of volatilization is equal to the pesticide density on the leaves.

The second process is the dispersion of the resulting pesticide vapor from turf surface into the overlying atmosphere by diffusion and turbulent transport (Taylor et al., 1990). This second process is the same one that controls the transfer of water vapor, carbon dioxide and other gasses between the turf surface and the overlying atmosphere. This dispersion process consists of molecular vapor diffusion through a thin laminar layer followed by turbulent transport. Turbulent transport may be visualized as macroscopic packets of air moving at random, there in convectively transporting their "cargoes" of energy, water and pesticide vapor from one spot to the next (Eagelson, 1970).

### Process 1: Partition between air, water, and plant surfaces

Although the variety of chemicals among the pesticides will show different patterns in their physiochemical behavior in soils, many have similar patterns that are important in controlling their partition between the air, water, soil or plant surfaces. The partition of pesticide material between the plant surface and water phase depends on the partition between adsorption on the grass blade and the sorption and permeation into the cuticular waxes and the epidermal layer of the grass blade (Taylor and Spencer, 1990). The vapor density of the pesticide in the thin layer of air immediately in contact with the turf, to be referred to as the laminar boundary layer, is proportional to the pesticide solution concentration according to Equation 1. In order to relate this concentration to the amount applied, we introduce a factor "b" that represents the relationship between the vapor pressure in the air above the leaves and the amount of pesticide (either in dissolved or solid form) on the leaves. Thus, we can write:

$$C_p = \frac{P_A}{b} \qquad (2)$$

where

$P_A$ = pesticide on plant leaves per unit area, mole $m^{-2}$

Later on, we will define the b-term more closely. In this chapter, "b" will be used as a component of a fitting parameter; the units for "b" are $m^3$ $m^{-2}$.

Process 2: Atmospheric transport

The flow of air over a turf surface is invariably turbulent except in a shallow layer with a depth of about 1 mm in which the flow may be regarded as laminar (Monteith, 1973). In this thin region of laminar flow, vapor transport is governed by molecular diffusion. Outside this zone in the overlying turbulent boundary layer, the dispersal of vapors, F, can be described in terms of an eddy diffusivity coefficient as (Taylor and Spencer 1990; Dingman 2002):

$$F = k_z \frac{dp}{dz} \tag{3}$$

where

F = vertical flux of vapor, mole $m^{-2}$ $sec^{-1}$

$k_z$ = mean eddy diffusivity coefficient or transport coefficient, $m^2$ $sec^{-1}$

p = vapor concentration, mole $m^{-3}$

z = z coordinate in the vertical direction, m

Since Equation 3 is valid for turbulent transport, the molecular diffusion effects in the laminar flow layer are neglected (Taylor and Spencer, 1990). Since, both pesticide and water vapor transport from the turf layer through the laminar layer are similar molecular processes, the omission of molecular diffusion should not introduce a large error and in fact can be accounted for by using the eddy diffusivity approach. In turbulent transport theory, the eddy diffusion coefficient for water and pesticide vapor can be assumed to be the same, since it is the same transport phenomena governing both. Similar but in contrast, Jury and coworkers assumed that the molecular diffusion processes governed the pesticide release into a stagnant air layer immediately above the turf (Jury *et al.*, 1983) and then proceeded to calculate the flux of pesticide into this stagnant boundary layer. The inherent assumption by Jury *et al.* being that what is transported by diffusion into the stagnant boundary layer will eventually be transported away by convection into the overlying atmosphere. Although the two approaches are conceptually the same in that they are both transport phenomena, the difference in approach is extremely important since the concentration gradient will be very different, as we will see later.

The equation for water vapor flux, $F_w$, becomes when averaged over sufficient long time that temporal variation can be neglected:

$$F_w = -k_z \frac{e_1 - e_2}{z_1 - z_2} \tag{4}$$

where

$F_w$ = vapor flux of water, mole $m^{-2}$ $hr^{-1}$

$e_1$ = vapor concentration of water at $z_1$, mole $m^{-3}$

$e_2$ = vapor concentration of water at $z_2$, (mole $m^{-3}$ )

$z_1$ = vertical direction at height 1, m

$z_2$ = vertical direction at height 2, m

Similarly for pesticide vapor transport flux, $F_p$

$$F_p = -k_z \frac{d_1 - d_2}{z_1 - z_2} \tag{5}$$

where

$F_p$ = vapor flux of pesticide, mole $m^{-2}$ $hr^{-1}$

$d_1$ = vapor concentration of pesticide at $z_1$, mole/$m^3$

$d_2$ = vapor concentration of pesticide at $z_2$, mole/$m^3$

The subscripts 1 and 2 refer to the two different planes where the observations are made. In the following, we will take the plane with subscript 1 to be just above the turf grass surface and the second plane will be at the standard meteorological observation for vapor pressure measurement of 2 m. Because pesticides are applied only locally, we can take the pesticide concentration at this height equal to zero, i.e., $d_2 = 0$. By dividing Equation 4 and 5 and noting that the two eddy diffusion coefficients are assumed to be equal, we obtain:

$$F_p = F_w \frac{d_1}{e_1 - e_2} \tag{6}$$

By taking the first level ($z_1$) just above the turf surface, we can set the pesticide vapor concentration from Equation 1 equal to the $d_1$ in Equation 6. Moreover, since the turf is usually well watered we can also set $e_1$ equal to the saturated vapor concentration, $e_s$.

Then, if we were to assume that pesticide vapor is the only pesticide loss, we can write the amount of pesticide flux per unit area, $\frac{dP_A}{dt}$, as:

$$\frac{dP_A}{dt} = -F_w \frac{hC_p}{e_s - e_2} \tag{7}$$

where

$P_A$ = pesticide evaporation on a mass per unit area basis, mole $m^{-2}$

Substituting the value of $C_p$ in Equation 2 into Equation 7 gives:

$$\frac{dP_A}{dt} = -F_w \frac{h \cdot P_A}{b(e_s - e_2)} \tag{8}$$

Integrating Equation 8 and given at time 0, $t = 0$, $P_A = (P_A)_o$, then

$$P_A = (P_A)_o \cdot \exp\left[-\left(\frac{F_w}{(e_s - e_2)} \frac{h}{b}\right) \cdot t\right] \tag{9}$$

where

$(P_A)_o$ = the initial mass of pesticide per unit area at time $t = 0$, mole $m^{-2}$

The cumulative volatilized pesticide loss, $L_p$, can be expressed as:

$$L_p = (P_A)_o - P_A \tag{10}$$

Substituting $P_A$ in Equation 9 to Equation 10 and we obtain

$$L_p = (P_A)_o \cdot \left[1 - \exp\left[\left(\frac{F_w}{(e_s - e_2)}\frac{h}{b}\right)\cdot t\right]\right] \tag{11}$$

If the pesticide mass loss is disappearing by both volatilization (Equation 7) and also by degradation concurrently and degradation is occurring as a first order reaction, then Equation 9 could be modified

$$\frac{dP_A}{dt} = -\left(F_w \frac{h/b}{e_s - e_2} + a\right)P_A \tag{12}$$

where

a = degradation rate of pesticide, day$^{-1}$

Integrating Equation 12 gives

$$P_A = (P_A)_o \cdot \exp\left[-\left(\frac{F_w}{(e_s - e_2)}\frac{h}{b} + a\right)\cdot t\right] \tag{13}$$

**Development of Aero Model Constants**

In the theoretical aerodynamic approach, there are two parameters which are not available from the literature. The first is the "b" term that includes the effect of adsorption and the second is the a-term term that includes the disappearance of the pesticide other than by volatilization. Also, Henry's constant is a variable during the whole experiment, since pesticides were mixed with water when sprayed onto the turfgrass (in liquid phase), but the pesticides may change to their solid phase (this means that a different value of Henry's constant would apply) due to lack of water on the surface of leaves. Instead of finding the b-term by itself, we determined the h/b-term as a single term instead of finding h and b terms separately to allow closure of the

Aero model. We did this because both the h and b-terms are known for only certain temperature and phase value conditions; these values were not always known for the field data being used to develop the Aero model. These constants ( a-term and h/b-term) will be determined for turfgrass by a regression analysis of observed pesticide volatilization data[1] (Haith *et al.*, 2002)

We have assumed that at each measurement, the amount of pesticide remaining on the leaves ($(P_A)_{\bar{t}}$) could be expressed as:

$$(P_A)_{\bar{t}} = (P_A)_o \cdot \exp\left(-a\bar{t}\right) \tag{14}$$

where

$(P_A)_{\bar{t}}$ = amount of pesticide remaining on the leaves at time $\bar{t}$, mole m$^{-2}$
$\bar{t}$ = time since initial pesticide spraying, day

Given the above assumption (Equation 14), pesticide volatilization loss could be described by combing Equation 8 and Equation 14:

$$\Delta(P_{A,v})_{\bar{t}} = (P_A)_{\bar{t}} \cdot F_w \cdot \frac{h}{b} \cdot \frac{1}{e_s - e_2} \Delta t \tag{15}$$

where

$\Delta(P_{A,v})_{\bar{t}}$ = pesticide loss (volatilization) at time $\bar{t}$ in short period of time $\Delta$t

$\Delta$t = sampling period of pesticide volatilization, day

Further rearranging Equation 15, we can obtain

$$\Delta(P_{A,v})_{\bar{t}} = (P_A)_o \cdot \exp\left(-a\bar{t}\right) \cdot F_w \cdot \frac{h}{b} \cdot \frac{1}{e_s - e_2} \Delta t \tag{16}$$

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[1] Haith *et al.* (2002) provides most of the data used in this analysis to develop the Aero model. Some data may not be explicitly shown in Haith *et al.* (2002) and for these cases, this data is shown either in the Tables of this Chapter or the Chapter Appendix; the original data were collected at the University of Massachusetts Turfgrass Research Center in South Deerfield, MA. When the text of this Chapter refers to Haith *et al.* (2002), this infers that it may be referring to the University of Massachusetts data.

By rearranging Equation 16, we obtain

$$\frac{\frac{\Delta(P_{A,v})_{\bar{t}}}{(P_A)_o}}{F_w \cdot \frac{1}{e_s - e_2} \Delta t} = \exp\left(-a\bar{t}\right) \cdot \frac{h}{b} \cdot \tag{17}$$

By taking the natural log of both sides of the equal sign in Equation 17, we obtain

$$\ln \frac{\frac{\Delta(P_{A,v})_{\bar{t}}}{(P_A)_o}}{F_w \cdot \frac{1}{e_s - e_2} \Delta t} = -a\bar{t} + \ln \frac{h}{b} \cdot \tag{18}$$

Since $\Delta(P_{A,v})_{\bar{t}}$, $(P_A)_o$, $F_w$, $e_s$, $e_2$ and $\Delta t$ are accessible values, we can obtain a and $\frac{h}{b}$ by

plotting $\ln \frac{\frac{\Delta(P_{A,v})_{\bar{t}}}{(P_A)_o}}{F_w \cdot \frac{1}{e_s - e_2} \Delta t}$ versus $\bar{t}$ from the regression line. Note that $\Delta(P_{A,v})_{\bar{t}}$ here is the observed pesticide volatilization. The values for $\Delta(P_{A,v})_{\bar{t}}$, $(P_A)_o$, $\Delta t$ and the procedure to calculate $F_w$, $e_s$, $e_2$ are described by Haith *et al.* (2002).

Once a-term and $\frac{h}{b}$-term were determined, we can insert these two values into Equation 16. This then becomes the Aero model and can be used as a general prediction equation to predict pesticide volatilization.

In order to compare observed and predicted data from field studies as given by Haith *et al.* (2002), it was necessary to change the units used in the Aero model developed above. Since the unit of $\Delta(P_{A,v})_{\bar{t}}$ in Equation 16 is mole m$^{-2}$, the units were changed to g ha$^{-1}$ as used in Haith *et al.* (2002) paper. By multiplying $\Delta(P_{A,v})_{\bar{t}}$ with (10,000 $M_w$), we obtain $\Delta(P_{A,v})_{\bar{t}}$ in the same units of g ha$^{-1}$, where $M_w$ is the molecular weight of the particular pesticide.

## 2.2 Haith Model

The Haith *et al.* (2002) model (to be referred to as the Haith model from here on out) was developed by linking pesticide volatilization rates to evapotranspiration values, as determined by the Penman equation (Jensen et al., 1990):

$$\Delta(\mathrm{P}_{\mathrm{A,H}})_{\bar{t}} = k \cdot \left(F_{W,H} \cdot \Delta t\right) \cdot \left(\frac{d_s}{e_s}\right) \cdot \left(\frac{\lambda_{w,t}}{\lambda_{p,t}}\right) \cdot (P_{A,H})_t \tag{19}$$

$$(P_{A,H})_{t+1} = \cdot (P_{A,H})_t \cdot e^{-\alpha \cdot t'} - \Delta(\mathrm{P}_{\mathrm{A,H}})_{\bar{t}} \tag{20}$$

where

$\Delta(\mathrm{P}_{\mathrm{A,H}})_{\bar{t}}$ = pesticide vaporized from surface vegetation during time $\Delta t$ at time step t of Haith model, g ha$^{-1}$

k = volatilization constant, mm$^{-1}$

$F_{w,H} \cdot \Delta t$ = water evapotranspiration during time $\Delta t$, mm

$d_s$ = saturated pesticide vapor pressure, the same unit as $e_s$, kPa or mole m$^{-3}$

$\lambda_{p,t}$ = latent heat of vaporization of the chemical during time $\Delta t$ at time step t, J g$^{-1}$ or kJ kg$^{-1}$

$\lambda_{w,t}$ = latent heat of vaporization of water during time $\Delta t$ at time step t, J g$^{-1}$ or kJ kg$^{-1}$

$(P_{A,H})_t$ = pesticide available for volatilization on vegetation at the beginning time step t, g ha$^{-1}$

$(P_{A,H})_{t+1}$ = pesticide available for volatilization on vegetation at the beginning of time step t+1, g $ha^{-1}$

$\alpha$ = degradation rate of pesticide on vegetation surface, $hr^{-1}$

t' = time elapsed between successive sampling periods, hr

Note that t' is the time elapsed between successive sampling periods. Note that $\Delta t$ is usually only a portion of t', e.g. t' might be 6 hours or 24 hours and $\Delta t$ is usually around 2 to 4 hours of sampling time. Only the Haith model uses the variable t'.

The evapotranspiration value as shown in Equation 19 was adjusted based upon the ratios of water and chemical saturated vapor pressures ($d_s / e_s$) and latent heats of vaporization ($\lambda_{w,t}/\lambda_{p,t}$) to predict pesticide vaporization (Haith et al., 2002). The pesticide chemicals or simply pesticides are assumed to have first order degradation on turf grass over time. Field data as used by Haith *et al.* (2002) for eight pesticides was available to use in model comparisons made between the Aero and the Haith models. The eight pesticides were Bendiocarb, Diazinon, Ethoprop, Isazofos, Carbaryl, Chlorpyrifos, Isofenphos and Trichlorfon. These eight pesticides were classified into being either high volatilization or low volatilization pesticides, based upon their pesticide saturation vapor pressure (Haith *et al.*, 2002).

Haith *et al.* (2002) found by calibration that k = 130 $mm^{-1}$ for high volatilization pesticide (classified as Group 1 in Haith *et al.*, 2002) and 405 $mm^{-1}$ for low volatilization pesticide (classified as Group 2 in Haith *et al.*, 2002)

All the chemical characteristics and calculations related to $F_{w,H}$, $d_s$, $e_s$, $\lambda_{w,t}$, $\lambda_{p,t}$ and $C_t$ are described by Haith *et al.*, 2002. Values used in the simulation analysis for saturated vapor pressure, molecular weight, solubility, Henry's constant and $K_{oc}$ are shown in Table 2.1.

Table. 2.1. Characteristics of pesticides used in this modeling effort.

| | $K_{oc}$, cm$^3$g$^{-1}$, from Haith *et al.*, 2002 | Saturated Vapor Pressure at 25 °C, from Haith *et al.*, 2002, kPa | ** Molecular Weight, g mole$^{-1}$ | ** Solid or Liquid at room temperature | ** Solubility in Water, ppm | ** Henry's Constant (h), dimensionless |
|---|---|---|---|---|---|---|
| Bendiocarb | 385 | 4.6E-06 | 223.2 | Solid | 40~260 @20°C | 9.03E-07 |
| Diazinon | 1520 | 1.2E-05 | 304.3 | Liquid | 40~68 @20 °C | 1.53E-05 |
| Ethoprop | 104 | 4.3E-05 | 242.3 | Liquid | 700~750 @20 °C | 3.78E-06 |
| Isazofos | 155 | 1.2E-05 | 313.7 | Liquid | 34~69 @ 20 °C | 5.71E-06 |
| Carbaryl | 288 | 4.9E-08 | 201.2 | Solid | ~105 @ 20 °C | 1.86E-08 |
| Chlorpyrifos | 9930 | 2.7E-06 | 350.6 | Solid | 1.18 @ 25 °C | 1.93E-04 |
| Isofenphos | 777 | 4.4E-07 | 345.4 | Liquid | 18~23 @ 20 °C | 1.73E-06 |
| Trichlorfon | 15 | 5.0E-07 | 257.4 | Solid | 130000 @ 20 °C | 2.54E-10 |

** Agricultural Research Service, USDA database, 2001.

## 2.3 Parameter Adjusting for Haith Model and Aero Model

The Haith model, $\Delta(P_{A,H})_{\bar{i}}$, (Equation 19) and Aero model, $\Delta(P_{A,v})_{\bar{i}}$, (Equation 16) were compared by predicting the same observed data set as used by Haith *et al.* (2002). The input parameters used by the Haith model $\Delta(P_{A,H})_{\bar{i}}$ include $F_{w,H}\cdot\Delta t$, k, $d_s$, $e_s$, $\lambda_{p,t}$, $\lambda_{w,t}$, α and t'. The input parameters used in the Aero model to predict $\Delta(P_{A,v})_{\bar{i}}$ include $(P_A)_0$, $F_w\Delta t$, h/b, $e_s$, $e_2$ and·Δt. The methods used to develop the closure constants for the Aero model are discussed below.

### 2.3.1 $F_{w,H}\cdot\Delta t$ and $F_w$ Δt:

Water evaporation during time Δt in the Haith model , $E_w\cdot\Delta t$, is in units of mm and $E_w$ is calculated from the Penman equation as described in Haith *et al.*, 2002 and described by Jensen *et al*., (1990). The detailed equations are given in Appendix 2.3. The input parameters to obtain $F_{w,H}\cdot\Delta t$ such as air temperature, solar radiation, wind speed, duration time (Δt) and lowest temperature of a day are listed on Appendix 2.1.

Water evaporation during time Δt in the Aero model, $F_w\cdot\Delta t$, is in units of mole $m^{-2}$. These units can be converted to the same units used to describe $F_{w,H}\cdot\Delta t$ of mm as follows:

$$F_w \cdot \Delta t = F_{w,H} \cdot \Delta t \cdot \frac{1000}{18} \qquad (21)$$

### 2.3.2 $e_s$ and $e_2$

Saturated water vapor pressure can be directly related to air temperature as described by Jensen *et al*., (1990):

$$e'_s = 3.38639[(0.00738\,T + 0.8072)^8 - 0.000019|1.8\,T + 48| + 0.001316] \quad (22)$$

where

$e'_s$ = saturated water vapor pressure at air temperature T, kPa

T = air temperature during time Δt, °C

The units of $e'_s$ are kPa and need to be converted to units of mole $m^{-3}$ as is used in the Aero model, $e_s$ (Equation 16). The relationship between $e'_s$ and $e_s$ can be obtained by using the ideal gas law (see Appendix 2.4):

$$e_s = e'_s \cdot \frac{1000}{R \cdot T_a} \tag{23}$$

where

R = gas constant, 8.314 J $mole^{-1}$ $K^{-1}$

$T_a$ = air temperature during time Δt, K

The actural water vapor pressure, $e'_2$ ( units of kPa), can be calculated as:

$$e'_2 = e'_s \cdot RH \tag{24}$$

where

RH = relative humidity during time Δt, dimensionless

Since there was no RH data recorded during the experiments, the alternative method, addressed in Haith (2002), to estimate water vapor pressure is to use the dew point temperature ($T_d$) for the temperature value of T in Equation 22. The dew point temperature is estimated as the lowest temperature of the day (Timmons and Gates, 1986). Once $e'_2$ is calculated, then $e_2$ (in unit of mole $m^{-3}$) can be calculated by using Equation 23 to convert to units of mole $m^{-3}$.

### 2.3.3 $d_s$,

Calculation of the saturated vapor pressure of pesticide at temperature T, $d_s$, in the Haith model (Equation 19) can be described as (Haith *et al.*, 2002, Grain, 1982):

$$\ln\left(\frac{d_s}{d_{s,T_{a0}}}\right) = \left[\frac{M_w \cdot \lambda_{p,T_{a0}}}{\Delta Zb \cdot R \cdot T_{a_0}}\right] \cdot \left(1 - \left(3 - 2 \cdot \frac{T_a}{T_{a_0}}\right)^m \cdot \frac{T_{a_0}}{T_a} \cdot -2m\left(3 - 2 \cdot \frac{T_a}{T_{a_0}}\right)^{m-1} \cdot \ln\frac{T_a}{T_{a_0}}\right) \tag{25}$$

where

$d_{s,T_{a_0}}$ = saturated pesticide vapor pressure at temperature $T_{a_0}$, kPa

$T_{a_0}$ = temperature at the addressed $d_{s,T_{a_0}}$, K

$\lambda_{p,T_{a0}}$ = latent heat of pesticide vaporization at temperature $T_{a_0}$, J/g

$\Delta Z_b$ = compressibility factor at boiling point, dimensionless, 0.97 (Grain, 1982)

m = constant, 0.8 (Haith *et al.*, 2002)

The data for saturated vapor pressure of each tested pesticide at 25 °C are shown on Table 2.1.

### 2.3.4 $\lambda_{w,t}$, $\lambda_{p,t}$

The latent heat of vaporization of water ($\lambda_{w,t}$) and pesticide ($\lambda_{p,t}$) used in the Haith model (Equation 19) can be described as (Haith *et al.*, 2002, Jensen 1990)

$$\lambda_{w,t} = 2501 - 2.361\ T_t \qquad (26)$$

where

$T_t$ = temperature during time $\Delta t$, °C

The pesticide latent heat of vaporization ($\lambda_{p,t}$) used in the Haith model (Equation 19) can be estimated as (Haith, 2002; Grain, 1982):

$$\frac{M_w \cdot \lambda_{P,T_{a0}}}{R \cdot T_{a_0}} = K_f \cdot \left(9.03 + \ln \frac{T_{a_0}}{d_{s,T_{a0}}}\right) \qquad (27)$$

where

$K_f$ = constant, dimensionless, 1.06 (Haith *et al.*, 2002)

For different temperatures, e.g. $T_a$, the pesticide latent heat of vaporization could also be estimated by using the same equation (Equation 27) and substituting $T_{a_0}$ with $T_a$.

### 2.3.5 Initial Pesticide Applied

The initial amount of pesticide applied for each experiment is shown in Appendix 2.2. Note that the units for the initial amount of pesticide in Haith *et al.*, 2002 ($(P_{A,H})_0$) is g $ha^{-1}$ and the units used in the Aero model ($(P_A)_o$) is mole $m^{-2}$. The conversion of these units could be described as:

$$(P_A)_0 = \frac{(P_{A,H})_0}{10000 \cdot M_w} \tag{28}$$

## 2.4 Model Comparison

Both the Aero and Haith models were used to predict pesticide volatilization for each period ($\Delta t$) within a data set for a particular pesticide. The cumulative pesticide volatilization for a particular pesticide (sum of the mass volatization for all the periods within a set of experiments for a particular pesticide) were also calculated and compared for both two models. Comparisons between the two models was facilitated by forcing the Aero model to predict volatilization in the same units as used by the Haith model.

## 2.5 Calculation of Half Life

The half life can be calculated as:

$$\Delta T_{hf} = \frac{0.693}{a} \tag{29}$$

where

$\Delta T_{hf}$ = half life of pesticide calculated from a, day

## Results and Discussion

The graphs of $\dfrac{\frac{\Delta(P_A)_{\bar{t}}}{(P_A)_o}}{F_w \cdot \frac{1}{e_s - e_2}\Delta t}$ versus $\bar{t}$ of each pesticide are shown in Figures 2.1–2.8. From these graphs, and by taking the natural log of $\dfrac{\frac{\Delta(P_A)_{\bar{t}}}{(P_A)_o}}{F_w \cdot \frac{1}{e_s - e_2}\Delta t}$, we obtain the a-term and h/b-term directly from the equation regression line (fitted curve) when done in log form. Since h (Henry's constant) is different when pesticide is either in liquid phase (at the first beginning of pesticide applied) or solid phase (after pesticide applied for a while), we represent h/b instead of b to address this issue. The a-term and h/b term of each pesticide as developed for the Aero model as just described are given in Table 2.2. It is customary to express the a-term as a half life. The relationship between a and half life is shown in Equation 29. The half life calculated from the a-term term ranged from 0.8 to 3.2 days.

Comparing to the half life values from USDA database (shown on Table 2.13), the half life calculated from the a-term term is relatively small. Since there are several forms of degradation, such as hydrolysis, photolysis, bio-degradation, then each of these forms of degradation could be represented by a different half life for the same pesticide. The half life of hydrolysis, photolysis and field dissipation also shown on Table 2.13. Also, the a-term term in the Aero model effectively lumped all degradation forms into one term; it also indirectly included any pesticide dissipation due to wash off. Thus, it is reasonable that the pesticide half life represented by the a-term is smaller than the half life from other individual sources.

Using the a-term and h/b-term which are uniquely determined for each of the eight pesticides modeled as given in Table 2.2 and inserting them into the Aero model, predictions are made and are given in Tables 2.3-2.10 along with the observed values and the Haith model predictions. The data is presented in all cases in Tables 2.3–2.10 as a percentage of total pesticide applied. A graphical comparison is shown in Figures 2.9–2.16 of the two prediction models versus observed data where a perfect fit would be 45°-line. Similarly, the observed cumulative sum of pesticide volatilization for each experiment versus both model's predicted volatilization are shown in Table 2.11.

The $R^2$ values for each model to predict the observed pesticide volatilization data are shown in Table 2.12. There are two different $R^2$ in this table. One is to compare each period of modeled volatilization with observed values ($R^2$, individually) and the other is to compare the sum of the quantity of pesticide volatized for each period over the entire experiment ($R^2$, sum). For the individual period predictions, the Aero model compared to the Haith model $R^2$ is larger in seven out of the eight pesticides. In comparing the cumulative sum of pesticide volatilization, both models appear to be similar as both models had the same quantity of larger $R^2$ values.

If $R^2$ is used as the tool to judge which model is superior, then the $R^2$ calculated from Aero model and observed values of most of the pesticide is greater than that calculated from Haith model. Thus, one could conclude that the Aero model is a better predictor of pesticide volatilization than the Haith model. One might expect that the Aero model should exhibit higher $R^2$ values than the Haith model for thie individual periods, since the Aero model is based upon the data which is then predicted. However, the Aero model in contrast to the Haith model does not require classifying the pesticides into a class of either high or low volatilization potential. Thus, one could argue that the Aero model is a more general model for predicting pesticide volatilization behavior. The Aero model has also introduced a different form of the degradation term. Additional pesticide data is needed to fully evaluate the comparisons between these two models.

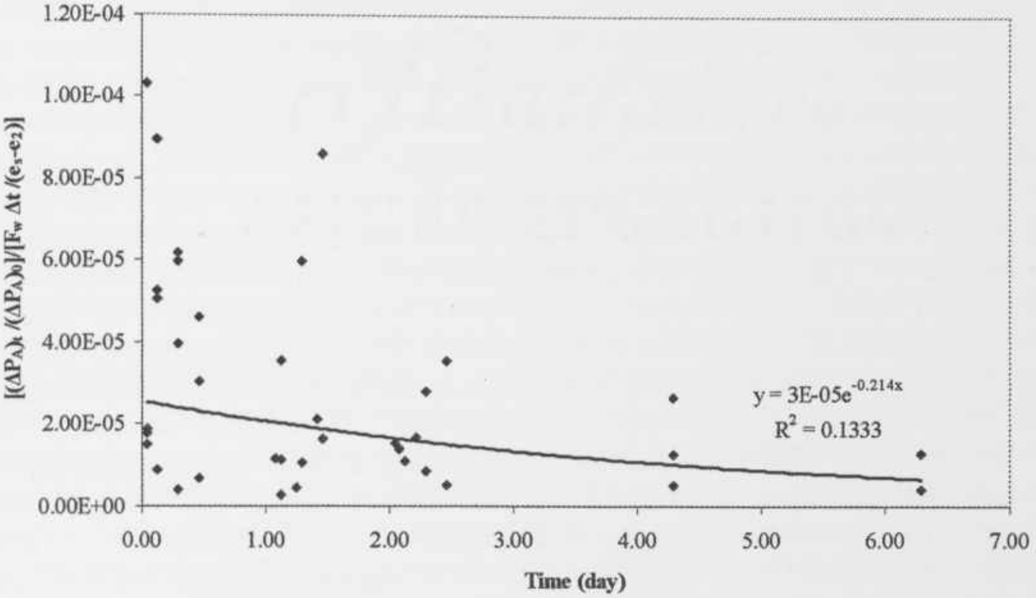

Figure 2.1. The graph of $\dfrac{\dfrac{\Delta(P_A)_t}{(P_A)_o}}{F_w \cdot \dfrac{1}{e_s - e_2}\Delta t}$ versus time of Bendiocarb.

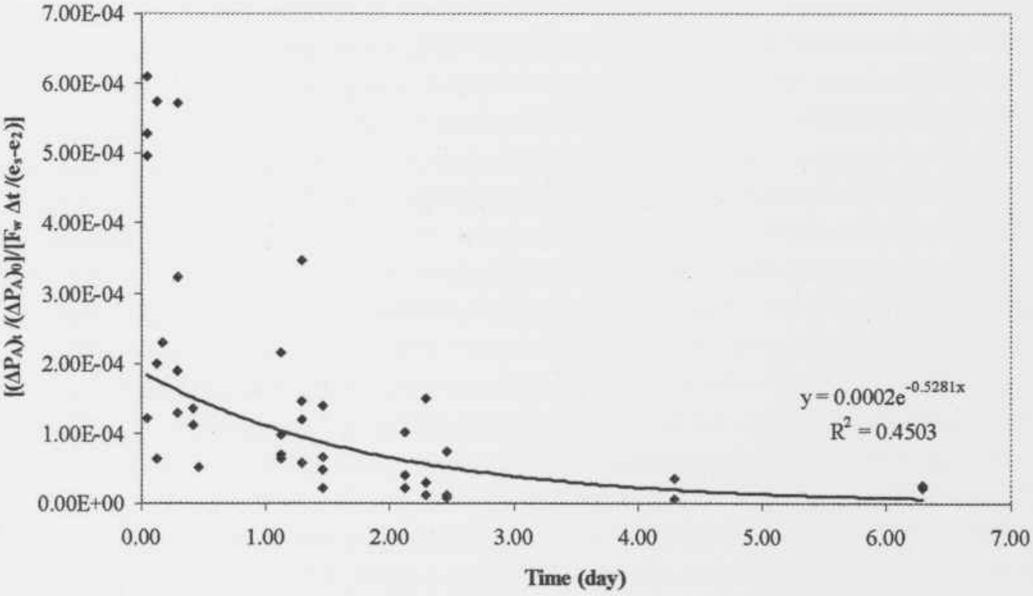

Figure 2.2. The graph of $\dfrac{\dfrac{\Delta(P_A)_{\bar{t}}}{(P_A)_o}}{F_w \cdot \dfrac{1}{e_s - e_2}\Delta t}$ versus time of Diazinon.

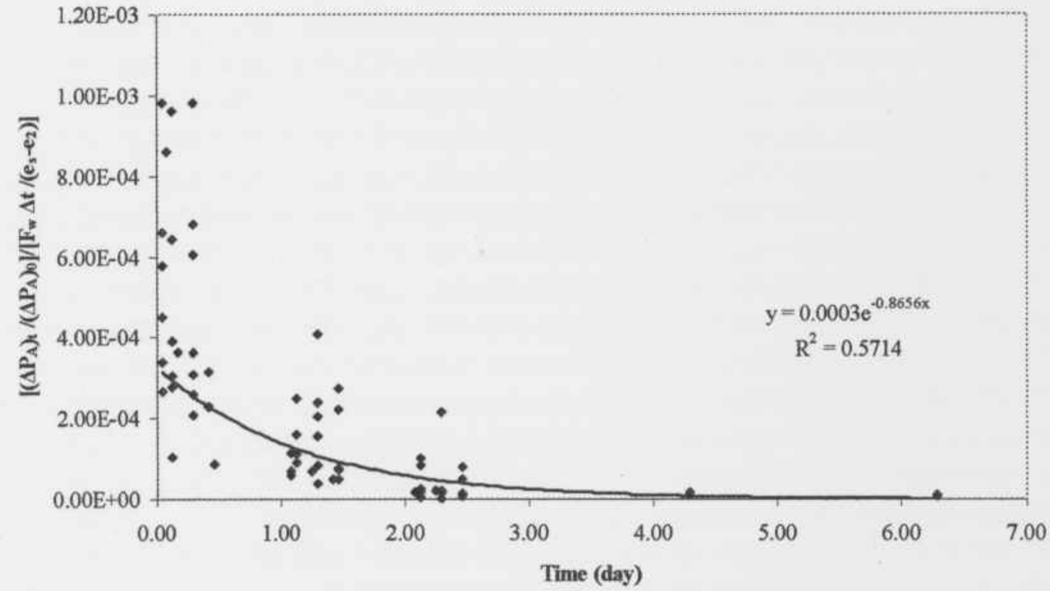

Figure 2.3. The graph of $\dfrac{\dfrac{\Delta(P_A)_{\bar{t}}}{(P_A)_o}}{F_w \cdot \dfrac{1}{e_s - e_2}\Delta t}$ versus time of Ethoprop.

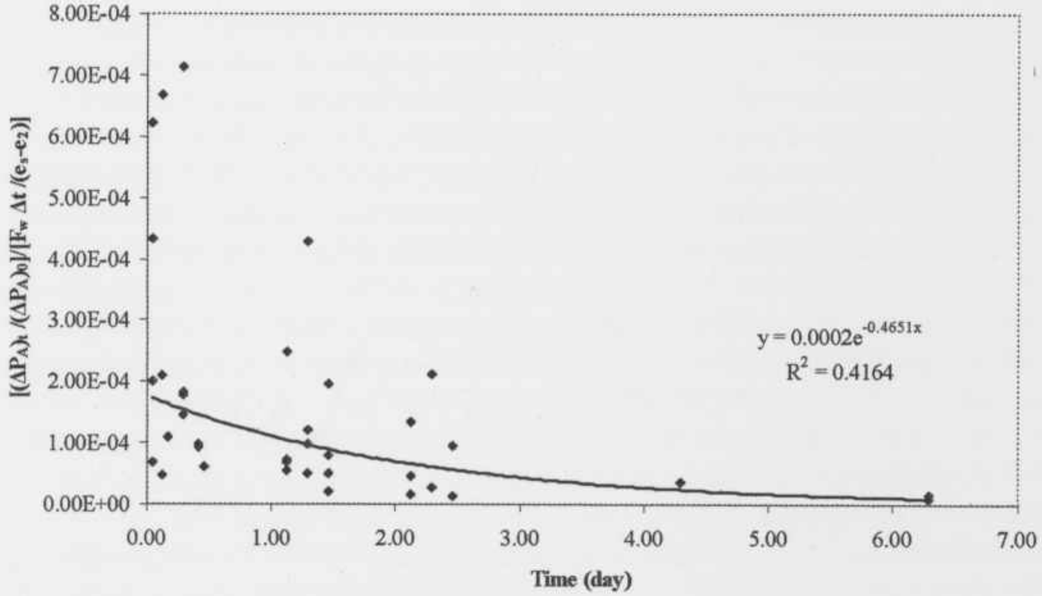

Figure 2.4. The graph of $\dfrac{\dfrac{\Delta(P_A)_{\bar{t}}}{(P_A)_o}}{F_w \cdot \dfrac{1}{e_s - e_2}\Delta t}$ versus time of Isazofos.

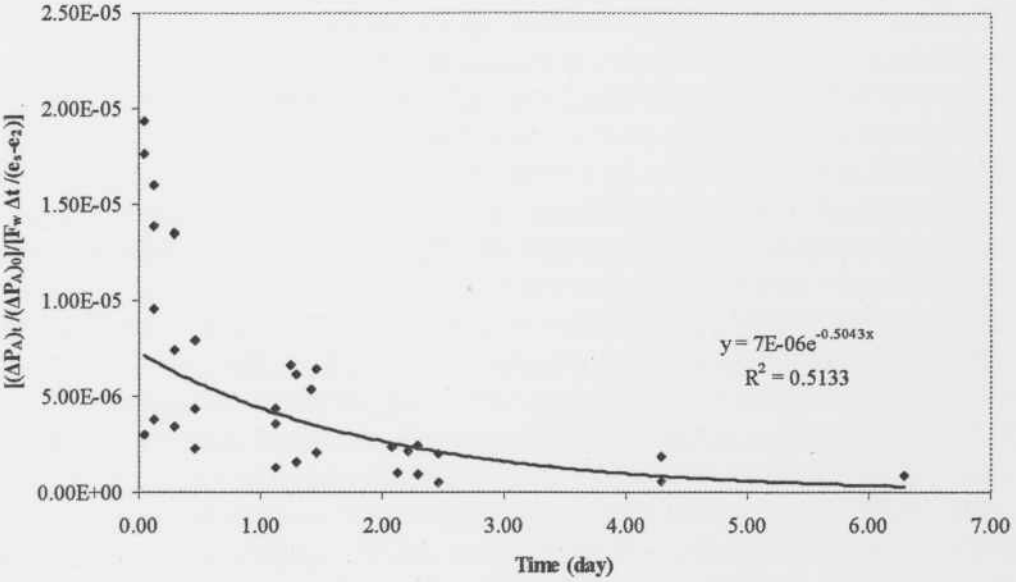

Figure 2.5. The graph of $\dfrac{\dfrac{\Delta(P_A)_{\bar{t}}}{(P_A)_o}}{F_w \cdot \dfrac{1}{e_s - e_2}\Delta t}$ versus time of Carbaryl.

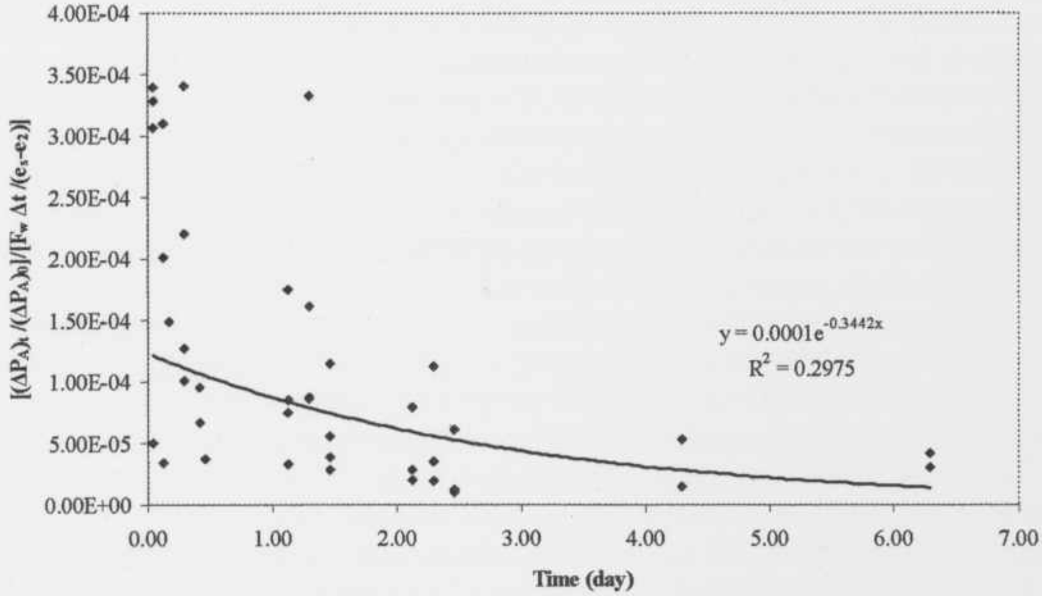

Figure 2.6. The graph of $\dfrac{\dfrac{\Delta(P_A)_{\bar{t}}}{(P_A)_o}}{F_w \cdot \dfrac{1}{e_s - e_2}\Delta t}$ versus time of Chlorpyrifos.

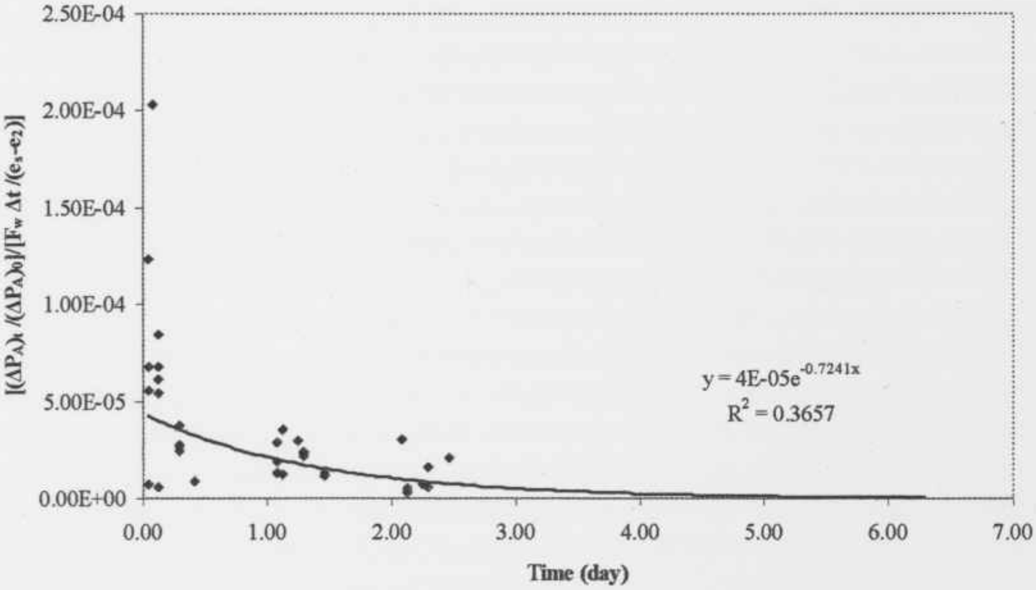

Figure 2.7. The graph of $\dfrac{\dfrac{\Delta(P_A)_t}{(P_A)_o}}{F_w \cdot \dfrac{1}{e_s - e_2}\Delta t}$ versus time of Isofenphos.

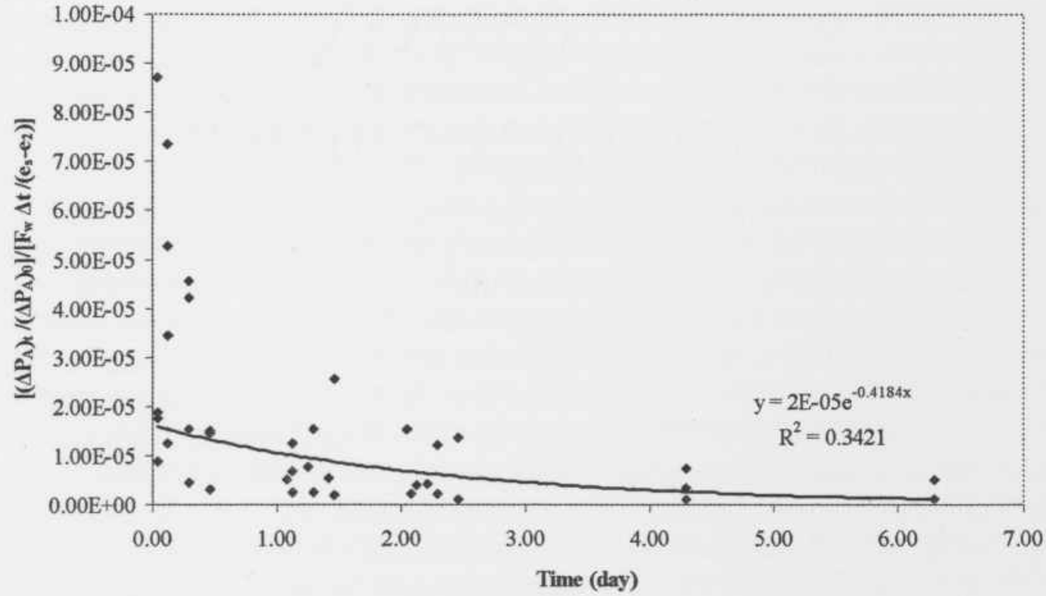

Figure 2.8. The graph of $\dfrac{\dfrac{\Delta(P_A)_{\bar{t}}}{(P_A)_o}}{F_w \cdot \dfrac{1}{e_s - e_2}\Delta t}$ versus time of Trichlorfon.

Table 2.2. The a-term and h/b-term of each pesticide as determined by regression analysis.

| | a ($day^{-1}$) | Half Life from a (day) | h/b ($m^3/m^2$) |
|---|---|---|---|
| Bendiocarb | 0.21 | 3.24 | 2.56E-05 |
| Diazinon | 0.53 | 1.31 | 1.88E-04 |
| Ethoprop | 0.87 | 0.80 | 3.28E-04 |
| Isazofos | 0.47 | 1.49 | 1.77E-04 |
| Carbaryl | 0.50 | 1.37 | 7.25E-06 |
| Chlorpyrifos | 0.34 | 2.01 | 1.23E-04 |
| Isofenphos | 0.72 | 0.96 | 4.37E-05 |
| Trichlorfon | 0.42 | 1.66 | 1.61E-05 |

Table 2.3. The comparison of Haith et.al model and Aero model of Bendiocarb. (High volatilization group)

| Exp | Exp | Exp. # | Time (day) | Observed (%) | Haith (%) | Aero (%) |
|---|---|---|---|---|---|---|
| Week 3 | 95-2 | D1-V1 | 0.04 | 0.32 | 0.14 | 0.08 |
| | | D1-V2 | 0.13 | 0.45 | 0.38 | 0.13 |
| | | D1-V3 | 0.29 | 0.32 | 0.33 | 0.19 |
| | | D2-V1 | 1.13 | 0.13 | 0.15 | 0.23 |
| | | D2-V2 | 1.25 | 0.04 | 0.26 | 0.18 |
| | | D2-V3 | 1.42 | 0.04 | 0.01 | 0.04 |
| | | D3-V1 | 2.08 | 0.06 | 0.06 | 0.07 |
| | | D3-V2 | 2.21 | 0.08 | 0.16 | 0.08 |
| | | D5-V1 | 4.29 | 0.05 | 0.21 | 0.10 |
| | | D7-V1 | 6.29 | 0.04 | 0.12 | 0.06 |
| Week 6 | 95-4 | D1-V1 | 0.04 | 0.03 | 0.05 | 0.04 |
| | | D1-V2 | 0.13 | 0.22 | 0.24 | 0.11 |
| | | D1-V3 | 0.29 | 0.62 | 0.69 | 0.25 |
| | | D1-V4 | 0.46 | 0.35 | 0.21 | 0.18 |
| | | D2-V1 | 1.13 | 0.20 | 0.14 | 0.11 |
| | | D2-V2 | 1.29 | 0.39 | 0.37 | 0.13 |
| | | D2-V3 | 1.46 | 0.27 | 0.09 | 0.06 |
| | | D3-V1 | 2.04 | 0.04 | 0.04 | 0.04 |
| | | D3-V2 | 2.29 | 0.23 | 0.24 | 0.13 |
| | | D3-V3 | 2.46 | 0.18 | 0.08 | 0.08 |
| | | D5-V1 | 4.29 | 0.29 | 0.25 | 0.11 |
| | | D7-V1 | 6.29 | 0.15 | 0.14 | 0.08 |
| Week 9 | 95-6 | D1-V1 | 0.04 | 0.02 | 0.01 | 0.03 |
| | | D1-V2 | 0.13 | 0.11 | 0.01 | 0.05 |
| | | D1-V3 | 0.29 | 0.23 | 0.04 | 0.09 |
| | | D1-V4 | 0.46 | 0.14 | 0.05 | 0.11 |
| | | D2-V1 | 1.08 | 0.09 | 0.17 | 0.16 |
| Week 13 | 96-2 | D1-V1(rain | 0.04 | 0.05 | 0.03 | 0.09 |
| | | D1-V2 | 0.13 | 0.07 | 0.17 | 0.20 |
| | | D1-V3(rain | 0.29 | 0.07 | 0.53 | 0.42 |
| | | D1-V4(rain | 0.46 | 0.09 | 0.27 | 0.30 |
| | | D2-V1(rain | 1.13 | 0.04 | 0.16 | 0.31 |
| | | D2-V2(rain | 1.29 | 0.20 | 0.42 | 0.37 |
| | | D2-V3(rain | 1.46 | 0.16 | 0.14 | 0.18 |
| | | D3-V1 | 2.13 | 0.22 | 0.05 | 0.33 |
| | | D3-V2 | 2.29 | 0.19 | 0.30 | 0.35 |
| | | D3-V3(rain | 2.46 | 0.10 | 0.10 | 0.29 |
| | | D5-V1(rain | 4.29 | 0.22 | 0.17 | 0.18 |
| $R^2$ | | | | | 0.351 | 0.013 |

Table 2.4. The comparison of Haith et.al model and Aero model of Diazinon.

(High volatilization group)

| Exp | Exp | Exp. # | Time (day) | Observed (%) | Haith (%) | Aero (%) |
|---|---|---|---|---|---|---|
| Week 1 | 95-1 | D1-V1 | 0.04 | 1.08 | 0.08 | 0.33 |
| | | D1-V2 | 0.13 | 1.35 | 0.13 | 0.41 |
| | | D1-V3 | 0.29 | 2.22 | 0.17 | 0.62 |
| | | D2-V1 | 1.13 | 3.88 | 0.74 | 1.86 |
| | | D2-V2 | 1.29 | 4.30 | 1.54 | 1.18 |
| | | D2-V3 | 1.46 | 0.45 | 0.12 | 0.28 |
| | | D3-V1 | 2.13 | 0.86 | 1.14 | 0.52 |
| | | D3-V2 | 2.29 | 1.53 | 2.62 | 0.57 |
| | | D3-V3 | 2.46 | 0.72 | 0.68 | 0.51 |
| | | D5-V1 | 4.29 | 0.37 | 2.29 | 0.20 |
| | | D7-V1 | 6.29 | 0.26 | 2.18 | 0.07 |
| Week 4 | 95-3 | D1-V1 | 0.04 | 0.42 | 0.02 | 0.16 |
| | | D1-V2 | 0.17 | 1.47 | 0.70 | 1.10 |
| | | D1-V3 | 0.29 | 3.29 | 2.51 | 1.64 |
| | | D1-V4 | 0.42 | 0.68 | 0.43 | 0.76 |
| | | D2-V1 | 1.13 | 0.66 | 1.03 | 0.70 |
| | | D2-V2 | 1.29 | 1.37 | 2.75 | 0.89 |
| | | D2-V3 | 1.46 | 0.35 | 0.93 | 0.65 |
| | | D3-V2 | 2.29 | 0.33 | 1.98 | 0.62 |
| | | D3-V3 | 2.46 | 0.15 | 0.68 | 0.64 |
| | | D5-V1 | 4.29 | 0.00 | 0.10 | 0.05 |
| | | D7-V1 | 6.29 | 0.00 | 1.75 | 0.09 |
| Week 7 | 95-5 | D1-V1 | 0.04 | 1.20 | 0.17 | 0.42 |
| | | D1-V2 | 0.13 | 1.20 | 0.74 | 1.06 |
| | | D1-V3 | 0.29 | 2.12 | 2.14 | 2.64 |
| | | D1-V4 | 0.46 | 0.65 | 0.48 | 1.87 |
| | | D2-V1 | 1.13 | 0.51 | 0.80 | 0.82 |
| | | D2-V2 | 1.29 | 0.57 | 2.18 | 0.92 |
| | | D2-V3 | 1.46 | 0.16 | 0.58 | 0.64 |
| | | D3-V1 | 2.13 | 0.18 | 0.52 | 0.52 |
| | | D3-V2 | 2.29 | 0.17 | 1.61 | 0.78 |
| | | D3-V3 | 2.46 | 0.09 | 0.45 | 0.64 |
| | | D5-V1 | 4.29 | 0.03 | 0.50 | 0.10 |
| | | D7-V1 | 6.29 | 0.00 | 1.96 | 0.06 |
| Week 12 | 96-1 | D1-V1(rain) | 0.04 | 0.53 | 0.07 | 0.80 |
| | | D1-V2 | 0.13 | 0.58 | 0.35 | 1.61 |
| | | D1-V3 | 0.29 | 3.52 | 1.27 | 2.98 |
| | | D1-V4 | 0.42 | 0.78 | 0.36 | 1.06 |
| | | D2-V1 | 1.13 | 1.16 | 0.46 | 1.72 |
| | | D2-V2 | 1.29 | 1.68 | 1.63 | 1.33 |
| | | D2-V3 | 1.46 | 0.50 | 0.48 | 0.66 |
| | | D3-V1 | 2.13 | 0.25 | 0.11 | 0.38 |
| | | D7-V1(rain) | 6.29 | 0.22 | 0.46 | 0.07 |
| | | | | | | |
| $R^2$ | | | | | 0.050 | 0.431 |

Table 2.5. The comparison of Haith et.al. model and Aero model of Ethoprop. (High volatilization group)

| Exp | Exp | Exp. # | Time (day) | Observed (%) | Haith (%) | Aero (%) |
|---|---|---|---|---|---|---|
| Week 1 | 95-1 | D1-V1 | 0.04 | 1.74 | 0.25 | 0.560 |
| | | D1-V2 | 0.13 | 2.26 | 0.39 | 0.692 |
| | | D1-V3 | 0.29 | 3.81 | 0.52 | 0.987 |
| | | D2-V1 | 1.13 | 4.45 | 2.23 | 2.224 |
| | | D2-V2 | 1.29 | 5.07 | 4.37 | 1.328 |
| | | D2-V3 | 1.46 | 0.72 | 0.33 | 0.300 |
| | | D3-V1 | 2.13 | 0.84 | 3.09 | 0.439 |
| | | D3-V2 | 2.29 | 2.18 | 6.72 | 0.461 |
| | | D3-V3 | 2.46 | 0.79 | 1.74 | 0.386 |
| | | D5-V1 | 4.29 | 0.19 | 5.34 | 0.081 |
| | | D7-V1 | 6.29 | 0.12 | 4.67 | 0.015 |
| Week 4 | 95-3 | D1-V1 | 0.04 | 0.56 | 0.07 | 0.268 |
| | | D1-V2 | 0.17 | 2.33 | 2.06 | 1.817 |
| | | D1-V3 | 0.29 | 6.18 | 7.02 | 2.601 |
| | | D1-V4 | 0.42 | 1.58 | 1.19 | 1.145 |
| | | D2-V1 | 1.13 | 0.74 | 2.74 | 0.839 |
| | | D2-V2 | 1.29 | 1.91 | 6.96 | 1.004 |
| | | D2-V3 | 1.46 | 0.56 | 2.29 | 0.692 |
| | | D3-V2 | 2.29 | 0.25 | 4.63 | 0.503 |
| | | D3-V3 | 2.46 | 0.14 | 1.57 | 0.485 |
| | | D5-V1 | 4.29 | 0 | 0.23 | 0.020 |
| | | D7-V1 | 6.29 | 0 | 3.73 | 0.018 |
| Week 7 | 95-5 | D1-V1 | 0.04 | 1.31 | 0.52 | 0.718 |
| | | D1-V2 | 0.13 | 1.67 | 2.14 | 1.775 |
| | | D1-V3 | 0.29 | 3.4 | 6.12 | 4.176 |
| | | D1-V4 | 0.46 | 1.11 | 1.36 | 2.801 |
| | | D2-V1 | 1.13 | 0.7 | 2.19 | 0.975 |
| | | D2-V2 | 1.29 | 0.79 | 5.66 | 1.040 |
| | | D2-V3 | 1.46 | 0.35 | 1.50 | 0.682 |
| | | D3-V1 | 2.13 | 0.21 | 1.32 | 0.440 |
| | | D3-V2 | 2.29 | 0.23 | 3.92 | 0.624 |
| | | D3-V3 | 2.46 | 0.17 | 1.10 | 0.489 |
| | | D5-V1 | 4.29 | 0.05 | 1.14 | 0.043 |
| | | D7-V1 | 6.29 | 0 | 4.21 | 0.01 |
| Week 12 | 96-1 | D1-V1(rain) | 0.04 | 1.16 | 0.22 | 1.38 |
| | | D1-V2 | 0.13 | 0.96 | 1.09 | 2.70 |
| | | D1-V3 | 0.29 | 6.7 | 3.83 | 4.71 |
| | | D1-V4 | 0.42 | 1.6 | 1.06 | 1.61 |
| | | D2-V1 | 1.13 | 2.64 | 1.39 | 2.06 |
| | | D2-V2 | 1.29 | 3.35 | 4.53 | 1.50 |
| | | D2-V3 | 1.46 | 2.07 | 1.31 | 0.71 |
| | | D3-V1 | 2.13 | 0.53 | 0.31 | 0.33 |
| | | D7-V1(rain) | 6.29 | 0.08 | 1.16 | 0.01 |
| Week 16 | 97-1 | D1-V1 | 0.04 | 2.19 | 0.82 | 2.04 |
| | | D1-V2 | 0.13 | 3.64 | 2.26 | 3.54 |
| | | D1-V3 | 0.29 | 4.28 | 4.29 | 4.19 |
| | | D2-V1 | 1.08 | 1.87 | 1.48 | 2.08 |
| | | D2-V2 | 1.29 | 3.05 | 4.58 | 2.09 |
| | | D2-V3 | 1.46 | 0.62 | 1.59 | 0.79 |
| | | D3-V1 | 2.13 | 0.55 | 0.30 | 1.78 |
| | | D3-V2 | 2.25 | 0.25 | 0.47 | 0.60 |
| | | D3-V3 | 2.46 | 0.32 | 0.45 | 0.26 |
| Week 18 | 97-2 | D1-V1 | 0.04 | 3.06 | 0.79 | 2.15 |
| | | D1-V2 | 0.13 | 3.43 | 1.79 | 2.58 |
| | | D1-V3 | 0.29 | 3.54 | 2.92 | 2.94 |
| | | D2-V1 | 1.08 | 0.82 | 1.84 | 1.52 |
| | | D2-V2 | 1.25 | 0.59 | 1.81 | 0.93 |
| | | D3-V1 | 2.13 | 0.11 | 1.81 | 1.44 |
| | | D3-V2 | 2.29 | 0.03 | 2.80 | 0.98 |

Table 2.6. The comparison of Haith et.al model and Aero model of Isazofos.

(High volatilization group)

| Exp | Exp | Exp. # | Time (day) | Observed (%) | Haith (%) | Aero (%) |
|---|---|---|---|---|---|---|
| Week 1 | 95-1 | D1-V1 | 0.04 | 1.10 | 0.09 | 0.31 |
| | | D1-V2 | 0.13 | 1.57 | 0.14 | 0.39 |
| | | D1-V3 | 0.29 | 2.76 | 0.18 | 0.60 |
| | | D2-V1 | 1.13 | 4.47 | 0.78 | 1.88 |
| | | D2-V2 | 1.29 | 5.30 | 1.59 | 1.20 |
| | | D2-V3 | 1.46 | 0.63 | 0.12 | 0.29 |
| | | D3-V1 | 2.13 | 1.13 | 1.18 | 0.55 |
| | | D3-V2 | 2.29 | 2.17 | 2.67 | 0.62 |
| | | D3-V3 | 2.46 | 0.95 | 0.71 | 0.56 |
| | | D5-V1 | 4.29 | 0.38 | 2.33 | 0.24 |
| | | D7-V1 | 6.29 | 0.16 | 2.21 | 0.10 |
| Week 4 | 95-3 | D1-V1 | 0.04 | 0.17 | 0.03 | 0.15 |
| | | D1-V2 | 0.17 | 0.70 | 0.73 | 1.05 |
| | | D1-V3 | 0.29 | 1.87 | 2.55 | 1.57 |
| | | D1-V4 | 0.42 | 0.47 | 0.45 | 0.73 |
| | | D2-V1 | 1.13 | 0.47 | 1.06 | 0.71 |
| | | D2-V2 | 1.29 | 0.91 | 2.78 | 0.91 |
| | | D2-V3 | 1.46 | 0.37 | 0.96 | 0.67 |
| | | D3-V2 | 2.29 | 0.31 | 2.01 | 0.68 |
| | | D3-V3 | 2.46 | 0.17 | 0.70 | 0.70 |
| | | D5-V1 | 4.29 | 0.00 | 0.11 | 0.06 |
| | | D7-V1 | 6.29 | 0.00 | 1.80 | 0.12 |
| Week 7 | 95-5 | D1-V1 | 0.04 | 0.98 | 0.18 | 0.39 |
| | | D1-V2 | 0.13 | 1.26 | 0.76 | 1.01 |
| | | D1-V3 | 0.29 | 2.39 | 2.21 | 2.53 |
| | | D1-V4 | 0.46 | 0.78 | 0.51 | 1.81 |
| | | D2-V1 | 1.13 | 0.43 | 0.83 | 0.82 |
| | | D2-V2 | 1.29 | 0.49 | 2.23 | 0.94 |
| | | D2-V3 | 1.46 | 0.15 | 0.61 | 0.66 |
| | | D3-V1 | 2.13 | 0.14 | 0.54 | 0.55 |
| | | D3-V2 | 2.29 | 0.00 | 1.66 | 0.84 |
| | | D3-V3 | 2.46 | 0.00 | 0.47 | 0.71 |
| | | D5-V1 | 4.29 | 0.00 | 0.51 | 0.13 |
| | | D7-V1 | 6.29 | 0.00 | 2.00 | 0.08 |
| Week 12 | 96-1 | D1-V1(rain | 0.04 | 0.30 | 0.07 | 0.76 |
| | | D1-V2 | 0.13 | 0.43 | 0.37 | 1.53 |
| | | D1-V3 | 0.29 | 3.27 | 1.33 | 2.85 |
| | | D1-V4 | 0.42 | 0.69 | 0.38 | 1.02 |
| | | D2-V1 | 1.13 | 1.22 | 0.49 | 1.74 |
| | | D2-V2 | 1.29 | 1.69 | 1.69 | 1.36 |
| | | D2-V3 | 1.46 | 0.61 | 0.50 | 0.68 |
| | | D3-V1 | 2.13 | 0.28 | 0.12 | 0.41 |
| | | D7-V1(rain | 6.29 | 0.09 | 0.48 | 0.09 |
| $R^2$ | | | | | 0.030 | 0.337 |

Table 2.7. The comparison of Haith et.al model and Aero model of Carbaryl.

(Low volatilization group)

| Exp | Exp | Exp. # | Time (day) | Observed (%) | Haith (%) | Aero (%) |
|---|---|---|---|---|---|---|
| Week 3 | 95-2 | D1-V1 | 0.04 | 0.06 | 0.00 | 0.02 |
| | | D1-V2 | 0.13 | 0.07 | 0.01 | 0.03 |
| | | D1-V3 | 0.29 | 0.06 | 0.01 | 0.05 |
| | | D2-V1 | 1.13 | 0.05 | 0.00 | 0.05 |
| | | D2-V2 | 1.25 | 0.06 | 0.01 | 0.03 |
| | | D2-V3 | 1.42 | 0.01 | 0.00 | 0.01 |
| | | D3-V1 | 2.08 | 0.01 | 0.00 | 0.01 |
| | | D3-V2 | 2.21 | 0.01 | 0.01 | 0.01 |
| | | D5-V1 | 4.29 | 0.00 | 0.01 | 0.01 |
| | | D7-V1 | 6.29 | 0.00 | 0.01 | 0.00 |
| Week 6 | 95-4 | D1-V1 | 0.04 | 0.03 | 0.00 | 0.01 |
| | | D1-V2 | 0.13 | 0.07 | 0.01 | 0.03 |
| | | D1-V3 | 0.29 | 0.14 | 0.02 | 0.06 |
| | | D1-V4 | 0.46 | 0.06 | 0.01 | 0.04 |
| | | D2-V1 | 1.13 | 0.02 | 0.00 | 0.02 |
| | | D2-V2 | 1.29 | 0.04 | 0.01 | 0.02 |
| | | D2-V3 | 1.46 | 0.02 | 0.00 | 0.01 |
| | | D3-V1 | 2.04 | 0.00 | 0.00 | 0.01 |
| | | D3-V2 | 2.29 | 0.02 | 0.01 | 0.02 |
| | | D3-V3 | 2.46 | 0.01 | 0.00 | 0.01 |
| | | D5-V1 | 4.29 | 0.02 | 0.02 | 0.01 |
| | | D7-V1 | 6.29 | 0.01 | 0.01 | 0.00 |
| Week 9 | 95-6 | D1-V1 | 0.04 | | 0.00 | 0.01 |
| | | D1-V2 | 0.13 | 0.02 | 0.00 | 0.01 |
| | | D1-V3 | 0.29 | 0.05 | 0.00 | 0.02 |
| | | D1-V4 | 0.46 | 0.02 | 0.00 | 0.03 |
| | | D2-V1 | 1.08 | | 0.00 | 0.03 |
| Week 13 | 96-2 | D1-V1(rain) | 0.04 | 0.01 | 0.00 | 0.02 |
| | | D1-V2 | 0.13 | 0.03 | 0.00 | 0.05 |
| | | D1-V3(rain) | 0.29 | 0.06 | 0.01 | 0.11 |
| | | D1-V4(rain) | 0.46 | 0.03 | 0.01 | 0.08 |
| | | D2-V1(rain) | 1.13 | 0.02 | 0.00 | 0.06 |
| | | D2-V2(rain) | 1.29 | 0.03 | 0.01 | 0.07 |
| | | D2-V3(rain) | 1.46 | 0.02 | 0.00 | 0.03 |
| | | D3-V1 | 2.13 | 0.02 | 0.00 | 0.05 |
| | | D3-V2 | 2.29 | 0.02 | 0.01 | 0.05 |
| | | D3-V3(rain) | 2.46 | 0.01 | 0.00 | 0.04 |
| | | D5-V1(rain) | 4.29 | 0.01 | 0.01 | 0.01 |
| $R^2$ | | | | | 0.147 | 0.246 |

Table 2.8. The comparison of Haith et.al model and Aero model of Chlorpyrifos.

(Low volatilization group)

| Exp | Exp | Exp. # | Time (day) | Observed (%) | Haith (%) | Aero (%) |
|---|---|---|---|---|---|---|
| Week 1 | 95-1 | D1-V1 | 0.04 | 0.58 | 0.06 | 0.21 |
| | | D1-V2 | 0.13 | 0.73 | 0.10 | 0.28 |
| | | D1-V3 | 0.29 | 1.32 | 0.13 | 0.43 |
| | | D2-V1 | 1.13 | 3.15 | 0.55 | 1.50 |
| | | D2-V2 | 1.29 | 4.12 | 1.19 | 0.98 |
| | | D2-V3 | 1.46 | 0.37 | 0.08 | 0.24 |
| | | D3-V1 | 2.13 | 0.67 | 0.89 | 0.50 |
| | | D3-V2 | 2.29 | 1.15 | 2.06 | 0.57 |
| | | D3-V3 | 2.46 | 0.61 | 0.52 | 0.52 |
| | | D5-V1 | 4.29 | 0.54 | 1.80 | 0.28 |
| | | D7-V1 | 6.29 | 0.43 | 1.70 | 0.15 |
| Week 4 | 95-3 | D1-V1 | 0.04 | 0.26 | 0.02 | 0.10 |
| | | D1-V2 | 0.17 | 0.95 | 0.55 | 0.74 |
| | | D1-V3 | 0.29 | 2.25 | 1.98 | 1.14 |
| | | D1-V4 | 0.42 | 0.48 | 0.34 | 0.53 |
| | | D2-V1 | 1.13 | 0.58 | 0.82 | 0.57 |
| | | D2-V2 | 1.29 | 1.51 | 2.18 | 0.74 |
| | | D2-V3 | 1.46 | 0.29 | 0.74 | 0.56 |
| | | D3-V2 | 2.29 | 0.39 | 1.57 | 0.62 |
| | | D3-V3 | 2.46 | 0.16 | 0.54 | 0.66 |
| | | D5-V1 | 4.29 | 0 | 0.08 | 0.07 |
| | | D7-V1 | 6.29 | 0 | 1.37 | 0.18 |
| Week 7 | 95-5 | D1-V1 | 0.04 | 0.77 | 0.14 | 0.28 |
| | | D1-V2 | 0.13 | 1.21 | 0.58 | 0.71 |
| | | D1-V3 | 0.29 | 1.66 | 1.68 | 1.83 |
| | | D1-V4 | 0.46 | 0.47 | 0.37 | 1.34 |
| | | D2-V1 | 1.13 | 0.59 | 0.62 | 0.66 |
| | | D2-V2 | 1.29 | 0.84 | 1.73 | 0.77 |
| | | D2-V3 | 1.46 | 0.21 | 0.45 | 0.55 |
| | | D3-V1 | 2.13 | 0.24 | 0.41 | 0.50 |
| | | D3-V2 | 2.29 | 0.26 | 1.27 | 0.77 |
| | | D3-V3 | 2.46 | 0.13 | 0.35 | 0.66 |
| | | D5-V1 | 4.29 | 0.08 | 0.38 | 0.15 |
| | | D7-V1 | 6.29 | 0 | 1.54 | 0.13 |
| Week 12 | 96-1 | D1-V1(rain) | 0.04 | 0.22 | 0.05 | 0.53 |
| | | D1-V2 | 0.13 | 0.31 | 0.25 | 1.08 |
| | | D1-V3 | 0.29 | 2.35 | 0.95 | 2.06 |
| | | D1-V4 | 0.42 | 0.47 | 0.26 | 0.75 |
| | | D2-V1 | 1.13 | 0.55 | 0.33 | 1.39 |
| | | D2-V2 | 1.29 | 1.23 | 1.26 | 1.11 |
| | | D2-V3 | 1.46 | 0.42 | 0.36 | 0.57 |
| | | D3-V1 | 2.13 | 0.13 | 0.08 | 0.37 |
| | | D7-V1(rain) | 6.29 | 0.3 | 0.34 | 0.14 |
| | | | | | | |
| $R^2$ | | | | | 0.100 | 0.355 |

Table 2.9. The comparison of Haith et.al model and Aero model of Isofenphos.

(Low volatilization group)

| Exp | Exp | Exp. # | Time (day) | Observed (%) | Haith (%) | Aero (%) |
|---|---|---|---|---|---|---|
| Week 4 | 95-3 | D1-V1 | 0.04 | 0.00 | 0.00 | 0.04 |
| | | D1-V2 | 0.17 | 0.00 | 0.09 | 0.25 |
| | | D1-V3 | 0.29 | 0.00 | 0.34 | 0.36 |
| | | D1-V4 | 0.42 | 0.00 | 0.05 | 0.16 |
| | | D2-V1 | 1.13 | 0.24 | 0.14 | 0.13 |
| | | D2-V2 | 1.29 | 0.00 | 0.40 | 0.16 |
| | | D2-V3 | 1.46 | 0.00 | 0.13 | 0.11 |
| | | D3-V2 | 2.29 | 0.00 | 0.29 | 0.09 |
| | | D3-V3 | 2.46 | 0.00 | 0.09 | 0.09 |
| | | D5-V1 | 4.29 | 0.00 | 0.01 | 0.00 |
| | | D7-V1 | 6.29 | 0.00 | 0.26 | 0.01 |
| Week 7 | 95-5 | D1-V1 | 0.04 | 0.28 | 0.02 | 0.10 |
| | | D1-V2 | 0.13 | 0.51 | 0.09 | 0.24 |
| | | D1-V3 | 0.29 | 0.00 | 0.27 | 0.58 |
| | | D1-V4 | 0.46 | 0.00 | 0.06 | 0.40 |
| | | D2-V1 | 1.13 | 0.00 | 0.10 | 0.15 |
| | | D2-V2 | 1.29 | 0.00 | 0.30 | 0.17 |
| | | D2-V3 | 1.46 | 0.00 | 0.07 | 0.11 |
| | | D3-V1 | 2.13 | 0.00 | 0.07 | 0.08 |
| | | D3-V2 | 2.29 | 0.00 | 0.22 | 0.11 |
| | | D3-V3 | 2.46 | 0.00 | 0.06 | 0.09 |
| | | D5-V1 | 4.29 | 0.00 | 0.07 | 0.01 |
| | | D7-V1 | 6.29 | 0.00 | 0.30 | 0.00 |
| Week 12 | 96-1 | D1-V1(rain | 0.04 | 0.03 | 0.01 | 0.19 |
| | | D1-V2 | 0.13 | 0.05 | 0.04 | 0.37 |
| | | D1-V3 | 0.29 | 0.45 | 0.14 | 0.65 |
| | | D1-V4 | 0.42 | 0.06 | 0.04 | 0.23 |
| | | D2-V1 | 1.13 | 0.20 | 0.05 | 0.32 |
| | | D2-V2 | 1.29 | 0.32 | 0.20 | 0.24 |
| | | D2-V3 | 1.46 | 0.09 | 0.06 | 0.12 |
| | | D3-V1 | 2.13 | 0.02 | 0.01 | 0.06 |
| | | D7-V1(rain | 6.29 | 0.00 | 0.06 | 0.00 |
| Week 16 | 97-1 | D1-V1 | 0.04 | 0.36 | 0.03 | 0.27 |
| | | D1-V2 | 0.13 | 0.74 | 0.09 | 0.48 |
| | | D1-V3 | 0.29 | 0.44 | 0.17 | 0.58 |
| | | D2-V1 | 1.08 | 0.21 | 0.06 | 0.32 |
| | | D2-V2 | 1.29 | 0.47 | 0.20 | 0.33 |
| | | D2-V3 | 1.46 | 0.11 | 0.07 | 0.13 |
| | | D3-V1 | 2.13 | 0.13 | 0.01 | 0.32 |
| | | D3-V2 | 2.25 | 0.09 | 0.02 | 0.11 |
| | | D3-V3 | 2.46 | 0.14 | 0.02 | 0.05 |
| Week 18 | 97-2 | D1-V1 | 0.04 | 0.46 | 0.03 | 0.29 |
| | | D1-V2 | 0.13 | 0.47 | 0.07 | 0.35 |
| | | D1-V3 | 0.29 | 0.43 | 0.12 | 0.41 |
| | | D2-V1 | 1.08 | 0.34 | 0.08 | 0.24 |
| | | D2-V2 | 1.25 | 0.25 | 0.08 | 0.15 |
| | | D3-V1 | 2.13 | 0.14 | 0.08 | 0.26 |
| | | D3-V2 | 2.29 | 0.12 | 0.13 | 0.18 |
| Week 20 | 97-3 | D1-V1 | 0.08 | 0.97 | 0.13 | 0.20 |
| | | D1-V2 | 0.13 | 0.28 | 0.14 | 0.16 |
| | | D1-V3 | 0.29 | 0.16 | 0.10 | 0.21 |
| | | D2-V1 | 1.08 | 0.14 | 0.07 | 0.15 |
| | | D2-V2 | 1.29 | 0.23 | 0.17 | 0.19 |
| | | D2-V3 | 1.42 | 0.00 | 0.05 | 0.09 |
| | | D3-V1 | 2.08 | 0.13 | 0.03 | 0.04 |
| | | D3-V2 | 2.29 | 0.13 | 0.12 | 0.07 |
| $R^2$ | | | | | 0.005 | 0.227 |

Table 2.10. The comparison of Haith et al. model and Aero model of Trichlorfon.

(Low volatilization group)

| Exp | Exp | Exp. # | Time (day) | Observed (%) | Haith (%) | Aero (%) |
|---|---|---|---|---|---|---|
| Week 3 | 95-2 | D1-V1 | 0.04 | 0.27 | 0.055 | 0.05 |
| | | D1-V2 | 0.13 | 0.37 | 0.154 | 0.08 |
| | | D1-V3 | 0.29 | 0.34 | 0.131 | 0.12 |
| | | D2-V1 | 1.13 | 0.08 | 0.061 | 0.12 |
| | | D2-V2 | 1.25 | 0.07 | 0.118 | 0.09 |
| | | D2-V3 | 1.42 | 0.01 | 0.006 | 0.02 |
| | | D3-V1 | 2.08 | 0.01 | 0.031 | 0.03 |
| | | D3-V2 | 2.21 | 0.02 | 0.082 | 0.03 |
| | | D5-V1 | 4.29 | 0.01 | 0.142 | 0.03 |
| | | D7-V1 | 6.29 | 0.01 | 0.111 | 0.01 |
| Week 6 | 95-4 | D1-V1 | 0.04 | 0.03 | 0.020 | 0.03 |
| | | D1-V2 | 0.13 | 0.15 | 0.095 | 0.07 |
| | | D1-V3 | 0.29 | 0.16 | 0.276 | 0.15 |
| | | D1-V4 | 0.46 | 0.11 | 0.082 | 0.10 |
| | | D2-V1 | 1.13 | 0.07 | 0.058 | 0.06 |
| | | D2-V2 | 1.29 | 0.1 | 0.169 | 0.06 |
| | | D2-V3 | 1.46 | 0.08 | 0.040 | 0.03 |
| | | D3-V1 | 2.04 | 0.04 | 0.017 | 0.02 |
| | | D3-V2 | 2.29 | 0.1 | 0.126 | 0.05 |
| | | D3-V3 | 2.46 | 0.07 | 0.042 | 0.03 |
| | | D5-V1 | 4.29 | 0.08 | 0.171 | 0.03 |
| | | D7-V1 | 6.29 | 0.06 | 0.119 | 0.01 |
| Week 9 | 95-6 | D1-V1 | 0.04 | 0.02 | 0.002 | 0.02 |
| | | D1-V2 | 0.13 | 0.11 | 0.005 | 0.03 |
| | | D1-V3 | 0.29 | 0.17 | 0.014 | 0.05 |
| | | D1-V4 | 0.46 | 0.07 | 0.018 | 0.06 |
| | | D2-V1 | 1.08 | 0.04 | 0.070 | 0.08 |
| Week 13 | 96-2 | D1-V1(rain | 0.04 | 0.03 | 0.012 | 0.05 |
| | | D1-V2 | 0.13 | 0.1 | 0.061 | 0.12 |
| | | D1-V3(rain | 0.29 | 0.08 | 0.201 | 0.25 |
| | | D1-V4(rain | 0.46 | 0.04 | 0.101 | 0.17 |
| | | D2-V1(rain | 1.13 | 0.04 | 0.062 | 0.15 |
| | | D2-V2(rain | 1.29 | 0.05 | 0.179 | 0.18 |
| | | D2-V3(rain | 1.46 | 0.02 | 0.058 | 0.09 |
| | | D3-V1 | 2.13 | 0.08 | 0.025 | 0.14 |
| | | D3-V2 | 2.29 | 0.05 | 0.146 | 0.14 |
| | | D3-V3(rain | 2.46 | 0.02 | 0.046 | 0.11 |
| | | D5-V1(rain | 4.29 | 0.06 | 0.108 | 0.05 |
| $R^2$ | | | | | 0.0738 | 0.0181 |

Table 2.11. Comparison of Haith *et al.* model with Aero model in the sum of each set of experiment.

| Pesticide | Exp | Observed (%) | Haith (%) | Aero (%) |
|---|---|---|---|---|
| Bendiocarb | 95-2 | 1.53 | 1.83 | 1.15 |
| | 95-4 | 2.97 | 2.52 | 1.31 |
| | 95-6 | 0.59 | 0.28 | 0.43 |
| | 96-2 | 1.41 | 2.33 | 3.02 |
| | $R^2$ | | 0.65 | 0.03 |
| Diazinon | 95-1 | 17.02 | 11.69 | 6.54 |
| | 95-3 | 8.72 | 12.89 | 7.29 |
| | 95-5 | 6.88 | 12.16 | 10.47 |
| | 96-1 | 9.22 | 5.19 | 10.63 |
| | $R^2$ | | 0.01 | 0.51 |
| Ethoprop | 95-1 | 22.17 | 29.67 | 7.47 |
| | 95-3 | 14.25 | 32.49 | 9.39 |
| | 95-5 | 9.99 | 31.17 | 13.78 |
| | 96-1 | 19.09 | 14.90 | 15.02 |
| | 97-1 | 16.77 | 16.24 | 17.38 |
| | 97-2 | 11.64 | 15.11 | 12.94 |
| | 97-3 | 12.12 | 16.86 | 7.46 |
| | $R^2$ | | 0.00 | 0.01 |
| Isazofos | 95-1 | 20.62 | 12.01 | 6.74 |
| | 95-3 | 5.44 | 13.16 | 7.34 |
| | 95-5 | 6.62 | 12.52 | 10.48 |
| | 96-1 | 8.58 | 5.44 | 10.45 |
| | $R^2$ | | 0.00 | 0.31 |

Table 2.11 (Continued)

| Pesticide | Exp | Observed (%) | Haith (%) | Aero (%) |
|---|---|---|---|---|
| Carbaryl | 95-2 | 0.33 | 0.08 | 0.23 |
| | 95-4 | 0.44 | 0.11 | 0.26 |
| | 95-6 | 0.09 | 0.00 | 0.10 |
| | 96-2 | 0.26 | 0.08 | 0.59 |
| | $R^2$ | | 0.93 | 0.05 |
| Chlorpyrifos | 95-1 | 13.67 | 9.10 | 5.67 |
| | 95-3 | 6.87 | 10.18 | 5.91 |
| | 95-5 | 6.46 | 9.51 | 8.33 |
| | 96-1 | 5.98 | 3.87 | 8.00 |
| | $R^2$ | | 0.09 | 0.47 |
| Isofenphos | 95-3 | 0.24 | 1.80 | 1.41 |
| | 95-5 | 0.79 | 1.62 | 2.04 |
| | 96-1 | 1.22 | 0.59 | 2.17 |
| | 97-1 | 2.69 | 0.67 | 2.60 |
| | 97-2 | 2.21 | 0.59 | 1.87 |
| | 97-3 | 2.04 | 0.79 | 1.10 |
| | $R^2$ | | 0.69 | 0.11 |
| Trichlorfon | 95-2 | 1.19 | 0.89 | 0.56 |
| | 95-4 | 1.05 | 1.22 | 0.63 |
| | 95-6 | 0.41 | 0.11 | 0.24 |
| | 96-2 | 0.57 | 1.00 | 1.45 |
| | $R^2$ | | 0.45 | 0.01 |

Table 2.12. $R^2$ values of both models (Haith & Aero).

| Pesticide | Haith $R^2$, Individually | Aero $R^2$, Individually | Haith $R^2$, sum | Aero $R^2$, sum |
|---|---|---|---|---|
| *Bendiocarb | 0.35 | 0.01 | 0.65 | 0.03 |
| *Diazinon | 0.05 | 0.43 | 0.01 | 0.51 |
| *Ethoprop | 0.11 | 0.54 | 0.00 | 0.01 |
| *Isazofos | 0.03 | 0.34 | 0.00 | 0.31 |
| Carbaryl | 0.15 | 0.25 | 0.93 | 0.05 |
| Chlorpyrifos | 0.10 | 0.36 | 0.09 | 0.47 |
| Isofenphos | 0.01 | 0.23 | 0.69 | 0.11 |
| Trichlorfon | 0.07 | 0.02 | 0.45 | 0.01 |

* Classified as high volatilization group in Haith *et al.*, 2002. The others are low volatilization group.

Table 2.13. Comparison of degradation (Half Life) from different references.

| | Half Life from a (day) | Half Life from Haith et al. (day) | Half Life in soil from USDA (day) | Field Dissipation Half Life from USDA (day) |
|---|---|---|---|---|
| Bendiocarb | 2.12 | 2.9 | 0.94~3.5 | 3~21 |
| Diazinon | 1.05 | 39.0 | 39 | 2.8~48 |
| Ethoprop | 0.73 | 24.0 | 24 | 4~87 |
| Isazofos | 1.14 | 40.5 | 45 | 2.5~48.4 |
| Carbaryl | 1.16 | 17.0 | 7~27 | 4~13 |
| Chlorpyrifos | 1.44 | 30.5 | 30.5 | 1.3~139 |
| Isofenphos | 1.20 | 93.0 | 59~127 | 12~365 |
| Trichlorfon | 1.28 | 6.4 | 1.8~6.4 | < 1~2.2 |

* Half life data of USDA is from Agricultural Research Service. 2001.

Table. 2.13. (Continued)

| | Half Life of Hydrolysis from USDA (day) | Half Life of Photolysis from USDA (day) | Shortest Half Life of (Hydrolysis + Photolysis) Calculated. from USDA (day) |
|---|---|---|---|
| Bendiocarb | 0.03~5.0 | 0.29~37.3 | 0.03 |
| Diazinon | 11.8~77.0 | 4.6~5.1 | 3.30 |
| Ethoprop | 19.8 | 23.9 | 10.83 |
| Isazofos | 14.0~115.0 | 4.0~40.8 | 3.11 |
| Carbaryl | 10.5 | 45 | 8.51 |
| Chlorpyrifos | 15.8~77.0 | -- | 15.75 |
| Isofenphos | 30.1 | 72.2~99.0 | 21.26 |
| Trichlorfon | 34.7~103.4 | 11.8~110.2 | 0.02 |

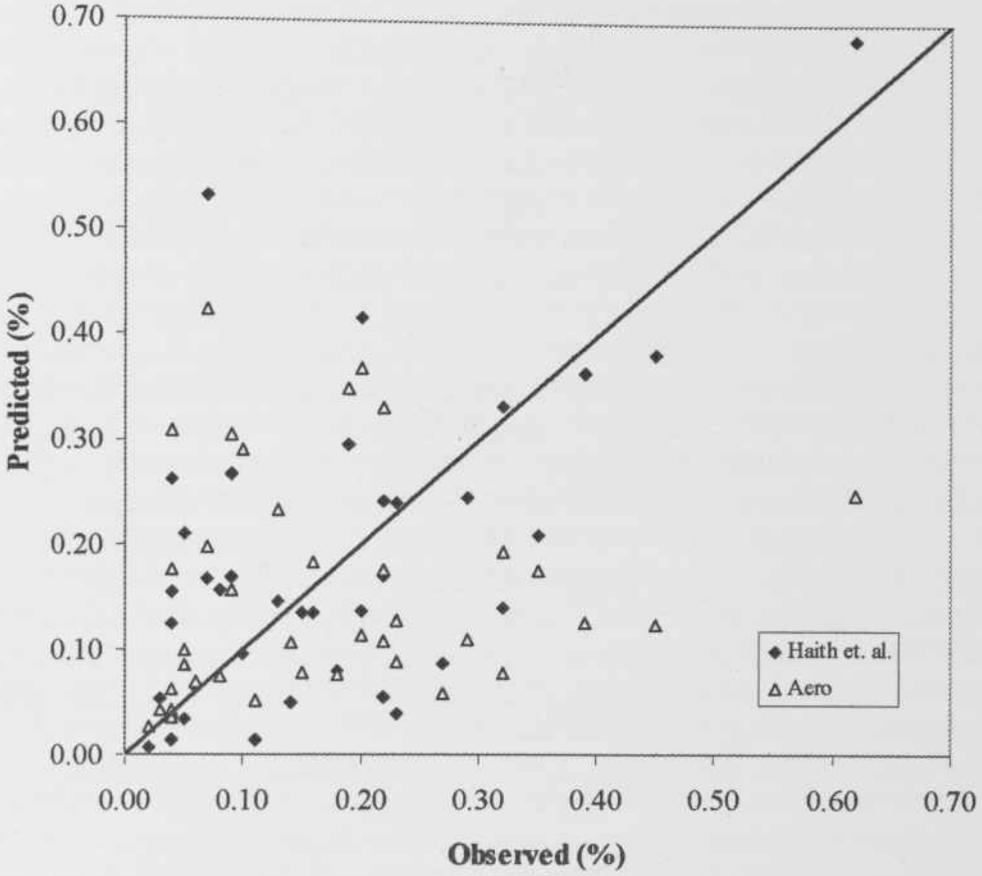

Figure 2.9. The comparison of predicted pesticide volatilization with observed volatilization of Bendiocarb.

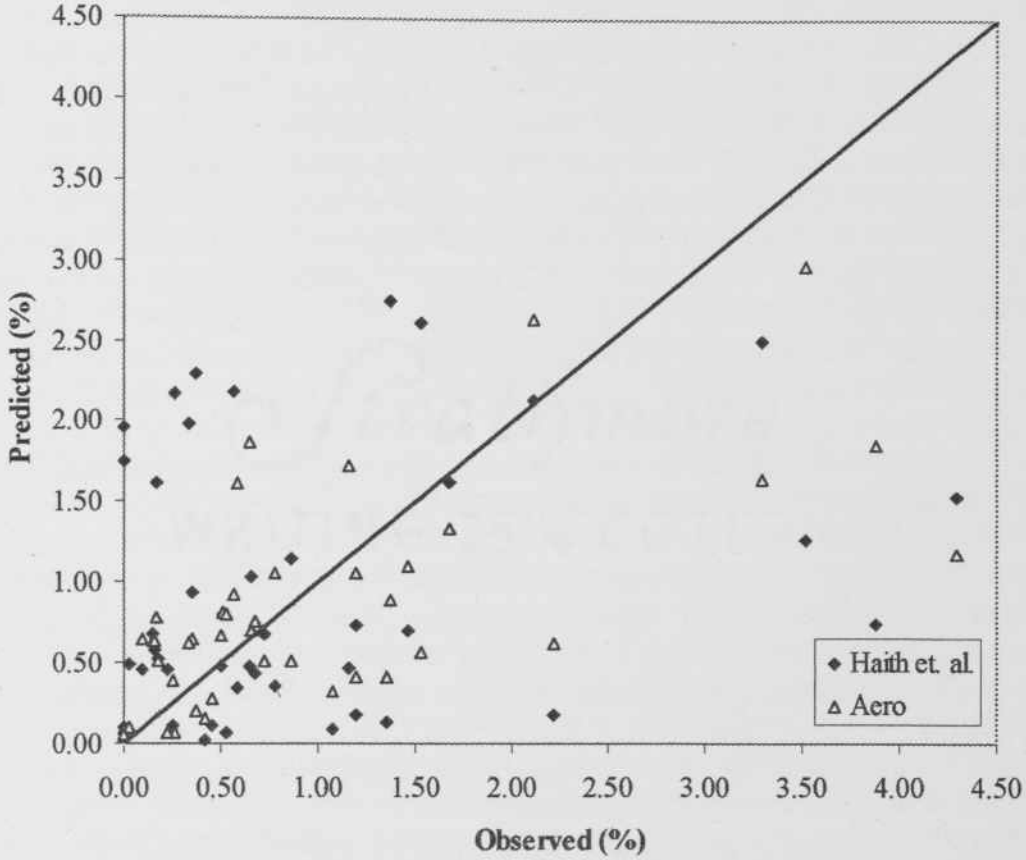

Figure 2.10. The comparison of predicted pesticide volatilization with observed volatilization of Diazinon.

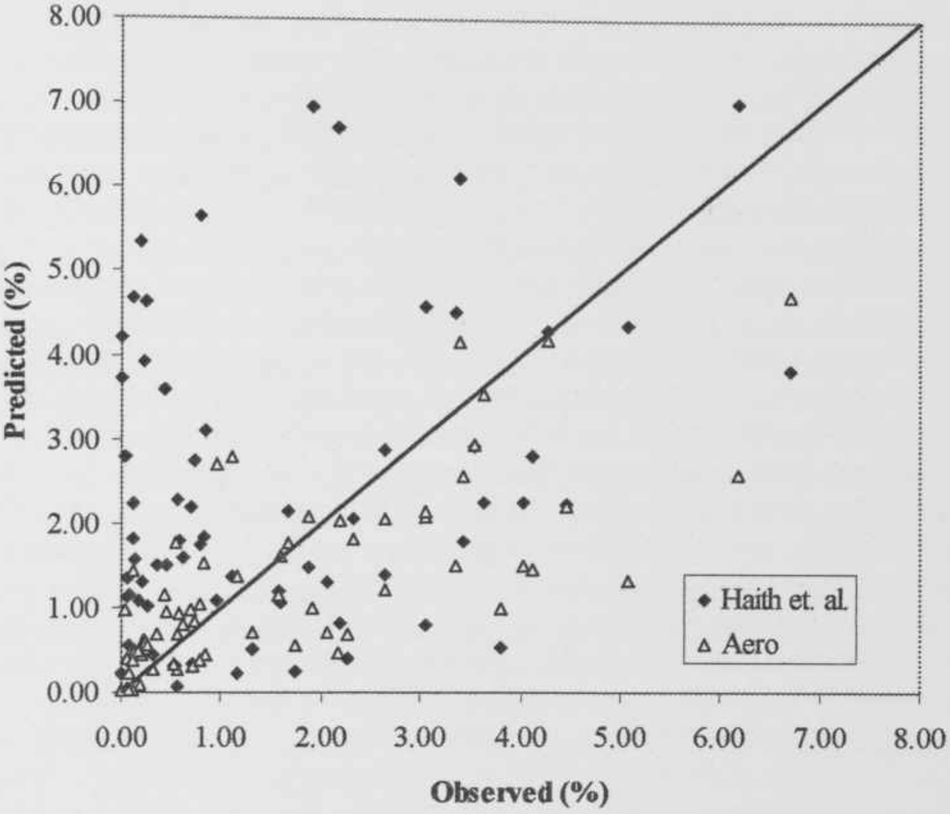

Figure 2.11. The comparison of predicted pesticide volatilization with observed volatilization of Ethoprop.

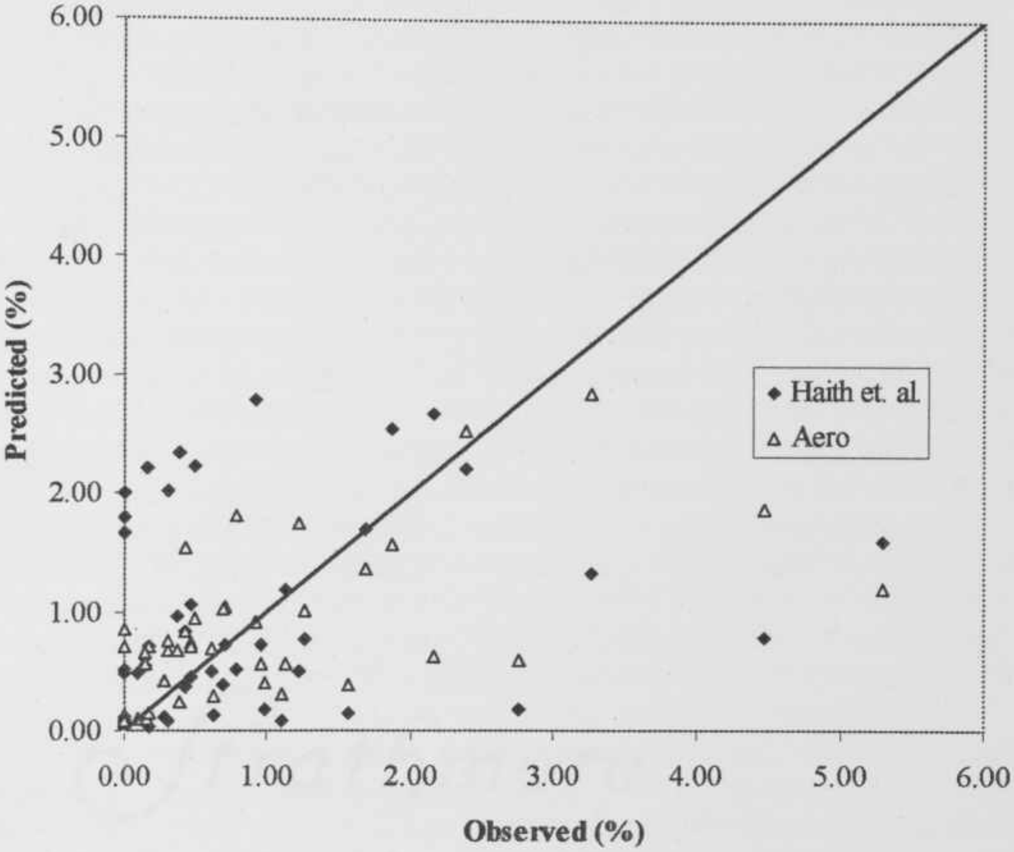

Figure 2.12. The comparison of predicted pesticide volatilization with observed volatilization of Isazofos.

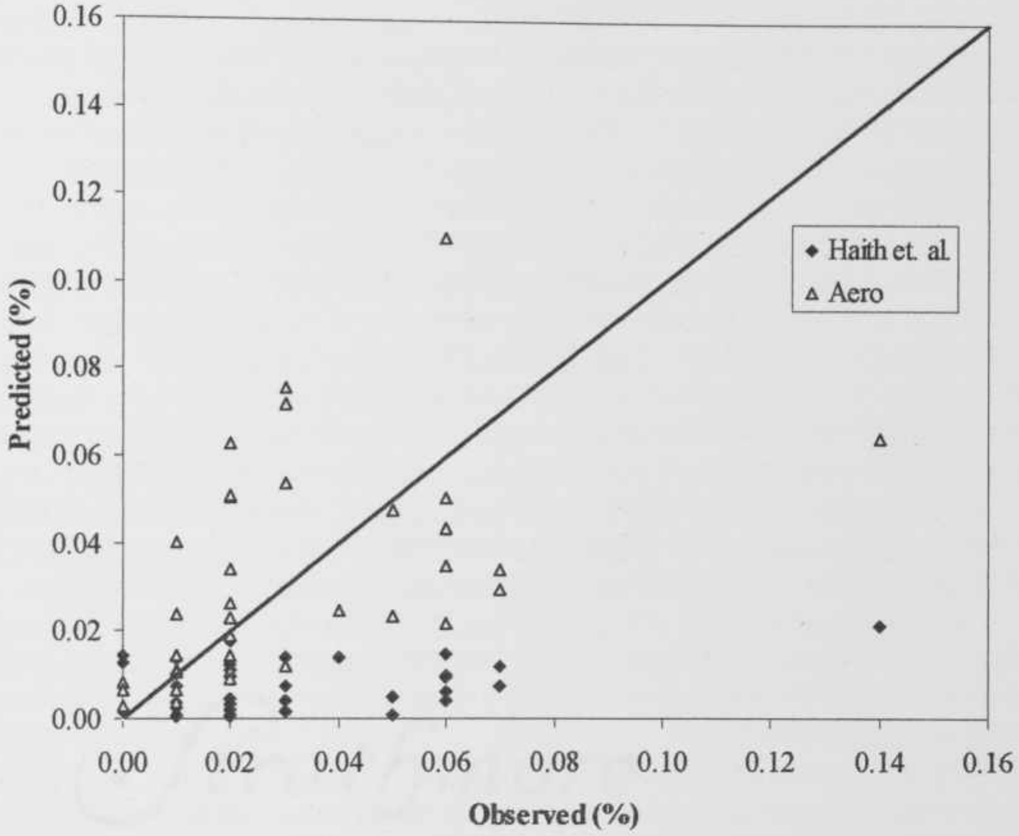

Figure 2.13. The comparison of predicted pesticide volatilization with observed volatilization of Carbaryl.

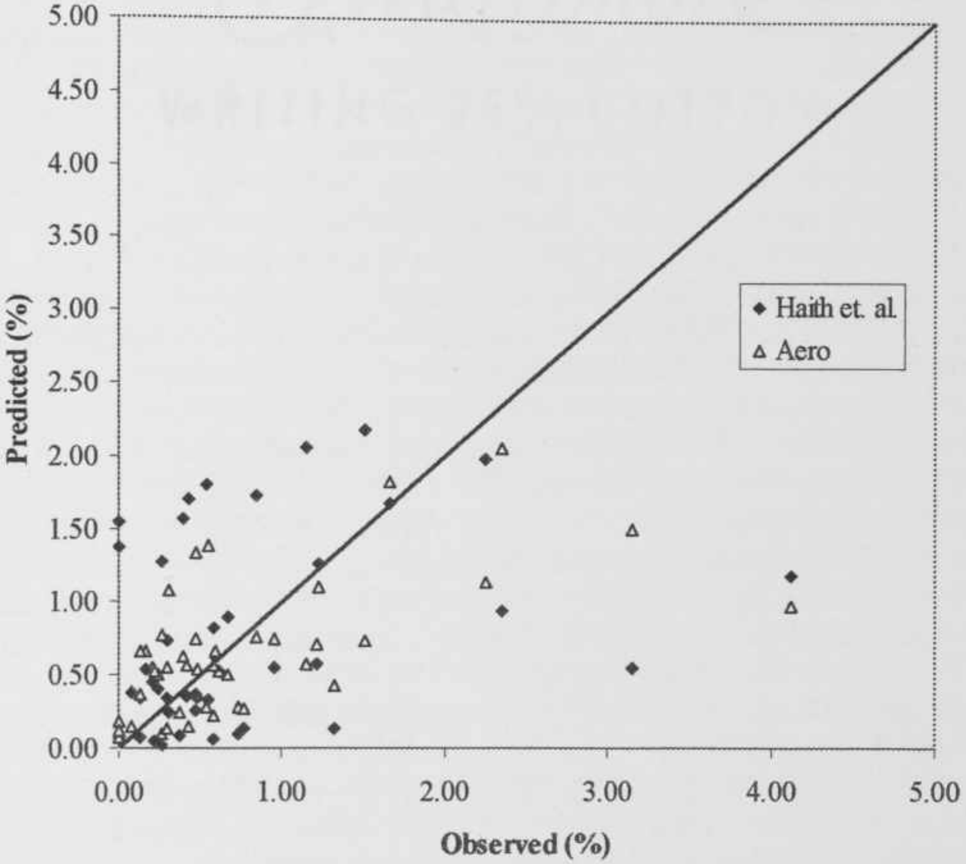

Figure 2.14. The comparison of predicted pesticide volatilization with observed volatilization of Chlorpyrifos.

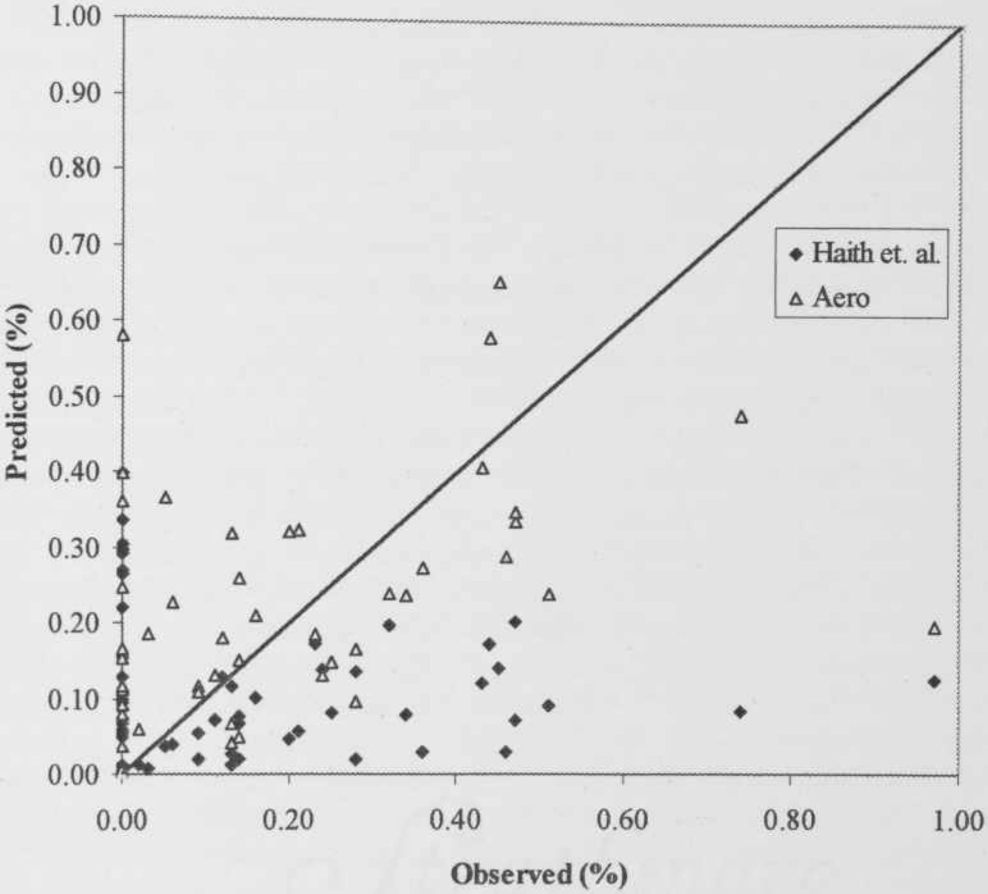

Figure 2.15. The comparison of predicted pesticide volatilization with observed volatilization of Isofenphos.

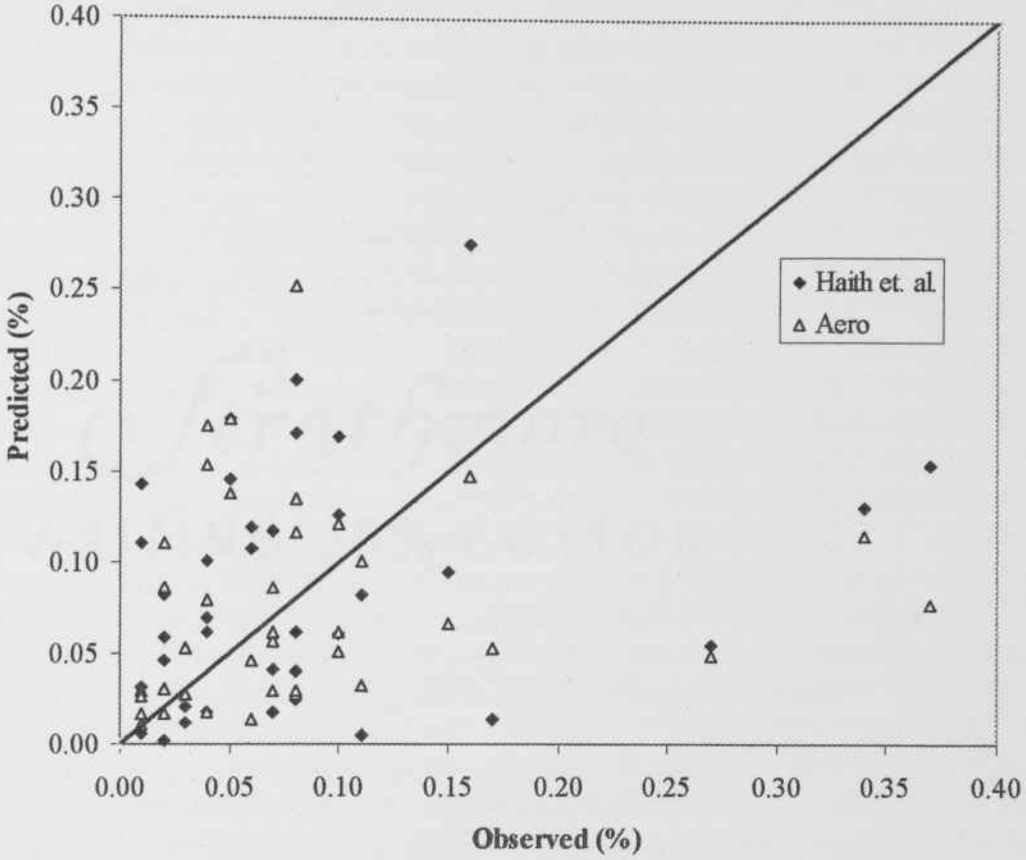

Figure 2.16. The comparison of predicted pesticide volatilization with observed volatilization of Trichlorfon.

**Symbols listed in this chapter**

a = degradation rate of pesticide, $day^{-1}$

b = adsorption parameter, $m^3$ $m^{-2}$

$C_p$ = solute concentration, mole/$m^3$

$C_s$ = concentration of pesticide on the solid phase, mole $g^{-1}$

d = vapor concentration of pesticide, mole/$m^3$

$d_1$ = vapor concentration of pesticide at $z_1$, mole/$m^3$

$d_2$ = vapor concentration of pesticide at $z_2$, mole/$m^3$

$d_s$ = saturated pesticide vapor pressure, the same unit as $e_s$, kPa or mole $m^{-3}$
$d_{s,T_{a_0}}$ = saturated pesticide vapor pressure at temperature $T_{a_0}$, kPa

$F_{w,H} \cdot \Delta t$ = water evapotranspiration during time $\Delta t$, mm

$e_1$ = vapor concentration of water at $z_1$, mole $m^{-3}$

$e_2$ = vapor concentration of water at $z_2$, (mole $m^{-3}$ )
$e'_s$ = saturated water vapor pressure at air temperature T, kPa

F = vertical flux of vapor, mole $m^{-2}$ $sec^{-1}$

$F_p$ = vapor flux of pesticide, mole $m^{-2}$ $hr^{-1}$

$F_w$ = vapor flux of water, mole $m^{-2}$ $hr^{-1}$

h = Henry's law constant, dimensionless

K = the adsorption partition coefficient, $m^3$ $g^{-1}$

k = volatilization constant, $mm^{-1}$

$K_f$ = constant, dimensionless, 1.06 (Haith, 2002)

$k_z$ = mean eddy diffusivity coefficient or transport coefficient, $m^2$ $sec^{-1}$

m = constant, 0.8 (Haith, 2002)

p = vapor concentration, mole $m^{-3}$

$P_A$ = pesticide on plant leaves per unit area, mole $m^{-2}$

$(P_A)_o$ = the initial mass of pesticide per unit area at time t = 0, mole $m^{-2}$

$(P_A)_{\bar{t}}$ = the amount of pesticide remaining on the leaves at time $\bar{t}$, mole $m^{-2}$

$(P_{A,H})_t$ = pesticide available for volatilization on vegetation at the beginning time step t, g $ha^{-1}$

$(P_{A,H})_{t+1}$ = pesticide available for volatilization on vegetation at the beginning of time step t+1, g $ha^{-1}$

R = gas constant, 8.314 J $mole^{-1}$ $K^{-1}$

RH = relative humidity during time Δt, dimensionless

S = weight of sorbent in contact with the pesticide, g $m^{-2}$

T = air temperature during time Δt, °C

$T_a$ = air temperature during time Δt, K

$T_{a_0}$ = temperature at the addressed $d_{s,T_{a_0}}$, K

$T_t$ = temperature during time Δt, °C

t' = time period between each sampling period, hr

$\bar{t}$ = time since initial pesticide spraying, day

W = amount of water per unit area on the plant leaves, $m^3/m^2$

z = z coordinate in the vertical direction, m

$z_1$ = vertical direction at height 1, m

$z_2$ = vertical direction at height 2, m

$\Delta(P_{A,v})_{\bar{t}}$ = pesticide loss (volatilization) at time $\bar{t}$ in short period of time Δt of Aero model, mole $m^{-2}$

$\Delta(P_{A,H})_t$ = pesticide vaporized from surface vegetation during time Δt at time step t of Haith model, g $ha^{-1}$

$\Delta Z_b$ = compressibility factor at boiling point, dimensionless, 0.97 (Grain, 1982)

Δt = sampling period of pesticide volatilization, day

$\alpha$ = degradation rate of pesticide on vegetation surface, $hr^{-1}$

$\lambda_{p,t}$ = latent heat of vaporization of the chemical during time $\Delta t$ at time step t, J $g^{-1}$ or kJ $kg^{-1}$

$\lambda_{p,T_{a_0}}$ = latent heat of pesticide vaporization at temperature $T_{a_0}$, J/g

$\lambda_{w,t}$ = latent heat of vaporization of water during time $\Delta t$ at time step t, J $g^{-1}$ or kJ $kg^{-1}$

Appendix 2.1. Input Data

| Experiment Set | 95-1 week 1 June 14 - 20, 1995 | | | | | |
|---|---|---|---|---|---|---|
| Period | Air Temperature, $T_t$, °C | Duration, hr | Penman Evaporation During Duration, $F_{w,H}\,\Delta t$, mm | Lowest temperature of a day, $Td_t$, °C | Solar Radiation, Rs, KJ $m^{-2}hr^{-1}$ | Wind speed, u, $ms^{-1}$ |
| D1-V1 | 23.1 | 1 | 0.17 | 13.3 | 990 | 1.7 |
| D1-V2 | 24.1 | 2 | 0.25 | 13.3 | 836 | 1.1 |
| D1-V3 | 22.8 | 4 | 0.35 | 13.3 | 631 | 2 |
| D2-V1 | 20 | 4 | 1.70 | 7.7 | 2029 | 2.8 |
| D2-V2 | 28.9 | 4 | 2.60 | 7.7 | 2520 | 2.4 |
| D2-V3 | 19.2 | 4 | 0.28 | 7.7 | 590 | 1.3 |
| D3-V1 | 29.8 | 4 | 1.94 | 6.6 | 2033 | 1 |
| D3-V2 | 36.5 | 4 | 3.66 | 6.6 | 3216 | 2.1 |
| D3-V3 | 24.2 | 4 | 1.47 | 6.6 | 1638 | 1.9 |
| D5-V1 | 36.9 | 4 | 3.41 | 12.2 | 2908 | 2.8 |
| D7-V1 | 38.3 | 4 | 3.31 | 18.3 | 3022 | 1.8 |

Appendix 2.1. (Continued)

| Experiment Set | 95-2 week 3 July 6 - 12, 1995 | | | | | |
|---|---|---|---|---|---|---|
| Period | Air Temperature, $T_t$, °C | Duration, hr | Penman Evaporation During Duration, $F_{w,H} \Delta t$, mm | Lowest temperature of a day, $Td_t$, °C | Solar Radiation, Rs, KJ $m^{-2}hr^{-1}$ | Windspeed, u, $ms^{-1}$ |
| D1-V1 | 34.5 | 1 | 0.70 | 19.4 | 2644 | 2.6 |
| D1-V2 | 39.3 | 2 | 1.69 | 19.4 | 2892 | 2.9 |
| D1-V3 | 34 | 4 | 1.74 | 19.4 | 1622 | 3 |
| D2-V1 | 28 | 4 | 1.14 | 20.5 | 1456 | 1.9 |
| D2-V2 | 33.6 | 3 | 1.78 | 20.5 | 2286 | 2.8 |
| D2-V3 | 26.1 | 3 | 0.13 | 20.5 | 442 | 1.2 |
| D3-V1 | 29.9 | 3 | 0.60 | 19.4 | 1040 | 1.6 |
| D3-V2 | 36.3 | 2 | 1.26 | 19.4 | 2325 | 2.3 |
| D5-V1 | 35 | 4 | 2.83 | 12.7 | 2539 | 2.4 |
| D7-V1 | 35.8 | 4 | 2.66 | 16.1 | 2541 | 1.5 |

Appendix 2.1. (Continued)

| Experiment Set | 95-3 week 4 July 13 - 19, 1995 | | | | | |
|---|---|---|---|---|---|---|
| Period | Air Temperature, $T_t$, °C | Duration, hr | Penman Evaporation During Duration, $F_{w,H}\,\Delta t$, mm | Lowest temperature of a day, $Td_t$, °C | Solar Radiation, Rs, KJ $m^{-2}hr^{-1}$ | Windspeed, u, $ms^{-1}$ |
| D1-V1 | 23.1 | 1 | 0.05 | 17.7 | 309 | 1.9 |
| D1-V2 | 30.7 | 3 | 1.09 | 17.7 | 1529 | 2.3 |
| D1-V3 | 37.6 | 4 | 3.17 | 17.7 | 2805 | 2.5 |
| D1-V4 | 29.2 | 3 | 0.73 | 17.7 | 1137 | 2.1 |
| D2-V1 | 34.3 | 4 | 1.50 | 19.4 | 1575 | 1.5 |
| D2-V2 | 40.4 | 4 | 3.42 | 19.4 | 2964 | 2.3 |
| D2-V3 | 33.1 | 4 | 1.48 | 19.4 | 1483 | 2.4 |
| D3-V2 | 37.6 | 4 | 2.81 | 23.3 | 2669 | 2 |
| D3-V3 | 30.1 | 4 | 1.25 | 23.3 | 1485 | 2.9 |
| D5-V1 | 25.3 | 4 | 0.23 | 17.2 | 476 | 1.1 |
| D7-V1 | 33.7 | 4 | 3.09 | 15.5 | 2835 | 2.8 |

Appendix 2.1. (Continued)

| Experiment Set | 95-4 week 6 August 13 - 19, 1995 | | | | | |
|---|---|---|---|---|---|---|
| Period | Air Temperature, $T_t$, °C | Duration, hr | Penman Evaporation During Duration, $F_{w,H}\Delta t$, mm | Lowest temperature of a day, $Td_t$, °C | Solar Radiation, Rs, KJ $m^{-2}hr^{-1}$ | Windspeed, u, $ms^{-1}$ |
| D1-V1 | 30.2 | 1 | 0.31 | 15.5 | 1425 | 1.1 |
| D1-V2 | 35.2 | 2 | 1.20 | 15.5 | 2299 | 1.6 |
| D1-V3 | 37.1 | 4 | 3.28 | 15.5 | 2924 | 2.3 |
| D1-V4 | 29.8 | 4 | 1.32 | 15.5 | 1344 | 2.6 |
| D2-V1 | 29.3 | 4 | 1.03 | 13.3 | 1193 | 1.3 |
| D2-V2 | 37.5 | 4 | 2.23 | 13.3 | 2031 | 1.6 |
| D2-V3 | 31.2 | 4 | 0.67 | 13.3 | 768 | 1.5 |
| D3-V1 | 29.7 | 2 | 0.34 | 20 | 929 | 1.7 |
| D3-V2 | 35.5 | 4 | 1.98 | 20 | 1872 | 2.4 |
| D3-V3 | 31.1 | 4 | 0.79 | 20 | 940 | 2.2 |
| D5-V1 | 38.3 | 4 | 3.05 | 22.2 | 2775 | 2.4 |
| D7-V1 | 33.6 | 4 | 3.11 | 12.2 | 2874 | 2.3 |

Appendix 2.1. (Continued)

| Experiment Set | 95-5 week 7 August 22 - 28, 1995 | | | | | |
|---|---|---|---|---|---|---|
| Period | Air Temperature, $T_t$, °C | Duration, hr | Penman Evaporation During Duration, $F_{w,H}\Delta t$, mm | Lowest temperature of a day, $Td_t$, °C | Solar Radiation, Rs, KJ $m^{-2}hr^{-1}$ | Windspeed, u, $ms^{-1}$ |
| D1-V1 | 27.7 | 1 | 0.30 | 16.6 | 1321 | 2.8 |
| D1-V2 | 31.1 | 2 | 1.13 | 16.6 | 2101 | 3.6 |
| D1-V3 | 31.7 | 4 | 3.24 | 16.6 | 2838 | 5 |
| D1-V4 | 23.8 | 4 | 0.98 | 16.6 | 1237 | 3.7 |
| D2-V1 | 27.6 | 4 | 1.45 | 8.8 | 1603 | 1.3 |
| D2-V2 | 35.3 | 4 | 3.12 | 8.8 | 2753 | 2.3 |
| D2-V3 | 25.8 | 4 | 1.16 | 8.8 | 1251 | 2.2 |
| D3-V1 | 26.3 | 4 | 1.04 | 15 | 1251 | 2.2 |
| D3-V2 | 31.1 | 4 | 2.77 | 15 | 2406 | 4.7 |
| D3-V3 | 23.2 | 4 | 1.04 | 15 | 1253 | 3.9 |
| D5-V1 | 27 | 4 | 1.03 | 5.5 | 1127 | 1.5 |
| D7-V1 | 36.7 | 4 | 3.15 | 8.3 | 2824 | 1.7 |

Appendix 2.1. (Continued)

| Experiment Set | 95-6 week 9 September 19 - 20, 1995 | | | | | |
|---|---|---|---|---|---|---|
| Period | Air Temperature, $T_t$, °C | Duration, hr | Penman Evaporation During Duration, $F_{w,H}\Delta t$, mm | Lowest temperature of a day, $Td_t$, °C | Solar Radiation, Rs, KJ $m^{-2}hr^{-1}$ | Windspeed, u, $ms^{-1}$ |
| D1-V1 | 15 | 1 | 0.07 | 3.3 | 46 | 1.8 |
| D1-V2 | 15.6 | 2 | 0.16 | 3.3 | 103 | 1.8 |
| D1-V3 | 18.5 | 4 | 0.37 | 3.3 | 293 | 1.7 |
| D1-V4 | 18.9 | 4 | 0.48 | 3.3 | 199 | 2.6 |
| D2-V1 | 26 | 3 | 1.41 | 4.4 | 1716 | 3.5 |

Appendix 2.1. (Continued)

| Experiment Set | 96-1 week 12 May 14 - 20, 1996 | | | | | |
|---|---|---|---|---|---|---|
| Period | Air Temperature, $T_t$, °C | Duration, hr | Penman Evaporation During Duration, $F_{w,H}\Delta t$, mm | Lowest temperature of a day, $Td_t$, °C | Solar Radiation, Rs, KJ $m^{-2}hr^{-1}$ | Windspeed, u, $ms^{-1}$ |
| D1-V1(rain) | 9.6 | 1 | 0.23 | -2.8 | 1613 | 1.2 |
| D1-V2 | 16.1 | 2 | 0.91 | -2.8 | 2370 | 1.5 |
| D1-V3 | 21.2 | 4 | 2.75 | -2.8 | 2879 | 3 |
| D1-V4 | 18.7 | 3 | 0.87 | -2.8 | 1348 | 2.1 |
| D2-V1 | 14.4 | 4 | 1.35 | -1.2 | 1934 | 1.2 |
| D2-V2 | 26.8 | 4 | 3.00 | -1.2 | 3055 | 1.6 |
| D2-V3 | 21.2 | 4 | 1.10 | -1.2 | 1222 | 2 |
| D3-V1 | 12.3 | 4 | 0.37 | 1.1 | 735 | 1.7 |
| D7-V1(rain) | 25 | 4 | 1.00 | 15.5 | 1279 | 2.2 |

Appendix 2.1. (Continued)

| Experiment Set | 96-2 week 13 May 22 - 28, 1996 | | | | | |
|---|---|---|---|---|---|---|
| Period | Air Temperature, $T_t$, °C | Duration, hr | Penman Evaporation During Duration, $F_{w,H}\Delta t$, mm | Lowest temperature of a day, $Td_t$, °C | Solar Radiation, Rs, KJ $m^{-2}hr^{-1}$ | Windspeed, u, $ms^{-1}$ |
| D1-V1(rain) | 19.9 | 1 | 0.29 | 8.8 | 1629 | 1.2 |
| D1-V2 | 25 | 2 | 1.17 | 8.8 | 2529 | 2.1 |
| D1-V3(rain) | 28.1 | 4 | 3.38 | 8.8 | 3221 | 3.4 |
| D1-V4(rain) | 25.2 | 4 | 1.97 | 8.8 | 2015 | 3 |
| D2-V1(rain) | 20.8 | 4 | 1.62 | 7.2 | 1996 | 1.7 |
| D2-V2(rain) | 27.1 | 4 | 3.52 | 7.2 | 3297 | 4.1 |
| D2-V3(rain) | 23.7 | 4 | 1.37 | 7.2 | 1498 | 2.4 |
| D3-V1 | 19.2 | 4 | 0.78 | 15 | 1300 | 2.5 |
| D3-V2 | 27.5 | 4 | 3.16 | 15 | 3227 | 3.2 |
| D3-V3(rain) | 22 | 4 | 1.32 | 15 | 1672 | 3.4 |
| D5-V1(rain) | 25.5 | 4 | 3.19 | 2.2 | 3181 | 2.7 |
| D7-V1(rain) | 25.1 | 4 | 2.65 | 9.4 | 2822 | 2.4 |

Appendix 2.1. (Continued)

| Experiment Set | 97-1 week 16 May 28 - May 30, 1997 | | | | | |
|---|---|---|---|---|---|---|
| Period | Air Temperature, $T_t$, °C | Duration, hr | Penman Evaporation During Duration, $F_{w,H}\,\Delta t$, mm | Lowest temperature of a day, $Td_t$, °C | Solar Radiation, Rs, KJ $m^{-2}hr^{-1}$ | Windspeed, u, $ms^{-1}$ |
| D1-V1 | 20.4 | 1 | 0.59 | 9 | 2945 | 1.3 |
| D1-V2 | 23.3 | 2 | 1.50 | 9 | 3381 | 1.8 |
| D1-V3 | 26.2 | 4 | 2.68 | 9 | 2892 | 1.5 |
| D2-V1 | 19.9 | 3 | 1.21 | 11 | 2158 | 1.3 |
| D2-V2 | 26.7 | 4 | 3.08 | 11 | 3263 | 1.9 |
| D2-V3 | 25.3 | 4 | 1.18 | 11 | 1279 | 2.7 |
| D3-V1 | 16.1 | 4 | 0.32 | 15 | 936 | 1.8 |
| D3-V2 | 18.9 | 3 | 0.45 | 15 | 1129 | 2 |
| D3-V3 | 21.2 | 4 | 0.40 | 15 | 754 | 2.7 |

Appendix 2.1. (Continued)

| Experiment Set | 97-2 week 18 July 8 - 10, 1997 | | | | | |
|---|---|---|---|---|---|---|
| Period | Air Temperature, $T_t$, °C | Duration, hr | Penman Evaporation During Duration, $F_{w,H}\Delta t$, mm | Lowest temperature of a day, $Td_t$, °C | Solar Radiation, Rs, KJ $m^{-2}hr^{-1}$ | Windspeed, u, $ms^{-1}$ |
| D1-V1 | 22.8 | 1 | 0.53 | 15 | 2620 | 1.7 |
| D1-V2 | 26.3 | 2 | 1.08 | 15 | 2499 | 1.3 |
| D1-V3 | 28 | 4 | 1.72 | 15 | 1936 | 1.5 |
| D2-V1 | 26.5 | 3 | 1.20 | 18 | 1868 | 2.5 |
| D2-V2 | 28.7 | 3 | 1.13 | 18 | 1659 | 2.5 |
| D3-V1(rain) | 21.4 | 4 | 1.48 | 16 | 1982 | 2.6 |
| D3-V2 | 24.9 | 4 | 2.10 | 16 | 2453 | 2.2 |
| D3-V3 | 25.4 | 4 | 1.04 | 16 | 1368 | 1.6 |

Appendix 2.1. (Continued)

| Experiment Set | 97-3 week 20 August 26 - 28, 1997 | | | | | |
|---|---|---|---|---|---|---|
| Period | Air Temperature, $T_t$, °C | Duration, hr | Penman Evaporation During Duration, $F_{w,H}\,\Delta t$, mm | Lowest temperature of a day, $Td_t$, °C | Solar Radiation, Rs, KJ $m^{-2}hr^{-1}$ | Windspeed, u, $ms^{-1}$ |
| D1-V1 | 34.3 | 2 | 1.35 | 12 | 2624 | 1.2 |
| D1-V2 | 36.4 | 2 | 1.35 | 12 | 2546 | 1.2 |
| D1-V3 | 30.7 | 4 | 1.27 | 12 | 1383 | 1.2 |
| D2-V1(rain) | 27.8 | 3 | 0.97 | 17 | 1551 | 1.6 |
| D2-V2 | 31.7 | 4 | 2.10 | 17 | 2082 | 2.4 |
| D2-V3 | 27.4 | 3 | 0.71 | 17 | 1094 | 2.9 |
| D3-V1 | 25.7 | 3 | 0.42 | 17 | 911 | 1.3 |
| D3-V2 | 30.9 | 4 | 1.46 | 17 | 1551 | 2 |

Appendix 2.2. Initial amount of pesticide applied in each set of experiment

| Pesticide | Experiment | Application (g $ha^{-1}$) |
|---|---|---|
| Bendiocarb | 95-2 | 5832 |
| | 95-4 | 4666 |
| | 95-6 | 4666 |
| | 96-2 | 5832 |
| Diazinon | 95-1 | 4204 |
| | 95-3 | 4605 |
| | 95-5 | 5146 |
| | 96-1 | 5676 |
| Ethoprop | 95-1 | 6327 |
| | 95-3 | 6907 |
| | 95-5 | 7719 |
| | 96-1 | 8514 |
| | 97-1 | 10256 |
| | 97-2 | 7137 |
| | 97-3 | 6883 |
| Isazofos | 95-1 | 2099 |
| | 95-3 | 2302 |
| | 95-5 | 2573 |
| | 96-1 | 2838 |

Appendix 2.2. (Continued)

| Pesticide | Experiment | Application (g ha$^{-1}$) |
|---|---|---|
| Carbaryl | 95-2 | 2803 |
| | 95-4 | 2243 |
| | 95-6 | 2243 |
| | 96-2 | 2803 |
| Chlorpyrifos | 95-1 | 6997 |
| | 95-3 | 7674 |
| | 95-5 | 8577 |
| | 96-1 | 9460 |
| Isofenphos | 95-3 | 2301 |
| | 95-5 | 2573 |
| | 96-1 | 2838 |
| | 97-1 | 3419 |
| | 97-2 | 2379 |
| | 97-3 | 2294 |
| Trichlorfon | 95-2 | 11484 |
| | 95-4 | 9187 |
| | 95-6 | 9187 |
| | 96-2 | 11484 |

Appendix 2.3. Penman equation (Haith, 2002; Jensen ,1990)

The Penman equation provides an estimate of water evapotranspiration for "well water short grass" (Jensen, 1990). The Penman equation could be described as:

$$F_{w,H,t} = \left( \frac{\Delta_t}{\Delta_t + \gamma_t} \cdot (Rn_t - G_t) + \frac{\gamma_t}{\Delta_t + \gamma_t} \cdot 268 \cdot (1 + 0.53 \cdot u_t) \cdot (e'_{s,t} - e'_{2,t}) \right) / \lambda_{w,t} \quad \text{(A2.1)}$$

$F_{w,H,t}$ = evapotranspiration during hour t, mm

$\lambda_{w,t}$ = latent heats of vaporization water during hour t, J $g^{-1}$.

$\Delta_t$ = slope of saturation vapor pressure curve during hour t, kPa °$C^{-1}$

$\gamma_t$ = psychrometric constant during hour t, kPa °$C^{-1}$

$Rn_t$ = net radiant energy available at surface during hour t, kJ $m^{-2}$ $h^{-1}$

$G_t$ = net sensible heat flux from the surface to soil during hour t, kJ $m^{-2}$ $h^{-1}$

$u_t$ = mean wind velocity during hour t, m $s^{-1}$

$e'_{s,t}$ = saturated water vapor pressure during hour t, kPa

$e'_{2,t}$ = actual water vapor pressure during hour t, kPa

Parameters in Equation A2.1 are given in the following equations as described by Jensen, 1990 and Haith, 2002.

$$\lambda_{wt} = 2501 - 2.361\ T_t \quad \text{(A2.2)}$$

$$e'_s = 3.38639[\,(0.00738\,T + 0.8072)^8 - 0.000019\,|1.8\,T + 48| + 0.001316\,] \quad \text{(A2.3)}$$

$$\Delta_t = 0.2(0.00738\ T_t + 0.8072)^7 - 0.000116 \quad \text{(A2.4)}$$

$$\gamma_t = 1.013\ P/(0.622\ \lambda_{w,t}) \quad \text{(A2.5)}$$

$$P = 101.3 - 0.01055\ EL \quad \text{(A2.6)}$$

where

$T_t$ = air temperature during hour t,°C

P = mean atmospheric pressure at the site, kPa

EL = elevation, m

The net radiant energy term ($Rn_t$-$G_t$) in Equation A2.1 is given by incoming solar radiation minus reflected radiation and net thermal radiation. Only the first of these is generally known, and net energy is usually estimated from regression equation (Haith, 2002). Jensen (1990) provide a number of these equations determined for various covers and locations, including the following that was obtained for grass in Minnesota:

$$Rn_t = 0.79\ Rs_t - 470 \qquad \text{(A2.7)}$$

where

$Rs_t$ = solar radiation during hour t (kJ $m^{-2}$ $h^{-1}$)

Appendix 2.4. Ideal Gas Law

$$PV = nRT \tag{A2.8}$$

or

$$p = \frac{n}{V}RT \tag{A2.9}$$

where

P = gas pressure, Pa

V = volume of air, $m^3$

n = mole of gas, mole

R = gas constant, 8.314 J $mole^{-1}$ $K^{-1}$

T = temperature, K

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