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Assessing exposure to allied ground troops in the Vietnam War: A quantitative evaluation of the Stellman Exposure Opportunity Index model

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ABSTRACT

The Exposure Opportunity Index (EOI) is a proximity-based model developed to estimate relative exposure of ground troops in Vietnam to aerially applied herbicides. We conducted a detailed quantitative evaluation of the EOI model by using actual herbicide spray missions isolated in time and space. EOI scores were calculated for each of 36 hypothetical receptor location points associated with each spray mission for 30 herbicide missions for two time periods – day of herbicide application and day 2–3 post-application. Our analysis found an enormous range of EOI predictions with 500–1000-fold differences across missions directly under the flight path. This quantitative examination of the EOI suggests that extensive testing of the model's code is warranted. Researchers undertaking development of a proximity-based exposure model for epidemiologic studies of either Vietnam veterans or the Vietnamese population should conduct a thorough and realistic analysis of how precise and accurate the model results are likely to be and then assess whether the model results provide a useful basis for their planned epidemiologic studies.

1. Introduction

The problem of reconstructing exposures to ground troops from aerial application of herbicides during the Vietnam War, and in particular, Agent Orange, a 50:50 mixture by weight of the *n*-butyl esters of two phenoxy acids: 2,4-dichlorophenoxyacetic acid and 2,4,5-trichlorophenoxyacetic acid (2,4,5-T), has received considerable attention. Much of the concern about Agent Orange stemmed from the fact that 2,4,5-T was found to be contaminated with 2,3,7,8-tetrachlorodibenzo-p-dioxin (dioxin). In 1996, the Institute of Medicine (IOM), at the request of the Department of Veterans Affairs, convened the Committee on the Assessment of Wartime Exposure to Herbicides in Vietnam to oversee the development and evaluation of models of herbicide exposure for use in studies of Vietnam veterans. The research was intended to (1) develop and document a detailed methodology for retrospectively characterizing the exposure of Vietnam veterans to the major herbicides used by the military in Vietnam and (2) demonstrate the feasibility and appropriateness of the proposed methodology in sufficient detail to permit assessment of its potential for use in the conduct of epidemiologic studies (IOM, 1997). In 2003, investigators from Columbia University published the first of several descriptions of an "Exposure Opportunity Index (EOI) model" designed to characterize exposure to Agent Orange and other herbicides in Vietnam (Stellman et al., 2003; Stellman and Stellman, 2004, 2005).

Recently, an IOM committee (IOM, 2008) conducted an extensive evaluation of the potential utility of "proximity-based exposure assessment in epidemiologic studies of Vietnam veterans". Their report broadly discussed proximity-based approaches but focused primarily on the "Exposure Opportunity Index (EOI) model" developed by the investigators from Columbia. While this IOM report contains extensive qualitative discussion of the Columbia EOI model it does not evaluate its quantitative predictions.

In an earlier paper (Ginevan et al., 2009) we used three "isolated" spray mission examples to compare the predictions of this EOI model with the patterns of exposure that would be predicted using the AgDRIFT model. The AgDRIFT model, and its public version AgDISP, are the most widely used and validated tools for predicting dispersion and deposition of aerially applied pesticides including herbicides (Teske et al., 1993, 2002; Bird et al., 2002; Hewitt et al., 2002). Based upon this comparison, we suggested that the EOI model would have little utility as a basis of exposure estimation for epidemiologic studies. What our analysis did not address was the consistency and accuracy of the EOI model predictions across a large number of spray missions. The IOM (2008) report strongly endorsed a careful quantitative evaluation of the model. The work reported here is intended to provide a detailed quantitative evaluation of the methodology as implemented in the EOI model.

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2. The Stellman EOI model

The Stellman EOI model has been described in some detail (Stellman et al., 2003; Stellman and Stellman, 2004, 2005; IOM, 2008; Ginevan et al.,2009). The model consists of two components, direct exposure or "hits" (received at the time of herbicide application) and indirect exposure (contact with the sprayed environment after application; Stellman and Stellman, 2004). For direct hits, an additional exposure term is computed which assumes that the residence time of sprayed individuals extends from the date of spraying until 3 d later, with a decay half-life for dioxin (the toxic material of concern in the herbicide) of 1 year. They then multiply this result by a correction factor to represent the assumed ratio of dermal to respiratory absorption. The "direct hit score" is then added to the indirect exposure score obtained using the actual residence time and postulated half-life (the model default half-life for the indirect component is 30 d). The purpose of this correction is to avoid "the situation whereby an individual who was not directly sprayed could accumulate a larger EOI score than someone who was, simply by staying in a once-sprayed location for a very long time" (Stellman and Stellman, 2004).

The exposure opportunity score at a given point in space is an inverse weighted average of the distance of that point from the flight line modified by the amount of herbicide sprayed. Stellman and Stellman (2004) give the following equation for this component of the EOI:

$$f = \int \frac{\lambda}{D(x_s)}$$

or

$$f = \frac{\lambda}{\sqrt{1+m^2}} \log\left[2\left(\frac{x_s(m^2+1) - X - m(b-Y)}{\sqrt{1+m^2}}\right) + D(x_s)\right] \qquad (1)$$

here, f is the EOI score, which the authors term the E4 score, λ is the spray density (gallons of spray divided by length of the spray path), (X, Y) are the coordinates of the exposed point in the common Cartesian coordinate system, $D(x_s)$ is the distance along the spray path, m is the "slope" of the spray path relative to the grid to which exposure is assigned, and b is its intercept. Fig. 2 of Stellman and Stellman (2004) illustrates that the entire flight path contributes exposure at any given point. Note that while the actual width of a given spray swath varies with the number of aircraft all spray missions are defined as single line in the EOI model. The varying amount of herbicide sprayed is reflected in the λ term of Eq. (1).

The indirect portion of the EOI score is modified by time, and is reduced as a first order exponential decay process with a default half-life of 30 d. We note that the actual half-life used in this calculation can be reduced to as little as 1 d or increased at the investigator's discretion. Here time refers to time post-spraying (Stellman and Stellman, 2004, Eq. (1)).

3. Methods

The Stellman model uses Eq. (1) plus first order decay kinetics to assign exposures to points on a terrestrial grid with approximately 1.2 km spacing. If more than one mission affects a grid point, EOI scores are summed for this grid point (Stellman and Stellman, 2004). Thus, if a given point in space and time is specified, its EOI score may be affected by a number of missions and the spatial distribution EOI score attributable to a particular mission will be hard to determine. However, spray missions that are "isolated" in time and space can be identified and one can determine the E4 scores for "locations of interest" around these spray missions. Because the model does not calculate EOIs for locations beyond 5 km of a spray mission, we first required that any potential "isolated mission" must be separated from all contemporaneous missions by at least 12 km (5 km for each mission plus a 2 km uncertainty factor). In our earlier paper (Ginevan et al., 2009) we defined temporal isolation as missions with any spatially proximate (within 12 km) mission at least 4 months before or 1 month after the mission date. Defining it in this manner would have little impact on EOI calculations for a given mission because the 4 month period represents four times the default 30 d half-life of the model. However, this convention yielded only a small number of temporally isolated missions.

For our current expanded analysis we assumed that dioxin had a 5 d half-life (one-sixth the 30 d default), a value more consistent with measurements on foliage (Young et al., 2004), and used this assumption in our calculations done with the EOI model. We note that we have verified that the model handles user-specified half-lives correctly. Because of the 5 d half-life, we were able to define temporal isolation as missions separated from any spatially proximate mission by at least 30 d (six half-lives) before or 10 d after (two half-lives) the mission, because such missions would have little impact on the EOI calculation for a given isolated flight (Ginevan et al., 2009). Thus our criteria for an isolated mission are one which has no other spray mission path within 12 km of the isolated mission for a period of 30 d before or 10 d after the isolated mission. In order to identify representative missions we also limited consideration to those with a total flight length of at least 10 km to eliminate anomalies such as aborted missions. We also restricted our analysis to flights involving fixed wing aircraft (as opposed to helicopters) and focused on defoliation missions (as opposed to crop destruction) using the Agent Orange herbicide. The ArcView GIS system (ESRI, 2000) was used in conjunction with the version of the Herbicide Reporting System (HERBS) database provided with the EOI model (Version 1.0.2) to select spray missions that met these criteria. Our search identified a total of 30 missions. Mission characteristics, together with their identifiers, are listed in Table 1. Mission locations in time and space are shown in Fig. 1 Note that the mission numbers are the same identifiers as used in the HERBS database associated with the EOI model. The HERBS file was originally developed to provide the Military Assistance Command Vietnam, Chemical Operations Division with an automated system for processing, storing and retrieving information on herbicide missions. The file contained in the EOI describes all known herbicide applications (fixed wing, helicopter and ground spraying) that were carried out during the Vietnam War. Thus, readers can use these mission numbers to determine additional mission properties such as the UTM (Universal Transverse Mercator) Grid coordinates associated with the start and end of a given mission.

For quantitative evaluations of the EOI model performance, we calculated the EOI for each of 36 defined points. The exact locations of these points relative to the flight path are described in Ginevan et al. (2009) (Table 2). Fig. 2 shows a schematic of the positions of the points relative to the flight path. These points fall into six general groups:

- Control points which are 6 km from the nearest point on the flight path (just outside the solid ellipse in Fig. 2).
- Far outside points which are 4 km from the nearest point on the flight path (just inside the solid ellipse in Fig. 2).
- Outside points which are 1.5 km from the nearest point on the flight path (just outside the dotted ellipse in Fig. 2).
- Close points which are 800 m from the nearest point on the flight path (just inside the dotted ellipse in Fig. 2).
- Very close points which are 200 m from the nearest point on the flight path (nearest to the flight path in Fig. 2).
- On path points.