Global positioning system (GPS) tracking to characterize children's exposure to pesticides

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A dissertation submitted in partial fulfillment of the
requirements for the degree of

Doctor of Philosophy

University of Washington

2004

Program Authorized to Offer Degree: Environmental & Occupational Health Sciences

UMI Number: 3131151

University of Washington
Graduate School

This is to certify that I have examined this copy of a doctoral dissertation by

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and have found that it is complete and satisfactory in all respects,
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Abstract

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This dissertation documents the dynamic interaction between moving human receptors (children) and transient peaks in drifted pesticides proximal to treated fields. Validation of a novel dGPS instrument (the GPS Personal Acquisition Logger or GPS-PAL) to attain high-resolution time-location data required four tests: amenability, reception, resolution, and interference. Children were amenable to the GPS-PAL worn in a vest. Lack of reception limited the GPS-PAL inside concrete and metal framed buildings, though time of entry and exit are known. Resolution was 3.2 m RMS. Interferences were 'opaque' buildings constructed of concrete and steel, and high electromagnetic frequency emitters.

The GPS-PAL afforded greater resolution than an existing method, the National Human Exposure Assessment Study (NHEXAS) diary timeline, and showed in which categories subjects were likely to err. Low literacy (both English and Spanish) obstructed completion of the diary, but did not affect GPS-PAL compliance. GPS eliminates the need to categorize time-location data.

GPS data were collected for 8 children during and after aerial spraying of methamidophos on potato fields surrounding their community in Eastern Washington State. Children were active (from velocity data) and outside both days. Drift of most pesticide mass was short-range. Morning deposition was highest. Evening air concentration was highest, suggesting contribution of volatilization. Temperatures exceeded 40C in late afternoon. No deposited methamidophos was found indoors. Indoor air concentrations were not significantly different from baseline. Children's handwipe residues were detectable but low.

Models were calibrated from environmental samples. By combining model and GPS data, attributable fraction of dermal and inhalation routes was characterized. Using a transfer factor of 400 cm2/hr, dermal exposure was predicted much higher than inhalation. However, methamidophos absorbs almost completely in lungs, while ~ 5% absorbs from skin. Ingestion exposure was not measured. The GPS+Model method predicted mean inhaled exposure 3.5 times higher and mean dermal exposure 181 times higher than a 'standard' method. The utility of GPS tracking and modeling for capturing transience of drift in relation to hyperkinetic movement of moving children was well demonstrated. The potential of GPS tracking for exposure assessment is documented by this dissertation.

TABLE OF CONTENTS

LIST OF FIGURES

Figure Number Page

LIST OF TABLES

Table Number Page

ACKNOWLEDGEMENTS

Committee

- Rich Fenske
- Mike Yost
- John Kissel
- Tim Nyerges, Geography
- Ed Lipkin, Medicine (GSR)

Help & Support

- Sarah Weppner
- Maria Negrete
- Ming-Yi Tsai
- Gary Palcisko
- Jaya Ramaprasad
- Alex Lu
- Rob Crampton
- Rene Showlund
- Kathy Himes
- Stacey Holland
- Heidi Curtiss
- Kit Galvin
- Cole Fitzpatrick
- Gwen Wist
- Allan Felsot
- Vince Hebert
- Elizabeth Tomazekewska
- Growers
- Participating families
- Seattle Early HeadStart
- Bill Daniell
- Fellow PhD students
- People who housed me
- My family

Troubleshooting, Code, Sanity, Love & Support

- ➢ Beth Mullenbach

Funding

This work was supported by grants from the National Institute of Environmental Health Sciences (PO1 ES09601), and the Environmental Protection Agency (R826886) as part of the University of Washington's Center for Child Environmental Health Risks Research. Additional support was provided through National Institute for Occupational Safety and Health Cooperative Agreement No. U07/CCU012926 (Pacific Northwest Agricultural Safety and Health Center).

DEDICATION

To the people who grow and harvest our food

To the memory of Myra Jo Rose Dreyer

Chapter 1

Introduction

Fundamental Principle

Replacing assumptions and qualitative analyses with quantitative data is imperative for the advancement of exposure science. Human time-location and activity level data is important for a credible exposure assessment (Appendix 1A). A refined quantitative measure of time-location is important because contaminant releases are often transient, and people are moving receptors (Appendix 1B). A refined quantitative measure of activity level is similarly important because the amount of human exertion affects how much contaminant a person may breathe in at a given time-location (Appendix 1C).

Specific Aims

The broad goals of this research are to compare a global positioning systems (GPS) time-location method to the time-location diary timeline method prevalently used in exposure analysis, and to characterize time- and location- specific pesticide exposures among agricultural children. To reach these goals, a novel GPS instrument (the GPS-PAL) will be validated as a means of obtaining a time-location history. The development and reliability testing of this instrument has been conducted, and it must now be further validated in the field with larger numbers of children. Also, activity level will be evaluated using horizontal linear velocity calculated from GPS measurements to refine our estimates of exposure.

Two general hypotheses will be tested:

Hypothesis 1: Parent-reported child time-location diary data is not a good predictor of actual of child time-location.

A diary timeline will be compared to GPS time-location measurement. An assumption is made here that GPS-PAL data is a suitable surrogate for true 'actual' child time-location. The purpose of this study will be to compare child time-location reported by parents in the NHEXAS diary timeline to child time-location logged by GPS-PAL unit. This will allow us to evaluate the validity of this existing diary technique for time-location data collection. Thirty-five children between the ages of 3-5 years will be compared to evaluate this hypothesis.

Hypothesis 2: Children living proximal to agricultural fields receive measurable exposure to OP pesticides during spray events, and receive variable exposure depending on where they go and how active they are during this period.

Several factors are thought to increase a child's risk of exposure to pesticides following a spray event. The purpose of this study will be to test previous theories about the role of house proximity to treated land in the overall exposure pathway. Data suggest that proximity is an important predictor of exposure. The purpose will also be to determine which locations near the home pose the greatest exposure risks, and how children's activity levels at specific locations may increase exposure. Location and activity will be measured by GPS. Baseline measurements, followed by an exposure time-location profile of a 48-hour period before, during, and following a spray event will be logged for each of 8 children. Key to this analysis is finding evidence specific to spray drift exposure and not influenced by other pathways. Comparison of the GPS time-location method to a method that does not quantify variable movements of children will be necessary to determine if exposure estimates differ with and without the GPS data.

Children's exposure to organophosphorus (OP) pesticides: exposure pathways

Children are a susceptible population

Evaluation of children's exposure to environmental health hazards is essential for both epidemiology and risk assessment, and has become a recent focus of national concern (Olden and Guthrie 2000). OP pesticides are a health hazard, given their inherent human toxicity and children's increased susceptibility to toxic effects. Children's organ systems are not yet fully developed, and cannot metabolize and detoxify acetylcholinesterase-inhibiting compounds such as OP pesticides as rapidly as adults. Recent evidence has suggested that the OP pesticide chlorpyrifos may delay neurodevelopment in fetal and juvenile rats, causing persistent cholinergic presynaptic deficits after neonatal chlorpyrifos exposure (Slotkin et al. 2001). Also, chlorpyrifos and its metabolite TCP caused inhibition of neurite growth in the absence of cholinesterase inhibition in cell lines, suggesting an alternate mechanism may induce this growth inhibition (Das and Barone 1999). This evidence suggests this mechanism could also occur in children. Children are more likely than adults to come in contact with surfaces treated with pesticides, often have greater duration of contact, have greater skin surface area in contact with surfaces, and ingest dirt and dust via hand-to-mouth behavior (Zartarian et al. 1997; Reed et al. 1999). Thus, children are likely to receive more dermal and oral exposure to pesticides than adults in similar surroundings. Children may also be more exposed than adults via inhalation because children tend to be more active and thus have a higher respiratory rate. Children also spend more time outside than most adults, particularly in the spring and summer, which are peak spray seasons.

Exposure source: Diet

A recent study by our group at the UW suggests that diet is a major contributor to OP metabolite levels in children (Curl et al, 2003). Dietary intake of OP pesticides and/or their metabolites leads to a background level of OP metabolites in the urine of urban children who do not have any ties to agriculture. Urines of children who ate a mostly organic diet and a separate group of children who ate a conventional diet were analyzed for OP metabolites. Mean metabolite concentration was significantly higher in children who ate a conventional diet. These data suggest that a background level of OP metabolites exists in children consuming conventional diets (which it can be assumed is the majority of US children). In the proposed study, background level of pesticide attributable to diet is expected to be measurable from urinary metabolite of the compound during the time of year when that compound is never used. It is known that parents of these children do not ever use this compound occupationally, since it is not listed for use on crops the parents work (Hinman et al. 2001).

Exposure source: Parent take-home

Homes of families who work in agriculture were found to contain higher OP pesticide levels in dust and soil than the homes of non-agricultural worker families in an agricultural area (Simcox et al. 1995). Similarly, children of agricultural workers are more exposed to OP pesticides than children who live in agricultural communities whose parents do not work in agriculture (Loewenherz et al. 1997). This suggests that some amount of pesticide is tracked into the household by agricultural worker parents. Methods for collection of soil and dust are well-developed (Lu et al. 2000, Kedan 1999).

Exposure source: Spray drift

In the past decade, 'precision agriculture' techniques have become the norm in the production of crops. New chemical application practices deliver more product on target and less environmental contamination and human exposure occurs as a result (Bode 1990). In particular, the use of center-pivot irrigation to apply pesticides has reduced drift from fields that were once sprayed by tractor boom sprayers or aerial crop dusters (Byers et al., 1993, 2000). Despite advances, some amount of drift is inevitable. Crops such as tree fruits are still sprayed with air blast sprayers pulled behind tractors. This method can produce significant drift, comparable to that from aerial application (Salyani and Cromwell 1991). Despite conditions considered acceptable by the US EPA label instructions, drift was observed up to 195m away from the orchard boundary in this study. Pesticides are ideally sprayed under conditions of low temperature, high humidity, and low wind (<5m/s) and are sprayed as large droplets to minimize drift (Clark et al. 1991). Methods for collection of deposited drift droplets are well developed (Salyani and Cromwell 1991). The crop of most concern in this study, processing potatoes, are sprayed with OP pesticides via aerial ('crop-duster') application twice per year, on average, in the Columbia Basin of Washington State

(Hinman et al. 2001). This method is known to produce significant drift (Salyani and Cromwell 1991).

Proximity to treated land

Many children of agricultural workers live in close proximity to treated farmland. Gladen et al. (1998), in a study of agricultural families in Iowa and N. Carolina, reported that approximately 50% of homes were within 100 yards of the nearest field or orchard where pesticides are applied. Approximately 20% of these same homes were within 50 yards of areas where pesticides are mixed. Mixing can also be viewed as a source of drift, particularly if chemicals used are in powder form. The first data correlating children's urinary biomarkers of organophosphorous (OP) pesticide exposure to home proximity have recently been reported (Koch et al., 2002). These data suggest that close proximity is a risk factor for higher OP exposure.

Identifying the Most Exposed Children

Exposed children have been identified in past studies of agricultural children. Within each study a sub-population of agricultural children have been more exposed than children of non-agricultural workers and urban children (Fenske et al. 2001). A recent review of all data from our lab has revealed that children of pesticide applicators are likely the most exposed sub-population (Fenske et al. 2001). Upon analysis of these data all together, it appears that approximately 98% of agricultural children whose parents are not applicators have urinary OP metabolite levels that are no higher than those of urban children who eat a conventional diet. This is not to imply that these 2% of agricultural children are not important, as exposure was extremely high for a few. Rather, it suggests that we have located a few high exposures, and directs us to locate and study these *most* exposed children. There is evidence that only small numbers of the most exposed children have been identified in previous studies. It is logical to hone in on the children who we believe are the most exposed as the subject of future study. It is also logical to time our exposure analysis to coincide with pesticide spray events. This timing has not been coordinated or achieved in previous studies.

Exposure depends on child activity type, activity level and child location

Quantifying child activity type and activity levels

To receive exposure to OP pesticides, a child must inhale, contact, or ingest the pesticide. A child's type of activity affects exposure via each of these routes. Inhalation is also affected by a child's activity level.

- Inhalation: outdoor pesticide spray may more likely be inhaled during outdoor activities. Also, a more active child will have a higher respiration rate than and inactive child, increasing the volume of contaminated air that is inhaled.
- Contact: a child who exhibits more active play patterns may have increased contact time with contaminated surfaces, or contaminated dust or soil.
- Ingestion (non-food): a child who exhibits hand-to-mouth behavior may be more likely to ingest pesticides.

Inhalation exposure assessment can be more refined if ventilation rate can be estimated. Ventilation rate has been shown to be adequately predicted using heart rate, which is much easier to measure (Samet et al. 1993; Shamoo et al. 1991). Evidence suggests that using an activity diary method to predict ventilation rate is not reliable

(Terblanche et al. 1991). While heart rate monitoring shows promise, it is one more burden that must be placed on a child. Another problem is the potential for radio frequency (RF) interference between the heart rate monitor and the GPS receiver. Because heart rate monitoring is problematic, other alternatives for assessing activity level have been used with children. Most popular has been the use of accelerometry-based instruments, usually worn on the wrist or ankle. (Miller and Kraft 1994). These instruments were considered for field studies in this dissertation, but were too cost-prohibitive. Also, such a watch is one more piece of equipment with which to encumber a small child and perhaps decrease compliance. Given the practical and financial limitations of accelerometer watches, it was decided that the GPS itself would be used to indirectly assess activity level by calculating linear horizontal velocity from GPS positional measurements.

GPS used in tandem for time-location and for velocity-based assessment of energy expenditure among athletes and other volunteers has been demonstrated (Schutz and Chambz, 1997; Larsson and Henriksson-Larsen 2000). The average walking velocity of children has been well characterized in the transportation safety field (Knoblauch et al. 1996), providing a reference value to weight energy expenditures based on pedal velocity. Distributions of child breathing rate by age and basal metabolic rate (BMR) are well characterized (USEPA 2002; Layton 1993), and can be applied to weighting generated by velocity ratios.

Documenting child behaviors that cause exposure via contact and ingestion from non-food sources is best done with detailed videotaping analysis (Zartarian et al.1995, 1997 ; Reed et al. 1999; Quackenboss et al. 2000). Freeman et al. (2001)

showed that responses to the National Human Exposure Assessment Survey (NHEXAS) time-activity diary were concordant between 19 children whose activities were videotaped and 83 children who were not videotaped. Assumptions were then made for all 102 children based on the videotaped data. The videotaping approach has many limitations, however: review of tapes is extremely time-intensive, and subjects must be shadowed. In lieu of videotaping, parent-reported activity diaries (such as the NHEXAS instrument) have been utilized to report behaviors contributing to contact and ingestion exposure, as well as types of activity that contribute to inhalation exposure (Quackenboss et al. 2000; Freeman et al. 2001). For contact exposure, it is extremely important that the time-dependence of pesticide absorption across skin be considered (Kissel and Fenske, 2000). Thus the amount of time between when a child's skin contacts pesticide and the time the skin is washed must be carefully documented by the parent.

Quantifying Location of the Exposure

Exposure can occur inside the home as well as outside, even if no pesticide was sprayed indoors. Given the evidence that drift is inevitable and that closer proximity predicts higher exposure, it is important to examine where exposure is occurring. Simcox et al. (1995) and Bradman et al. (1997) found higher levels of OP pesticides in dust from agricultural households than dust from non-agricultural households. Simcox et al. also found a similar trend in soils around these houses. Subsequent studies by this group (Fenske et al.) have determined that dust in vehicles also contained OP pesticides.

With the data confirming the presence of pesticides in and around agricultural households and confirming exposure by biomonitoring, it would be easy to overlook one missing variable: we do not know *where* all the exposure is occurring. Current EPA models of exposure within and around the home rely on estimations that are not based on coincident child location and child exposure data. Previous work by Fenske et al. in agricultural communities has suggested that where young children spend their time can play a critical role in how, and to what extent, they are subjected to pesticide exposure (Lu et al. 2000).

To address this issue, we must attempt to quantify child time-location during the period(s) in which we believe children are most exposed.

Time-location analysis can provide information about 'microenvironments' that a child encounters throughout the course of a day. The EPA Guidelines for Exposure Assessment (1992) defines a microenvironment as a spatial region that can be treated as homogeneous (or well characterized) with respect to the concentrations of concern. Microenvironments can be delineated by walls within a home, for example, if contaminant concentrations differ between two rooms. Microenvironments can foreseeably have different boundaries with respect to the medium (and, thus, exposure route) of concern. For example, the air concentration of OP pesticide may be equivalent indoors in two rooms after a spray drift event, but the deposited concentrations in the two rooms may differ due to track-in of pesticides from outside on shoes. Another way to look at this, as noted by Georgopoulos et al. (1997), is that the various media within a microenvironment can be thought of as compartments that are related but not necessarily directly correlated with one another.

Validation of Current Time-Location Methods

An essential component of exposure assessment is knowledge of where individuals spend their time. Such time-location information can be linked with pollutant concentration data to produce exposure estimates for well-defined environments, often called microenvironments (Ott 1985). Conventional time-location analysis has relied on interviews or diaries (Wallace et al. 1987, 1993; Freeman et al. 1993; 1999). Such diaries are validated by several techniques. Freeman et al. (1999) define the objective of validation to be to "make sure that diary produces little systematic bias and random error in responses". These authors consider reliability as a separate issue, one of consistency.

There are two types of validation for an instrument, such as a diary, that is used in exposure measurement: tests that measure reproducibility of responses over repeated tests (within and between populations), and tests that measure the accuracy of that which is quantified (Armstrong et al. 1992). The first type of validation is standard protocol when a new instrument is developed. Both within and between group variability are measured. Within group methods include testing over several sampling cycles and comparing responses, as was performed in the evaluation of the NHEXAS time-activity diary in Maryland (Echols et al. 1999). Between groups (such as residents of different counties, or between people of different socioeconomic status (SES) within a region), variability is often tested to ensure that questions asked are equally valid for two or more groups. Such evaluation was performed in the development of the National Human Exposure Assessment Survey (NHEXAS) (Whitmore et al. 1999).

The second type of validation requires a 'gold standard' that measures the accuracy and precision of diary responses. This type of validation is rarely performed because no 'gold standard' is available. In place of a gold standard, internal checks within a survey instrument are often used, as reported in the responses to the NHEXAS time-activity diary in EPA Region 5 (Freeman et al. 1999). The timeline section of the NHEXAS diary is shown on the next page. Accuracy has only been measured by checking that all time, in hours and minutes, adds up to 24 hours. The NHEXAS timeline is limited by its hour unit of resolution. The NHEXAS timeline is also limited because it defines only 7 location categories. The number of categories possible is limited by subject's recall when completing the timeline. An evaluation of the timeline validity should address both of these time and space resolution issues. Being able to track and measure a subject's movement over time would allow more complete validation of the widely used NHEXAS timeline diary instrument.

Intuitively, one might think that a 'higher resolution' timeline with more categories and smaller time increments could work. Recall and poor compliance are serious problems, however. Efforts have been made to improve time-activity diaries, including 'shadowing' subjects with an observer and using a beeper to prompt self-reporting of time-location throughout a day (Robinson and Godbey 1999; Robinson and Silvers 2000). Other methods and technologies have been explored, but have not proven practical for human exposure studies (Moschandreas and Relwani 1991; Waldman et al. 1993). Evaluation of children's micro-activities (e.g., hand-to-mouth behavior) has used videotaping at single locations (Zartarian et al. 1995; Reed et al.

1999), but this approach cannot be applied realistically to track children's locations throughout the day.

The location of young children (<8 years old) has most often been documented through parental interviews and diaries (Simcox et al. 1995; Loewenherz et al. 1997; Cohen Hubal et al. 2000) since these children cannot be expected to reliably report on their whereabouts. While it has been asserted that diaries are adequate for gross location analysis (home/not home) (Robinson and Godbey, 1997), diaries appear to lack resolution needed for more detailed characterizations (time indoors or outdoors at home or daycare, time in vehicle, etc.). Recent aggregate exposure analyses have demonstrated refinement in sampling and sample analysis, but have diluted the impact of their findings by using a timeline to define time spent in microenvironments. For example, a study of persistent organic pollutants among nine preschool children used parent and teacher reporting for time-location measurement (Wilson et al. 2003). This study would have clearly benefited from a better time-location method, since many microenvironments were sampled for pollutants.

It is proposed that global positioning system (GPS) instruments could be utilized to validate existing time-activity diaries (such as the NHEXAS diary) and could eliminate the inherent categorization of time-location studies. Instead of categories, actual distance and direction of movement could be quantified. In the short term, GPS can validate new diaries as they are being designed. As the technology becomes more available and cheaper, GPS could potentially replace time-activity diaries as the instrument of choice in a prospective exposure assessment study.

Global Positioning System (GPS) and Geographic Information Systems (GIS) Technology

GPS Background

The essential aspects of GPS technology have been described in a report by the U.S. Environmental Protection Agency (US EPA 1992). A summary of how GPS units collect temporal and locational data is provided here. GPS satellites orbit the earth twice every 24 hours transmitting a 50-watt signal at 1575.42 MHz (the civilian frequency). GPS receivers on earth can detect this signal, which contains information necessary to establish coordinates for location. The GPS signal contains three components: a 'pseudo-random code', ephemeris data, and almanac data. The first identifies which satellites are 'seen' by the receiver. The second contains current time and date information. The third tells the GPS receiver where each GPS satellite should be at any time throughout the day. To determine location the GPS receiver compares the time a signal was transmitted by satellite with the time it was received on earth. The receiver calculates how far away that particular satellite is based on this time difference. When signals from three or more satellites are received simultaneously, the receiver is able to calculate a coordinate position on earth. With four or more satellites in view, a receiver can also provide altitude information.

The US Geodetic Survey manages a network of beacons that transmit differential GPS corrections from beacons across the country. The correction data are available as public domain information on the Internet from many sources that maintain continuously operating reference stations such as the US Forest Service, the

US Coast Guard, and the National Oceanic and Atmospheric Administration (NOAA). Data for this study was obtained from the closest station in Seattle, operated by NOAA.

On May 1, 2000, the United States stopped the intentional degradation, known as Selective Availability, of GPS signals available to the public (Ineragency GPS Executive Board 2000). This change allowed civilian GPS users to receive location information that is many times more accurate than was previously possible. Differential correction is essential for improved resolution when Selective Availability is in effect. When Selective Availability is not in effect it provides a less dramatic, but still important improvement in resolution. Renewal of Selective Availability remains an option for the U.S. government based on security concerns.

GPS signals can be received in all weather conditions and in almost all environments. Signal reception is impossible or limited inside most buildings. Reception is generally unaffected as long as there is some line of sight between receiver and satellite. Satellite relative geometry can affect GPS accuracy, a problem called positional dilution of precision (PDOP). Other errors can occur due to signal deflection between the satellite and the receiver, and by extremes in upper atmospheric conditions (US EPA 1992).

Applications of GPS Technology

Global positioning system (GPS) technology is now in widespread use for business and leisure activities. It is used to monitor tractors as they plant fields and apply pesticides to crops (Holton 2000), to measure short-term velocity of athletes (Schutz and Chambaz 1997), and has been employed to gather time-location data on hunters by the US Forest Service (Lyon and Burcham 1998). GPS and geographic information systems (GIS) have been used in tandem to address the problem of child exposure to agricultural pesticides, but not as a human tracking method, rather as a way to mark static distances between residences and fields (Royster et al. 2002, Himes 2003). Commercial GPS units were employed recently in an attempt to validate 24-hour time-activity diaries in the Oklahoma Urban Air Toxics Study (Phillips 2001). Poor GPS instrument performance prevented collection of sufficient data to realize this goal, but the investigators concluded that GPS technology showed promise as a method for tracking research subjects in community-based exposure studies. No studies to date have employed GPS technology with children.

Geographic Information Systems (GIS)

Data generated from GPS units can be effectively displayed with a geographic information system (GIS), a database system that contains coordinate-correct maps and locations. For example, GIS has been used to map data recorded by GPS receivers in precision agriculture to optimize fertilizer and pesticide application (Holton 2000). GIS has also been used to predict historical exposures to agricultural chemicals in a retrospective cohort study of cancers among rural Nebraskans (Ward et al. 2000). Use of GIS and GPS technologies in tandem holds potential for new insights in the field of human exposure assessment.

GIS has been utilized extensively for human risk assessment and risk management. Nyerges et al. (1997) outline 4 types of risk analyses incorporating a GIS: vulnerability analysis, screening analysis, refined analysis, and detailed analysis. For each type of analysis, the authors identify several published studies. Prospective exposure analysis falls under the umbrella of either a refined risk analysis or a detailed risk analysis. Georgopoulos et al. (1997) propose the integration of GIS for managing, analyzing and visualizing data from microenvironmental and pharmacokinetic models. Van Braun (1993) utilized a GIS for assessing exposure to lead using actual environmental contaminant data and biomonitoring data in a study of people living within and around the Superfund site near Kellogg, Idaho. Moore (1995) utilized a GIS for the preparation of multipathway air toxics health risk assessment. This risk assessment informed the California Air Toxics "Hot Spots" Information and Assessment Act. The child exposure assessment study outlined in this proposal similarly seeks to identify 'hot spots' using a GIS. 'Hot spot' identification is an important aspect of this dissertation.

Needs assessment for a children's time-location instrument

The use of GPS technology to evaluate children's locations throughout the day requires equipment that differs substantially from that available from commercial vendors (GPS World 2001, 2002, 2003). No commercial GPS units meet all of these criteria at present, although it is recognized that technological advances are occurring rapidly in this area. Thus, a pilot study was conducted to develop and test a novel GPS unit suitable for studies of children's exposure to environmental contaminants, particularly OP pesticides. Experiments focused on spatial resolution, reception efficiency in several environments, and major sources of signal interference. We then employed the GPS units in a field study to determine the feasibility of using GPS technology to track the movements of young children over the course of a day (Elgethun et al. 2003).

Summary

It is clear that a more refined time-location and activity level analysis could improve the estimation of children's exposures to pesticides. Technology (GPS and GIS) exists to accurately quantify and map children's time-location. Technology also exists to quantify linear velocity from time-location, which can then be used to estimate ventilation rate. The next step is to validate the technology against the current standard method (time-activity diary timeline), and to utilize the GPS in conjunction with proven exposure assessment strategies to answer questions that have arisen from previous studies of children's exposure to pesticides in agricultural communities. With the integration of GPS/GIS monitoring into a sampling plan, it is hoped we can discover the role of pesticide spray drift as an exposure pathway and elucidate which routes of exposure contribute most to exposure from drift. It is also hoped that pesticide 'hot-spots' following a spray event in this community will be identified so that subsequent risk communication can prevent future exposures.

Organization of the Dissertation

Each of the next 4 chapters (Chapters 2-5) of this dissertation are designed to be 1) an individual scientific publication or 2) contains all or portions of previously published or submitted work. Where necessary, appendices that will not be submitted to the journal have been included for each chapter at the end of the dissertation to show preliminary analyses and improve continuity between chapters. Chapter 2 was published as: *Elgethun K, Fenske RA, Yost MG, Palcisko GJ. Time-location analysis for exposure assessment studies of children using a novel global positioning system instrument. Environ Health Perspect 111: 115-122 (2003).* Chapters 3 and 5 have not yet been submitted for publication and will be stand-alone papers with myself as first author. Chapters 5 incorporates analyses from two submitted papers on which I have authorship:1) *Ramaprasad J, Tsai MY, Elgethun K, Yost MG and RA Fenske. The Washington aerial spray-drift study: Assessment of the atmospheric loading of pesticides via surface volatilization. Atmos Environ (accepted 5/04).* 2) *Tsai MY, Elgethun K, Ramaprasad J, Yost MG, Fenske RF, Felsot A and V Hebert. The Washington aerial spray-drift study: Modeling pesticide spray drift deposition from an aerial application. Atmos Environ (in progress 2004).*

Chapter 4 includes analyses, figures and tables I co-authored for a submitted paper: *Weppner S, Elgethun K, Galvin K, Lu C, Hebert V and RA Fenske. Methamidophos residues on residential surfaces, in air, and on children's hands following aerial application in Central Washington State. J Expo Anal Environ Epidemiol (submitted 8/2003).* The text of Chapter 4 is my own, and Chapter 4 will not be submitted as a new paper. Chapter 4 was accepted in 2004, and corrections to this chapter are currently in progress.

Chapter 6 is a summary and conclusions chapter that will not be published as a separate paper.

Note to Readers

The original copies of this dissertation contain color figures. For many of the maps, color is required to see contrast between the aerial photograph and the GPS path. An original copy of this dissertation containing color figures is available on loan from the University of Washington libraries.

Chapter 2

Time-Location Analysis for Exposure Assessment Studies of Children Using a Novel Global Positioning System Instrument

Introduction

This chapter was published under the same title: *Environmental Health Perspectives* 111: 115-122 (2003). Evaluation of children's exposure to environmental health hazards is essential for both epidemiology and risk assessment, and has become a recent focus of national concern (Olden et al. 2000). An essential component of exposure assessment is knowledge of where individuals spend their time. Such time-location information can be linked with pollutant concentration data to produce exposure estimates for well-defined environments, often called microenvironments (Ott 1985). Conventional time-location analysis has relied on interviews or diaries (Wallace et al. 1987, 1991; Freeman et al. 1993, 1999). Efforts have been made recently to improve the validity of these methods, including the 'shadowing' of subjects with an observer, and use of a beeper to prompt subjects to record time-location data (Robinson and Godbey 1999; Robinson and Silvers 2000). Other methods and technologies have been explored, but have not proven practical for human exposure studies (Moschandreas and Relwani 1991; Waldman et al. 1993). The purpose of the study reported in this paper was to identify and test a new method for tracking pre-school children throughout the course of a day.

The location of children has most often been documented through parental interviews and diaries (Simcox et al. 1995; Loewenherz et al. 1997; Cohen Hubal et al. 2000). While probably adequate for gross location analysis (home/not home), they are not considered reliable for more detailed characterizations (time indoors or outdoors at home or daycare, time in vehicle). Evaluation of children's micro-activities (e.g., hand-to-mouth behavior) has used videotaping at single locations (Zartarian et al. 1995; Reed et al. 1999), but this approach cannot be applied realistically to track children's locations throughout the day.

Global Positioning System (GPS) Technology. The essential aspects of GPS technology have been described in a report by the U.S. Environmental Protection Agency (US EPA 1992). A summary of how GPS units collect temporal and locational data is provided here. GPS satellites orbit the earth twice every 24 hours transmitting a 50-watt signal at 1575.42 MHz (the civilian frequency). GPS receivers on earth can detect this signal, which contains information necessary to establish coordinates for location. The GPS signal contains three components: a 'pseudo-random code', ephemeris data, and almanac data. The first identifies which satellites are 'seen' by the receiver. The second contains current time and date information. The third tells the GPS receiver where each GPS satellite should be at any time throughout the day. To determine location the GPS receiver compares the time a signal was transmitted by satellite with the time it was received on earth. The receiver calculates how far away that particular satellite is based on this time difference. When signals from three or more satellites are received simultaneously, the receiver is able to calculate a coordinate position on earth. With four or more satellites in view, a receiver can also provide altitude information.

The US Geodetic Survey manages a network of beacons that transmit differential GPS corrections from beacons across the country. The correction data are available as public domain information on the Internet from many sources that maintain continuously operating reference stations such as the US Forest Service, the US Coast Guard, and the National Oceanic and Atmospheric Administration (NOAA). Data for this study was obtained from the closest station in Seattle, operated by NOAA.

On May 1, 2000, the United States stopped the intentional degradation, known as Selective Availability, of GPS signals available to the public (Interagency GPS Executive Board 2000). This change allowed civilian GPS users to receive location information that is many times more accurate than was previously possible. Differential correction is essential for improved resolution when Selective Availability is in effect. When Selective Availability is not in effect it provides a less dramatic, but still important improvement in resolution. Renewal of Selective Availability remains an option for the U.S. government based on security concerns.

GPS signals can be received in all weather conditions and in almost all environments. Signal reception is impossible or limited inside most buildings. Reception is generally unaffected as long as there is some line of sight between receiver and satellite. Satellite relative geometry can affect GPS accuracy, a problem called positional dilution of precision (PDOP). Other errors can occur due to signal deflection between the satellite and the receiver, and by extremes in upper atmospheric conditions (US EPA 1992).

Applications of GPS Technology. Global positioning system (GPS) technology is now in widespread use for business and leisure activities. It is used to monitor tractors as they plant fields and apply pesticides to crops (Holton 2000), to measure short-term velocity of athletes (Schutz and Chambaz 1997), and has been employed to gather time-location data on hunters by the US Forest Service (Lyon and Burcham 1998). Commercial GPS units were employed recently in an attempt to validate 24-hour time-activity diaries in the Oklahoma Urban Air Toxics Study (Phillips et al. 2001). Poor GPS instrument performance prevented collection of sufficient data to realize this goal, but the investigators concluded that GPS technology showed promise as a method for tracking research subjects in community-based exposure studies. No studies to date have employed GPS technology with children.

Data generated from GPS units can be effectively displayed with a geographic information system (GIS), a database system that contains coordinate-correct maps and locations. For example, GIS has been used to map data recorded by GPS receivers in precision agriculture to optimize fertilizer and pesticide application (Holton 2000). GIS has also been used to predict historical exposures to agricultural chemicals in a retrospective cohort study of cancers among rural Nebraskans (Ward et al. 2000). Use of GIS and GPS technologies in tandem holds potential for new insights in the field of human exposure assessment. The use of GPS technology to evaluate children's locations throughout the day requires equipment that differs substantially from that available from commercial vendors (GPS World 2001). No commercial GPS units meet all of these criteria at present, although it is recognized that technological advances are occurring rapidly in this area.

The purpose of this study was to develop and pilot test a novel GPS unit suitable for studies of children's exposure to environmental contaminants, and particularly to pesticides. Our previous work in agricultural communities has suggested that where young children spend their time can play a critical role in how, and to what extent, they are subject to pesticide exposure (Lu et al. 2000). Time-location is not used as a proxy of exposure, rather as a way to map exposures at the intersections between humans and contaminated microenvironments. The GPS experiments reported here focused on spatial resolution, reception efficiency in several environments, and major sources of signal interference. We then employed the GPS units in a field study to determine the feasibility of using GPS technology to track the movements of young children over the course of a day.

Methods

Criteria for children's GPS unit. The following 10 features were deemed essential for an instrument to be used with young children: 1) ability to log path data; 2) ability to store raw pseudorandom satellite code required to post-process differential corrections; 3) ability to import data into GIS software; 4) memory and battery life capable of recording at least 24 hours of data at a frequent sampling rate (at least once every 30 seconds); 5) external antenna that can be positioned to optimize signal reception; 6) ability to be worn in way that is acceptable to both the child and parent; 7) light-weight (<300 grams or <0.75 pounds); 8) durable; 9) tamper-proof; 10) simple to operate. The following 2 performance characteristics were also considered essential to define location with sufficient accuracy and precision: 1) resolution of 3-5 meters; 2) reception under a wide range of field conditions.

GPS Instrument. Our group worked with Enertech Consultants (Campbell, CA) to design a GPS "personal acquisition logger", or GPS-PAL. The GPS-PAL unit consists of a battery pack, a central electronic unit, and an antenna (Figure 1). The cost of each unit, including software for downloading and post-processing data, is estimated at one-thousand US dollars. All components, including batteries, weigh 280 g. Separation of the antenna from the central unit allows flexibility in antenna positioning. The unit was designed for use by a layperson with no supervision required, and is operated by one small 'on/off' switch. The GPS-PAL has enough memory to store 30 hours of data when set to datalog every 5 seconds. Battery life at the 5-second sampling rate is 25 hours using 4 'AAA' alkaline batteries. The GPS-PAL is not an 'off-the-shelf' tool, but a standard operating procedure (SOP) was developed during the course of this pilot study to expedite these functions. Downloading, post-processing, and mapping of data can be accomplished by a user with basic Windows software competency when using the SOP.

Operating Procedures. Two GPS-PAL units were tested and used in feasibility studies. The units were allowed to prime for approximately 5 minutes when first switched on until a signal was received (indicated by a flashing light on the unit). The units were set to record time and location (latitude/longitude) data every 5 seconds. The time-location data that is logged delineates the path traveled. The GPS-PAL automatically deletes position data that are the result of poor satellite geometry to prevent spurious points from being included in the path. At the end of each data collection period, the units were connected to a desktop computer with a communications cable, and the GPS-PAL software was used to download data. GPS-PAL software uses modules licensed by Trimble Navigation Ltd. (Sunnyvale, CA). Once downloaded, data were post-processed to correct for errors using differential signal data obtained from the Seattle, Washington NOAA Continuously Operating Reference Station (CORS) found on the CORS Internet site operated by the National Geodetic Survey (NGS). The GPS-PAL software automatically links to this site, instructs the user how to download the required differential correction data from the nearest CORS site, and post-processes the GPS path data using the appropriate corrections.

After post-processing, the coordinate information was exported into ArcView Geographic Information Systems (GIS) software that included the Spatial Analyst extension and the COS.Point Distance and Nearest Features scripts (version 3.2; ESRI, Redlands, CA). ArcView allows the user to highlight points on a map by simply selecting points in the data table, and vice-versa. A GIS of Seattle area aerial photographic maps was utilized to visualize GPS-PAL data points and to analyze both reception and resolution. Maps used were United States Geological Survey (USGS) Digital Orthophoto Quarter Quadrangles (DOQQs) licensed by the City of Seattle to the University of Washington. They are orthorectified to attain the geometric properties of a map. The resolution of these maps is ± 1m. Registration errors of these DOQQs are not expected to exceed 0.1 m, and were thus not included in our analysis.

Field Studies. Adult subjects and older children wore GPS-PALs integrated into nylon vests (Figure 2). Young children (<4 years) wore GPS-PALs integrated into cotton bib overalls, which are more durable and more difficult to remove. Both types of clothing allowed for proper horizontal positioning of the antenna, and both allowed for secure attachment of the antenna cable inside the garment. The battery and GPS unit were concealed in closed pockets on the front of the garments. Positioning of battery and GPS unit was chosen to minimally encumber normal range of motion. The antenna was placed on the top of the shoulder to optimize signal reception. This design allowed research staff to simply hand the clothing to the parent or child, and prevented tampering or instrument removal.

Resolution Experiments. In the first experiment GPS-PAL units were left in a stationary position for 12 hours in two urban locations, outdoors in the open, and inside a single story wood-frame house. The resulting coordinate information was analyzed in ArcView to determine what percentage of points were recorded within 2m, 3.5m and 5m of the true position of the unit. Lines were plotted from each measured point to the true position on the ortho-photo map in ArcView. The true position was the center point of a 1m^2 landmark visible on the ortho-photo map. True position coordinates were determined in ArcView using the 'Latitude and Longitude' locator function. The number of points logged by time and the resolution by time was analyzed to investigate the existence of a relationship between bias and time. The root mean square (RMS) error distance, equal to the root of the sum of the squares of all individual errors, was computed for these data. RMS is a standard expression of location error for GPS receivers (US EPA 1992)

In a second experiment, GPS-PAL units were carried by two pedestrians walking the same 4km path on a city sidewalk. A line drawn down the center of the sidewalk was considered the true path. True path coordinates were determined in ArcView using the 'Line Theme' function. Coordinates were analyzed to determine what percentage of points were recorded within 2m, 3.5m and 5m of the true path walked. Parallel lines of these distances on either side, known as line buffers, were drawn around the true path on the ortho-photo map in ArcView. The variable width of the sidewalk was accounted for when determining the centerline.

Reception Experiments. The GPS-PAL units were left stationary inside a wood frame house and inside a concrete school building for 30 minutes, and were then worn by moving individuals inside these two structures for 30 minutes. GPS-PALs were also worn by moving individuals walking within 1-2 m of the perimeter of these buildings directly adjacent to the outside walls. The number of points logged in each situation was compared to 30-minute control data logged outside in an open area. Stationary test data were compared to stationary control data; mobile test data were compared to mobile control data.

Interference Experiments. Several known sources of GPS signal interference (Johnnessen 1997) were evaluated to test their effect on reception. Sources were evaluated on two separate days. One ten-minute period was measured when the interference source was proximal to the subject wearing a GPS-PAL unit. Disruption of reception was quantified by dividing number of points received by the number of points expected during 10 minutes when no interference is present. Interferences were evaluated separately. The following personal interference items were tested outdoors: a wool sweater and a nylon raincoat worn over the vest containing the unit; a 900 watt Amana microwave oven operating on the 'high' setting; a Motorola Fr60 Talkabout 465 MHz two-way radio; an Ericsson T19LX digital cellular phone receiving full signal at 1850-1990 MHz; and a V-Tech 900 MHz analog cordless telephone 5 m away from its base. Electronic devices were operated normally, as specified in Table 4, for 10 minutes.

Feasibility Study. This study was designed to evaluate child compliance and GPS-PAL functionality over the course of a day. Procedures were approved by the University of Washington Human Subjects Division. Eleven children (6 female, 5 male) in the Seattle area ages 2-8 years old (mean = 5.5) wore GPS-PAL units for approximately 7-11 hours. All parents involved in the study were faculty, staff or students in the Department of Environmental Health at the University of Washington. Recruited families responded to an announcement sent via departmental electronic mail listserver. Children selected were required to be potty trained. Written consent was obtained from parents, and verbal assent was obtained from children. Three of the children wore units to school on a weekday; the other eight wore units on a weekend day. Parents were allowed to select their child's monitoring period. Parents were asked to record if children complained about the weight or fit of the GPS-PAL garments. Parents were asked to switch the unit on when their child got dressed in the morning, and to turn the unit off at bedtime. Parents also provided home addresses for verifying location on the orthophoto maps. Data from the child study were grouped by the following five location categories: in vehicle, inside house, inside school, inside business, and outside. Time spent in each location and percent reception in each location were computed for each child.

Results

Resolution Experiments. Table 1 shows the number of points logged by stationary GPS-PAL units over 12 hours and the RMS distance of the points from the true location of each unit. The units had RMS errors of 3 and 3.4 m outdoors, and 5.7 and 5.9 m inside the wood-frame house. Analysis of resolution by time showed a few short periods (<1 min) when the distance from true location sharply increased (data not shown). Table 2 shows the number of points logged and the resolution of points logged by GPS-PAL units carried by two pedestrians during a 50 minute, 4 km walk on city sidewalks. Figure 3 shows a close-up of the true path walked, the points logged, and the line-buffers that were used to determine mobile resolution. Resolution was measured by percentage of points lying within 2m, 3.5m and 5m of the true path. About 96% of all points were logged within +/- 5m of the true path, 90% were logged within +/- 3.5 m, and 79% were logged within +/- 2m.

Reception Experiments. GPS-PAL reception data for a subject outdoors, inside two types of buildings, and proximal to two types of buildings are shown in Table 3. Data shown are for 30 minutes of operation. Better reception was attained next to a concrete/steel building than a wood frame building for one unit, while the opposite was true for the other unit. No points were logged inside the concrete/steel frame building. Reception inside the wood frame building was reduced almost twofold by moving around inside the house compared to remaining in one location.

Interference Experiments. Reception interference experiment results are shown in Table 4. Walking within 20m of power substation transformers caused a complete blockage of signal reception. Standing in front of an operating microwave oven caused a significant (38%) reduction in reception. Talking on a 2.7 kHz cordless phone reduced reception by 7%. Other potential interference sources had no effect or minimal effect on signal reception.

The performance of the GPS-PAL units in regard to resolution, reception and interference are illustrated in Figure 4. In this figure the upper panel is an orthophoto image with GPS-PAL data logged inside and proximal to a wood frame house (points shown in green). The lower panel is a 3:1 scale drawing of this house showing the same points. A 2m square grid is superimposed on this drawing. Based on data in Table 2, this grid approximates an 80^{th} percentile level of resolution for the GPS-PAL. Figure 4 illustrates that locations within and around a house can be defined so as to differentiate by rooms or other microenvironments in and around a residence.

Feasibility Study. Data were obtained for 8 of the 11 study children. The first three subjects had no data or minimal data logged due to failure of wiring or connectors leading from the battery pack. This problem was resolved and no further wiring problems were encountered. One parent noted that the receiver was accidentally turned off, then switched back on later, yielding only 3 hours of data. This subject was excluded from further analysis. Data from another subject were recorded without incident, but post-processing of the coordinates was not feasible due to base file differential signal errors recorded by the CORS station. The unprocessed data were not comparable to the post-processed data and were excluded from further analysis. The eleven parents all responded that their children did not complain about the weight or restrictiveness of the GPS inside the custom clothes. Two 2-year old children complained that they did not like the color and style of the bib overalls.

Table 5 shows the efficiency of reception by location for each child. Only two children spent appreciable time outdoors, where reception was high (79%). Reception inside homes was greater than reception inside vehicles (20% vs. 12%), and was lowest for inside schools and businesses (6% and 9%, respectively).

The fraction of time monitored for each child by location is presented in Table 6. A total of 2,964 minutes (49.4 hr) of data were collected for the six children, with monitoring times ranging from 387-700 minutes.

Figure 5 shows the path traveled by one child (Child 1) during the hours of a normal school day. Points on the street correspond to the child walking from the school bus to the school grounds. Points on the field in the upper half of the picture correspond to two distinct recess breaks. Points near the school's entrance at the center of the picture were logged before classes started in the morning and after classes were over in the afternoon. Points logged inside the school building, in the lower half of the picture, are sporadic due to the multilevel construction of the building. Figure 6 is a timeline illustrating the progression of location by time for each child throughout the day. Among the two children monitored on a weekday, Child 2 spent all of her time at school indoors, while Child 1 went outside three times for recess. Among the four children monitored on a weekend day, distribution of time in each location varied greatly, except for Child 4 and Child 5. These two were together for most of the day they were monitored.

Discussion

Once initial wiring problems were corrected, time-location data were collected successfully for the remaining 8study participants. Data adequate for 'all-day' analysis of time-location patterns were obtained from 7 of these 8 children. Accidental receiver shut-off, which caused the collection only three hours of data from one child, was prevented in subsequent trials by covering the 'on/off' switch. The CORS base file errors that obstructed post processing of one child's data are not preventable. The raw data are still readable, but are lower resolution when not post processed (approximately 15% greater RMS error). It would be possible to obtain base files from a private source if higher resolution data were deemed critical in future studies. Future GPS-PAL studies with greater numbers of subjects will incorporate solutions to data loss discovered in this pilot study. Randomization of children to either weekday or weekend sampling groups would also strengthen future studies and provide more insight into the utility of the GPS-PAL. Overall, it appears that the GPS-PAL is a practical tool for collection of children's time-location data, and that the technical criteria for this instrument described earlier have been met. The performance criteria of resolution and reception are addressed below.

Resolution. A critical factor for any device intended for time-location analysis is an assessment of the instrument position accuracy. Position accuracy depends on many factors, including the satellite constellation geometry (geometric dilution of precision or GDOP) and on biases or errors in the GPS signal components or receiver (e.g. clock errors, ephemeris, and propagation errors) (US EP 1992). Although uniform position accuracy under all conditions is desirable, varying accuracy over time and space is unavoidable due to GDOP and loss of satellite data from interference. Often the accuracy characteristic is summarized by the range error relative to a known fixed location. Since RMS error describes the magnitude of all errors without regard to direction, and since typically it is much greater than the mean error for a stationary instrument, this provides a more conservative estimate of the expected position accuracy of a GPS receiver.

An alternative measure of position accuracy is the proportion of readings that fall within a fixed range of a known location. This measure of position accuracy, as we have shown (Figure 3), can be applied to either stationary or moving subjects along a defined path. This metric is potentially more useful for time-location studies, since it also can describe the ability of the instrument to correctly classify a location within a spatial boundary, such as a schoolyard, or a room in a home (Figures 4 and 5).

Position accuracy is unit-specific for each GPS-PAL probably due to random clock errors in the receiver. The mean of the RMS errors for the two GPS-PAL units was 3.2 m outdoors and 5.8 m indoors, compared to a typical outdoor RMS error for most portable GPS units of 5-10 m (GPS World 2001). Published indoor RMS values were not found. Usually only large survey-quality GPS receivers are capable of attaining a lower RMS error than the GPS-PAL. The error of the map being used also must be considered as an independent factor. Thus, when GPS-PAL data is overlaid on USGS DOQQ Maps (nominal 1m resolution), overall RMS error is about 3.4m outdoors / 5.9m indoors, and the maximum error is 3.2m + 1.0m = 4.2m outdoors, 5.8m + 1.0m = 6.8m indoors. Analysis of resolution data by time (Table 1) showed a few short (<1 min) periods where resolution waned. The existence of a relationship between bias and time can be explained by temporary loss of satellite signal or transient shifts in high atmospheric conditions (US EPA 1992).

These data demonstrate that the position accuracy achieved by the GPS-PAL instrument under realistic conditions is sufficient for human time-location analysis. Note in Table 2 and Figure 3 that most points over the 4 km, 50 minute test were within 2-3m of the true path line. The 2m grid in Figure 4 illustrates that location in and around a house can be delineated at least 80% of the time within a 2 square meter area. At this scale, data based on position and photo maps would allow classification of activities such as entering a retail store, walking on a sidewalk, traveling by car or bus, playing on a schoolyard, or playing in and around a house. This suggests that the GPS-PAL units are capable of locating subjects with sufficient position accuracy to correctly classify a large variety of human activities.

Reception and Interference. Ideally, a GPS device for time-location studies would provide uninterrupted position data, regardless of the subject's location or activities. Clearly buildings and other objects can compromise GPS signal reception, so tracking subjects in and around structures is constrained by the limitations of current receiver (and antenna) technology. The inconsistency of reception for different children in similar locations can be explained by the high number of variables involved, including: building materials; location of a child within a building; type of vehicle and location of vehicle; and proximity of a child to windows and other signal-permeable materials. This is a limitation for being able to consistently locate an individual in a specific microenvironment in exposure analysis studies. While consistent time-location may not be feasible with GPS, the percent reception in most locations was sufficient to define a child's time-location. The following examples using data shown in Table 3 and Figures 4 and 5 illustrate this point. In Figure 5, signal is poorly received inside the school building; however, the time and location at which this child entered and exited the building was precisely recorded, producing a clear time-activity map. Reception within wood-frame buildings and next to both wood frame and concrete/steel buildings was adequate to characterize an individual's position in these locations (Table 3 and Figure 4). For example, since 31.4% of points were logged when the subject was moving inside the house (Figure 4), and the sampling rate was 5 seconds, a location was logged about once every 16 seconds. This is sufficient to detect movement between interior rooms, assuming that temporal distribution in reception for a given microenvironment is approximately uniform.

Further improvements can be gained by careful review of the logged points to account for the logical consistency of events in certain microenvironments. When data points fell close to the walls of a building (Figure 4), it was possible to differentiate indoor from outdoor environments and eliminate ambiguous data by examining the time sequence of points, and the location of exterior doors. It is unlikely that a single point will fall outside a house if points logged 16 seconds before and 16 seconds after are logged indoors, unless an exterior door is immediately adjacent to the area.

Interference experiments examined a variety of potential sources, representing devices that have become ubiquitous in our daily environments operating at many frequencies. The results suggest that electrical power distribution equipment, or the associated electric or magnetic fields from transformers or power lines, cause a greater decrease in reception than radio frequency (RF) equipment. The lack of interference from clothing is especially important, as this allows for total concealment of the unit within garments worn by subjects.

Future Applications. The GPS-PAL could be used in many settings to contribute to a refined exposure analysis of individuals. One target group for application of this technology is children living in rural agricultural communities. These subjects represent a potential high exposure group for spatial analysis, because pesticides are used routinely in crop production and may be dispersed over wide areas.

Children may come into contact with pesticides through various scenarios, such as playing in and around treated farmland, accompanying their parents into the fields, and by contact with pesticide residues brought into the home by their parents (Simcox et al. 1995; Loewenherz et al. 1997; Lu et al. 2000). We have also learned from more recent work that children in these communities exhibit peak exposures coincident with agricultural pesticide applications (Koch et al. 2002), but we do not know the pathways by which these spraying events produce elevated body burdens. GPS time-location analysis could allow us to characterize activities among these children so that we may better understand pesticide exposure pathways.

Conclusions

The GPS-PAL instrument combines high spatial resolution capabilities, a remote antenna, and data logging capability into a compact size suitable for monitoring adults or children. Spatial resolution is adequate to locate people within distinct sub-environments and to distinguish a variety of human activities. Reception is adequate for position determination outside, proximal to buildings, and inside certain buildings. A subject's position can be narrowed to a single room in a home, a specific area of a playground, or one side or another of a fence line. This provides a new level of accuracy for defining time-location in relation to exposure, and eliminates recall bias and reporting errors inherent with written subject-reported logs of time-location. Signal interference from common sources did not appear to limit the utility of the GPS devices in most environments. Data are readily transferred into GIS software for map overlays, allowing for linked visual and tabular analysis. Compliance was good among children age 2-8 years old wearing the GPS-PAL incorporated into their clothing. The GPS-PAL is a promising new instrument for quantification of time-location activity patterns in exposure assessment studies. The application of GPS and GIS technologies is the logical next step in the characterization of human time-location patterns.

Table 2.1. Measurement error of two stationary GPS-PAL units over 12 hours

	Points Logged[a]	Distance from true position (m)[b] Mean	Median	Stdev	RMS[c]
Outdoors					
GPS-PAL #1	6796	2.5	2.2	1.6	3.0
GPS-PAL #2	8514	2.8	2.5	1.9	3.4
Indoors[d]					
GPS-PAL #1	3920	4.8	4.0	3.2	5.7
GPS-PAL #2	4812	4.9	4.1	3.3	5.9

[a]Units log data every 5 seconds for a maximum of 8640 data points in 12 hours.

[b]True position defined by locating the coordinates of the units on the orthophotomap using GIS software.

[c]RMS=root mean square. Calculated by squaring each individual error, then taking the square root of the mean of these numbers.

[d]Indoors=inside a single story wood-frame building, away from windows.

Table 2.2. Resolution of GPS-PAL units on a 4km, 50 minute walk in the city

	Points Logged[a]	Fraction of points within each buffer (%) ±5 m	±3.5 m	±2 m
GPS-PAL #1	540	96.2	89.9	78.6
GPS-PAL #2	575	96.3	90.7	79.1

[a]Units log data every 5 seconds for a maximum of 600 data points in 50 minutes.

Table 2.3. Reception of GPS-PAL units over 30 minutes under stationary and mobile conditions: outdoors, indoors and proximal to two types of building

Test Conditions	Location	Unit #1 Reception Points Logged[a]	Unit #1 Reception % of Max	Unit #2 Reception Points Logged[a]	Unit #2 Reception % of Max
Outdoors					
Stationary	In the open	360	100.0	360	100.0
Mobile	In the open	358	99.4	360	100.0
Mobile	Proximal to CSF building[b]	110	30.6	127	35.3
Mobile	Proximal to WF building[b]	76	21.1	170	47.2
Indoors					
Stationary	WF building	190	52.8	192	53.3
Stationary	CSF building	0	0.0	0	0.0
Mobile	WF building	113	31.4	85	23.6

[a]Units log data every 5 seconds for a maximum of 360 data points in 30 minutes.

[b]Proximal = within 1-2m of the outside wall of the building. CSF = concrete/steel frame, WF = wood frame.

Table 2.4. Interference to GPS-PAL unit reception

Type of interference	Notes	Reception (% of Max)[a]
None		
Outdoor, in the open	>5m from any building	100
Spatial		
Power substation	<20m from transformers	0
High-tension power lines	30m overhead	98
Large metal reflective surface	against galvanized steel	99
Personal		
Clothing covering antenna	wool sweater and nylon raincoat	100
Microwave oven[b]	0.5m from oven on 'high'	68
2-way radio[c]	held to ear, transmit and receive	100
Digital cell phone[d]	held to ear while talking	100
Cordless phone[e]	held to ear while talking	93

[a]Units log data every 5 seconds for a maximum of 120 data points in 10 minutes.

[b]Amana 900 watt.

[c]Motorola Fr60 Talkabout 465 MHz.

[d]Ericsson T19LX 1850-1990 MHz.

[e]V-Tech analog 900 MHz.

Table 2.5. Reception by location and monitored time for children wearing GPS-PAL units

	Reception[a] (% of max)							
	Weekday		Weekend				*Mean* reception[a]	
Location (%)[b]	Child1	Child 2	Child 3	Child 4	Child 5	Child 6	by location	CV
Vehicle (inside)	26.9	8.8	1.1	15.9	11.0	na[e]	12.2	67.5
School (inside)	7.2	5.6	na[e]	na[e]	na[e]	na[e]	6.3	12.6
Home (inside)	26.1	42.5	14.3	na[e]	na[e]	20.9	19.8	43.6
Business (inside)[c]	na[e]	na[e]	8.3	12.5	6.6	na[e]	9.3	27.0
Outdoors[d]	86.0	na[e]	na[e]	na[e]	na[e]	73.7	79.1	7.7
Mean reception[a] by child	24.2	7.7	10.8	13.2	7.3	29.7		60.1
Monitored time (min)	513	480	468	416	387	700		

[a]Units log data every 5 seconds, maximum number of data points depends on monitored time for each child.
[b]CV = coefficient of variation = (SD / Mean) * 100%.
[c]Stores, restaurants, cinemas and other large buildings.
[d]Parks, playgrounds, sidewalks and yards.
[e]na = child spent no time in this location.

Table 2.6. Where children went: fraction of monitored time in each location and total monitored time for children wearing GPS-PAL units

	Fraction of monitored time (%)					
	Weekday		Weekend			
Location	Child1	Child 2	Child 3	Child 4	Child 5	Child 6
Vehicle (inside)	4.8	15.0	9.7	21.4	19.0	0.0
School (inside)	52.7	80.4	0.0	0.0	0.0	0.0
Home (inside)	5.8	4.6	52.5	0.0	0.0	83.4
Business (inside)[a]	0.0	0.0	37.8	78.6	81.0	0.0
Outdoors[b]	36.7	0.0	0.0	0.0	0.0	16.6
Monitored time (min)	513	480	468	416	387	700

[a]Stores, restaurants, cinemas and other large buildings.
[b]Parks, playgrounds, sidewalks and yards.

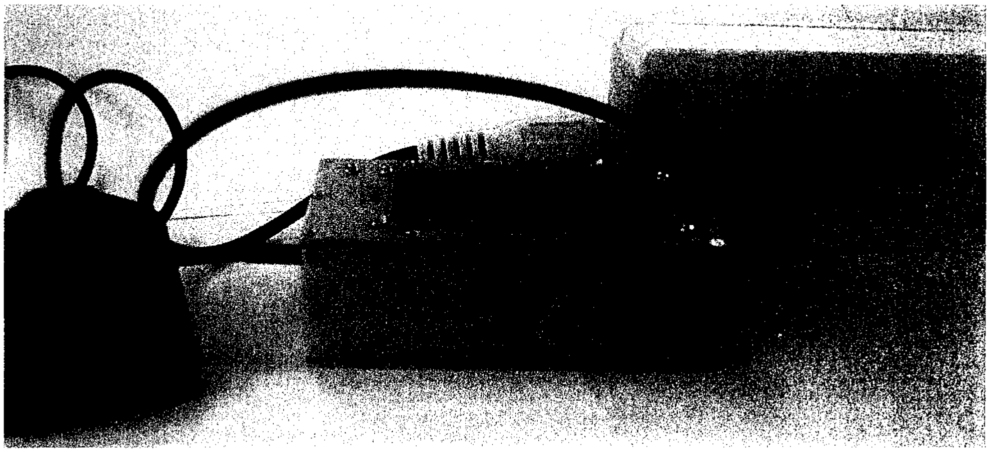


Figure 2.1. GPS-PAL antenna, electronics and battery pack (l-r)

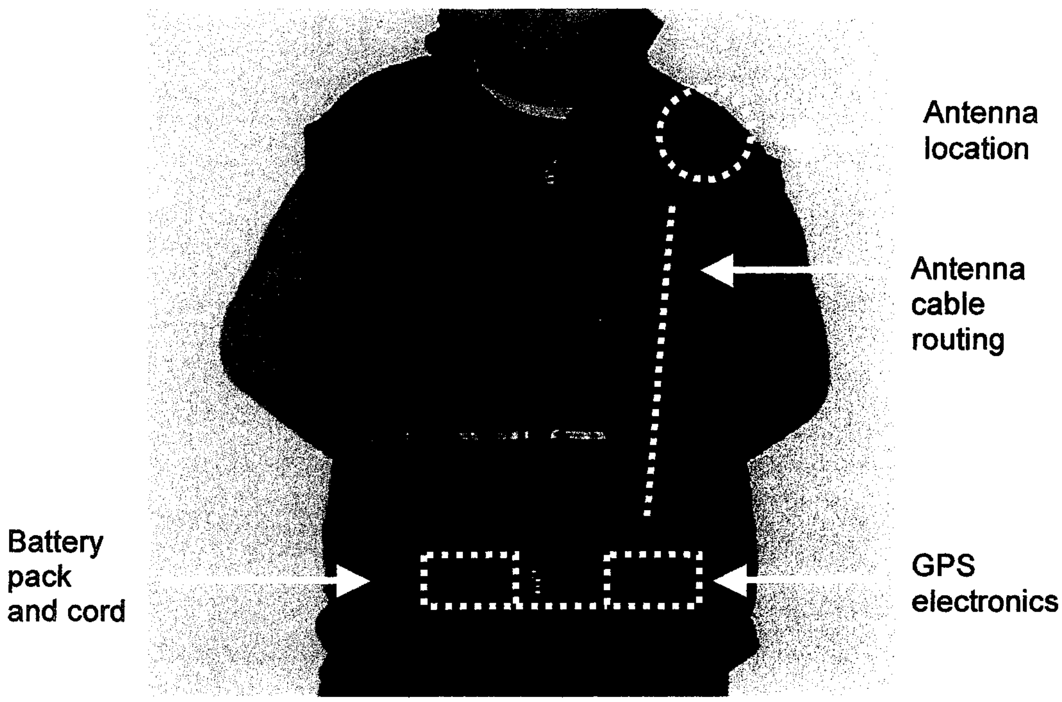


Figure 2.2. Child wearing GPS-PAL in a vest
Dashed lines indicate location of components inside the vest

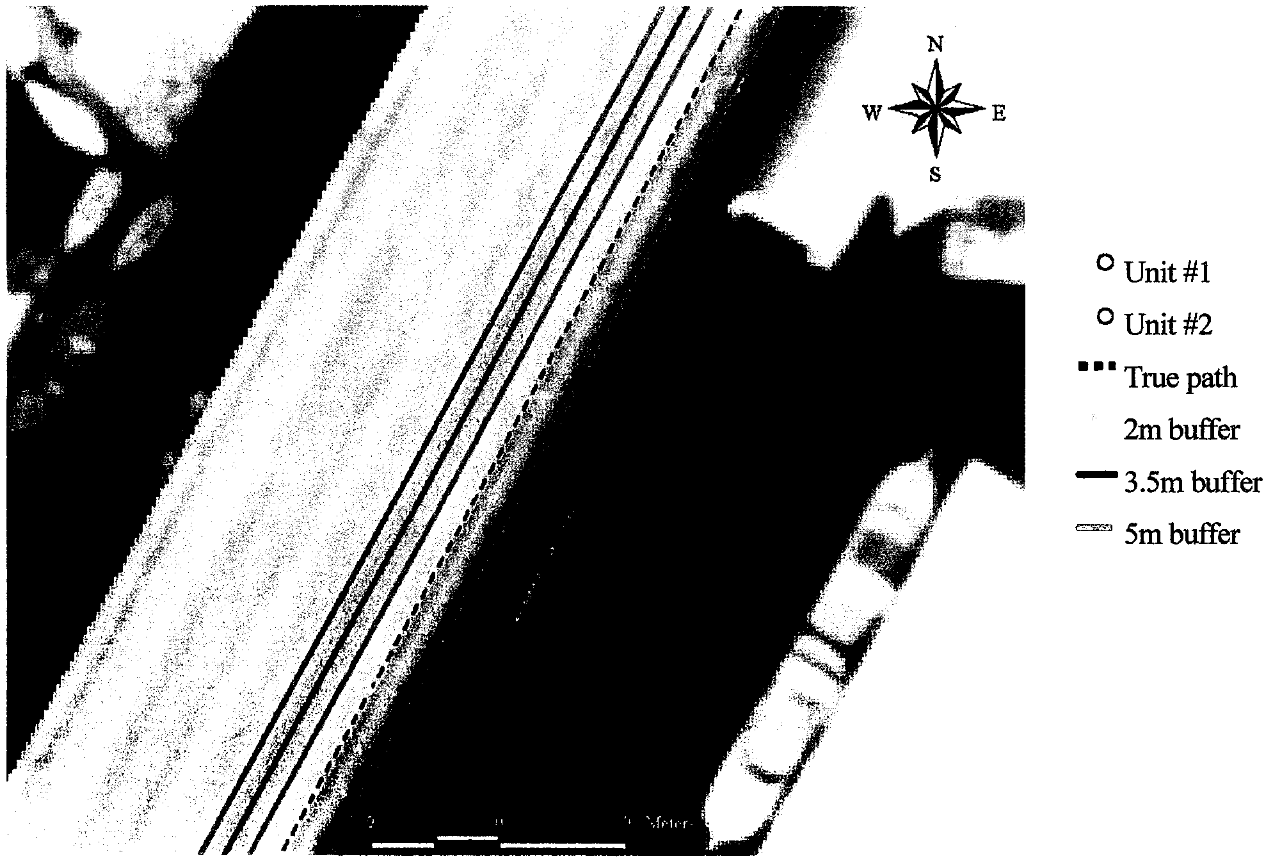
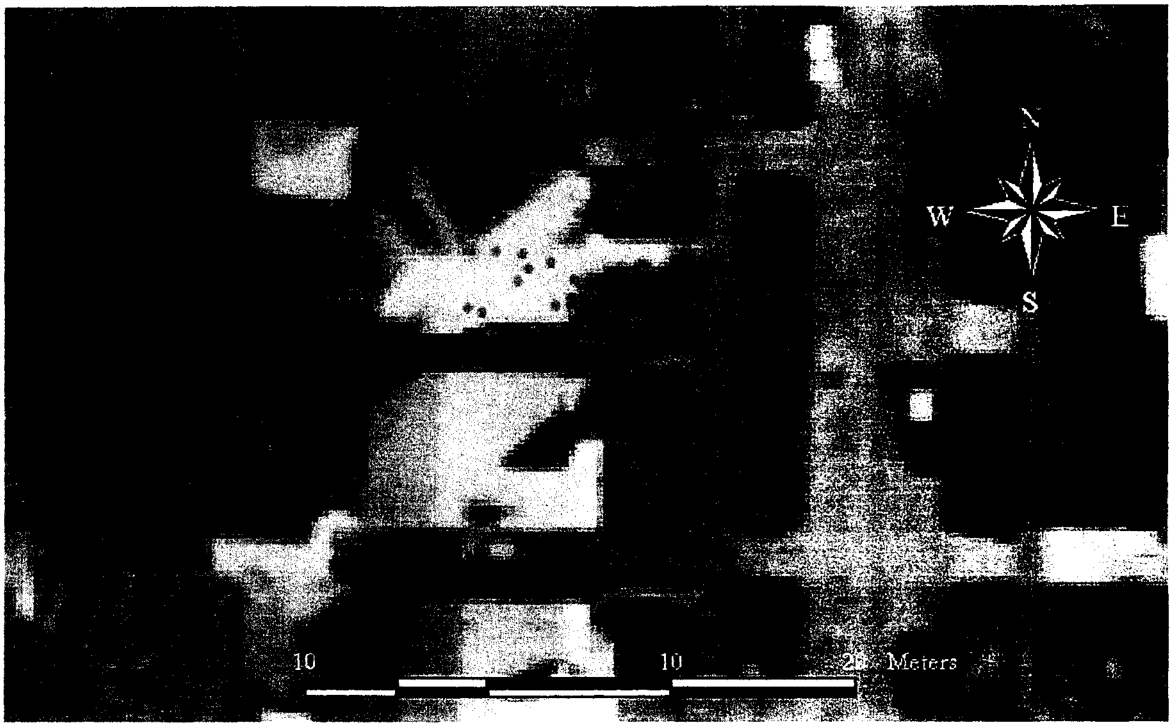


Figure 2.3. Sample of points logged by GPS-PAL units during 50 minute mobile test. Units worn by 2 pedestrians for 4km in the city. 9 points per unit shown along a path with ideal GPS reception: on a bridge, unobstructed. Complete 50 minute data shown in Table 2. True path is the center of the sidewalk. Variations in sidewalk width accounted for in this analysis.

Figure 2.4. Representation of GPS-PAL capability to differentiate between distinct areas inside and outside a house

Aerial photo of house (above) and 1:3 scale drawing of house floorplan (below) overlaid on 2m square grid. GPS-PAL logged locations are shown by green circles on both photo and floorplan. Approximately 80% of points logged by GPS-PAL fall within 2 square meters. Thus it is possible to differentiate a person's location in distinct areas of a house and surrounding yard. Discriminating between indoors and outdoors for points close to exterior walls is accomplished by comparing the time-sequence of points to the location of exterior doors.


N
W
E
S
10
10
20 Meters

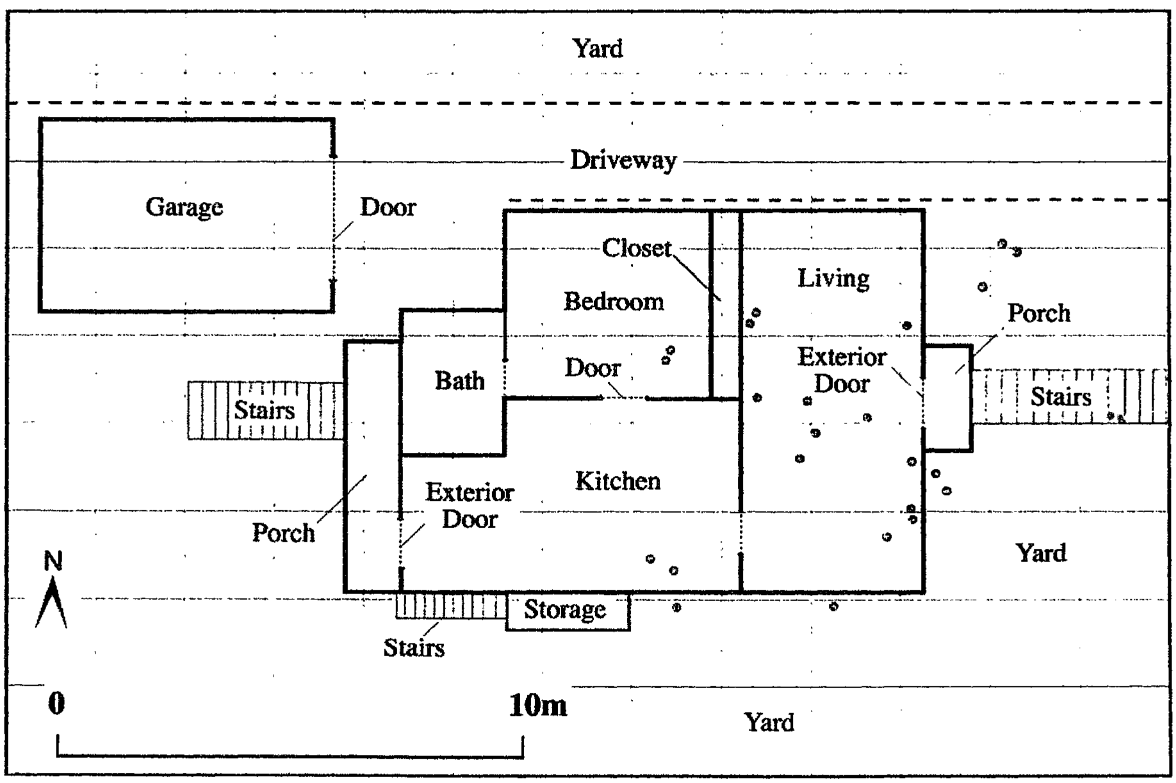

Yard
Driveway
Garage
Door
Closet
Bedroom
Living
Porch
Bath
Door
Exterior
Door
Stairs
Stairs
Kitchen
Exterior
Door
Porch
Yard
N
Storage
Stairs
0
10m
Yard

Figure 2.5. Path traveled by one child on a weekday during school hours
The playing field is located in the upper half of the picture. The school building is located in the lower half of the picture. The main entrance is located at the center. There is a street along the right side of the school grounds.

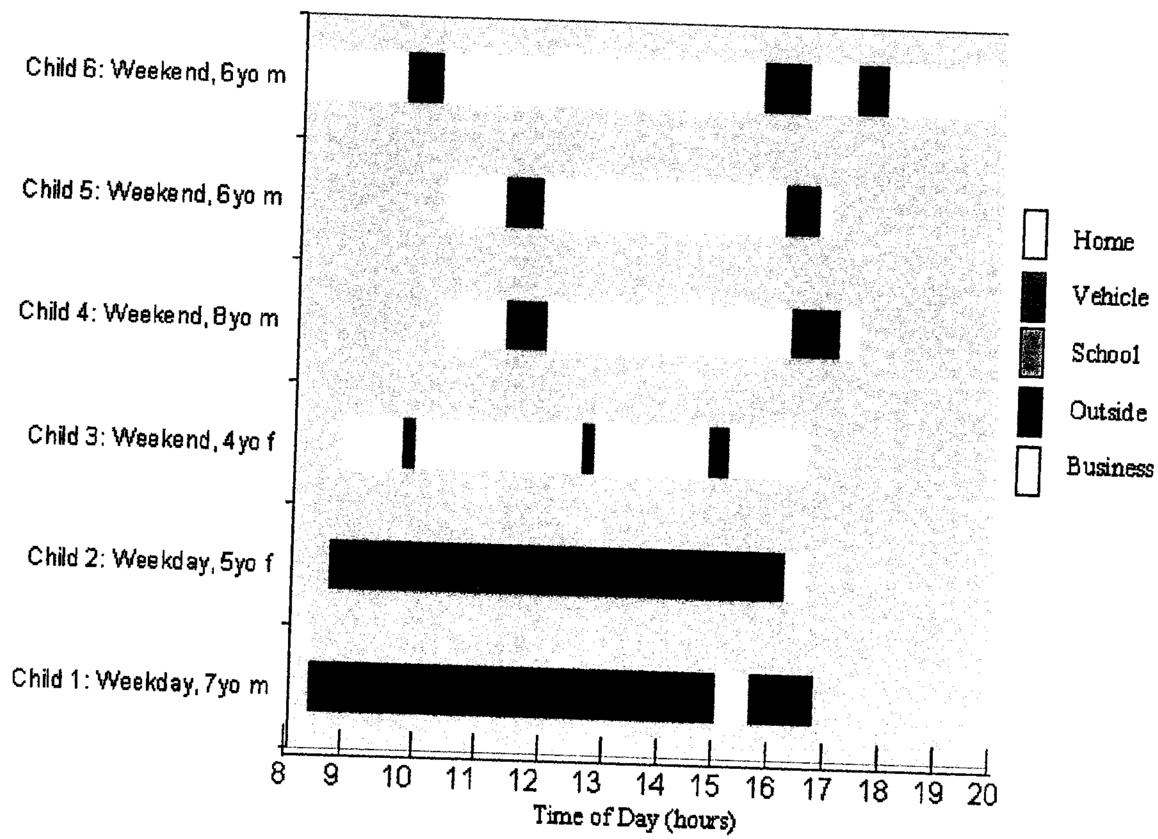


Figure 2.6.Children's monitored time-location during one day using GPS / GIS

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Chapter 3

Comparison of GPS Tracking to the NHEXAS Diary Timeline for Time-Location Measurement of Children

Introduction

Quantification of children's time-location, in conjunction with children's activity patterns, is essential for predicting exposure in microenvironments (Cohen-Hubal 2000). When dealing with transient peaks of environmental contaminants, knowing whether or not a person is in a particular microenvironment is the first step in determining whether exposure may occur (Klepeis et al. 2001; McCurdy and Graham 2003). Time-location has been measured using self-report diary instruments for many years (Robinson 1988; Wallace et al. 1987, 1991; Freeman et al.1993, 1999). The most widely used diary for human exposure assessment in the US was that used for the NHEXAS (National Human Exposure Assessment Survey). Approximately 600 people in four EPA regions participated in the survey between 1994 and 1999 (Freeman et al., 1999; Whitmore et al., 1999; Robertson et al., 1999; O'Rourke et al., 1999; Echols et al., 1999; Quackenboss et al., 2000; Freeman et al., 2001). The NHEXAS sought to characterize exposures to a wide range of pollutants from multiple sources and media using available methodologies (Sexton et al., 1995). The diary timeline was one component of the larger survey. The diary timeline was designed to provide data whose resolution was comparable to the temporal resolution of the environmental and human samples collected during the study (Freeman et al., 1999).

Time-location of children has been measured by parental-report using the same type of diary timeline (Dorre 1997; Freeman et al. 2001; Pellizzari et al. 2003). Dorre (1997) investigated a group of 52 children aged 2-3 years and found that 66.2% of time was spent at home, 20.4% was spent in nursery school, 1% indoors elsewhere, 11.2% outdoors and 1.2% in transit over the course of one week. The Minnesota Children's Pesticide Exposure Study utilized the NHEXAS diary to assess, among other things, children's time-location over one week (Freeman et al. 2001; Pellizzari et al. 2003). Parents completed the diary for children between 3-4 years old, and parents aided completion of the diary for children ages 5-9. All children between 3-9 years old reported spending about 16 hours inside the home and 1-1.5 hours outside each day. Neither study reported problems with completion of diaries. The demographics of the study populations (including literacy level) were not reported. Validity and reliability of responses was not tested in the Minnesota study.

The validity and reliability testing of the NHEXAS time/activity diary was published prior to the studies discussed above (Freeman et al., 1999). Validity was checked by comparison with questions outside of the diary or other external tests, and by comparing responses to related questions. Reliability was checked by looking for consistency of responses. Consistency in the NHEXAS timeline was checked by having a duplicate question on both a questionnaire and the timeline asking about time in a particular location (time in transit). The responses were compared, and reported times were highly correlated between a questionnaire and the timeline (0.811 to 0.922, $p<0.001$). Accuracy of the timeline was not tested, however. Accuracy requires an outside standard for means of comparison. The accuracy of any time/activity diary, including the timeline in the NHEXAS diary, is much more difficult to test. Diary timeline accuracy would be best tested by using a 'gold standard' that measures the accuracy of reported time-location. However, no true 'gold standard' is available. While not tested for accuracy, validity of the NHEXAS timeline was measured by checking that all time, in hours and minutes, adds up to 24 hours.

The NHEXAS diary timeline instructions instruct participants to estimate partial-hour fractions for location categories, but does not provide any requirement or structure to do so. Thus the resolution of a person's true time-location is likely low. The NHEXAS diary timeline is also low resolution because it defines only 7 location categories. The diary was designed this way "to facilitate participant responses" and to correspond with 'compartments' the questionnaire addresses in terms of exposures (Freeman et al. 1999). The accuracy of a diary timeline may also be limited by recall bias, though this has not been documented for the NHEXAS diary. It is very difficult to recall exact location throughout the course of one hour, even if subjects are faithfully recording once per hour (Moschandreas and Relwani 1991). Some type of measure independent from the diary is needed to illuminate recall bias, such as the 'shadow sensor' prototype developed by Moschandreas and Relwani (1991) that distinguished between indoors and outdoors.

Global positioning systems (GPS) tracking devices are fast becoming a part of everyday life. Low-resolution GPS watches are used by athletes to track velocity and position (Suunto, Vantaa, Finland; Timex, Middlebury, CT; Casio, Tokyo, Japan), and by parents to protect children in case of abduction or getting lost (Wherify, Redwood Shores, CA). Higher resolution GPS tracking telephones are used to enhance the safety of workers in remote locations (Benfon, Salo, Finland). The highest resolution GPS instruments use a process called differential correction to improve accuracy. The advantages of a differential-corrected global positioning systems (dGPS) method for logging time-location are that resolution is high and bias is minimal. GPS has been used for several studies involving human time-location measurements (Elgethun et al. 2003; Phillips et al., 2001; Larsson et al., 2001; Lyon et al., 1998).

Time can be logged every second, and space can be determined within 5 meters or less of true location. The GPS personal activity logger (GPS-PAL) instrument validated by University of Washington researchers achieved a resolution of 3.2 meters root mean square (RMS) while logging every 5 seconds (Elgethun et al., 2003). The overall resolution in this study can be considered <4.2 meters after accounting for orthophoto map error. Validity and reliability are simply a function of temporal-spatial resolution. Bias is minimized by requiring no input from the user. The only necessary question asked of participants is whether the GPS-PAL was kept on their person the whole duration of the study period. Provided the GPS-PAL is kept on the person, failure occurs just if participants forget to turn on the device. The GPS-PAL unit was designed to be small, lightweight, and amenable to children when worn in a vest. Compliance with keeping the vest on has been good in recent studies (Elgethun et al. 2003).

The problems of self-report diaries are evident when parents complete a diary to document the activities of their children. It is difficult for parents to remember where they themselves went throughout a day, and more difficult to see and then recall where their child went. Younger children, particularly pre-school and elementary school children, are very active and move rapidly between time-location categories defined by a diary. Temporal resolution of quarter or half-hours (which is about the limit of a diary) cannot capture these transient stays in a time-location category.

The purpose of this paper threefold: 1) to compare the GPS-PAL dGPS method to the parent-reported NHEXAS time-location diary; 2) to illuminate which child and household factors might affect accuracy of reporting in specific time-location categories; and 3) to demonstrate a new approach for exposure assessment, as dGPS allows for the replacement of categorized data with continuous positional data.

Methods

Study Populations

All human subjects protocols were approved by the University of Washington Human Subjects Review Board. The study was conducted in the late spring and early summer since children in northern climes are likely to go outside during this season and have frequent movement between indoors and outdoors. This variation was desirable for testing the two methods. Thirty-five families living in the city limits of Seattle were recruited from Early Head Start Programs in the spring of 2003. A letter was sent home to parents (in Spanish, Vietnamese and English) from four Early Head Start centers, and researchers attended evening meetings at centers to explain the study to parents. Early Head Start was chosen to afford access to lower-income (150% poverty level and below) and minority population in the region. Fifteen enrolled families spoke Spanish only or Spanish primarily, and all materials and interviews were given in Spanish to these families. No Vietnamese speaking families enrolled in the study. The racial profile of the children in this study (35 total) was: 17 Hispanic, 7 African American, 1 Pacific Islander, 1 Native American, 9 Caucasian. Early Head Start also afforded access to a specific age group, 3-5 years old. One child per family was enrolled. The division of subjects by gender was approximately equal (17 male, 18 female).

Parents filled out the NHEXAS diary timeline to document the time-location of each child. The NHEXAS time-location diary and the protocol for training interviewers and administering the diary were obtained from one of the diary's authors (N. Freeman, EOHSI, Rutgers University, Piscataway, NJ). The materials were printed in both Spanish and English. The original diary has 7 time-location categories. In this study, two categories, 'Inside Work or School' and 'Outside Work or School' were eliminated because the subjects were 3-5 year old children who participated on a non-school weekend day. The remaining five categories were: 'Inside at Home' (INHOME), 'Inside at Other' (INOTHER), 'Outside at Home' (OUTHOME), 'Outside at Other' (OUTOTHER), and 'In Transit' (TRANSIT). In addition to the time-location diary, University of Washington researchers administered a questionnaire to collect information about the child and about housing characteristics, family demographics, and income to determine if these factors influence either responses to the diary or compliance with the GPS protocol. Lightweight portable GPS-PAL dataloggers (Elgethun et al. 2003) were worn by children in vests. The vest allows for placement of an antenna on the horizontal shoulder surface. GPS-PALs were set to record data once every 5 seconds.

Researchers went to homes of enrolled families. On the first visit, researchers spent approximately 45 minutes explaining the purpose of the study, how to fill out the diary, how and when to turn on the GPS-PAL, and administering the questionnaire. Researchers had parents fill out a practice diary and corrected errors in notation, per NHEXAS guidelines. The practice diary and notes were kept by the parents as a guide for filling out the diary on the study day. Parents were asked to record time location as frequently as every 15 minutes, if possible. Families participated on weekends only to maximize the number of hours of parental supervision. The period of participation was 24 hours. The GPS-PAL was worn for all waking hours. Parents turned the GPS-PAL on and put the vest on when the child awoke in the morning. On the second visit, usually the day after participation, researchers returned to the home. Researchers reviewed the diary with the parents and had them make appropriate corrections if the total time did not add up to 24 hours. Researchers asked parents to verify the time the GPS-PAL vest was put on the child, the time the GPS-PAL vest was taken off, and to tell if the child ever left the house without the GPS-PAL vest on. Leaving the house without the vest on (or forgetting to turn on the GPS-PAL) would exclude the child from the analysis. Participating on a weekday instead of a weekend would also exclude the child from the analysis. Families were compensated regardless of compliance. Families were compensated $40 for their participation.

The completed diaries were totaled according to NHEXAS protocol. Time marked for each category, at specific time of day, was entered into a database. GPS-PAL data was likewise binned into these categories. This was accomplished by first drawing a buffer around each residence, as well as any other buildings into which the child entered. Points inside the buffers were coded as 'Inside at Home' or 'Inside at Other'. Similarly, a buffer was drawn around each child's yard. If there was no yard, a patio or shared outdoor space belonging to an apartment building, such as a courtyard, was considered the same as a yard. These points were coded 'Outside at Home'. 'In Transit' was coded by examining the path to see if the child was traveling from one place to another. Remaining points were coded 'Outside at Other'. To demonstrate the ability of the GPS-PAL to record continuous data, the dataset was also kept in its original format. These data were plotted as an hourly average of distance and direction from a 'tether' location. In this case, the tether was an air monitoring station in Seattle proximal to the children's homes.

GPS data was first processed using differential correction measurements obtained from the US Coast Guard/National Geodetic Survey CORS program to improve accuracy. The processed paths were mapped onto City of Seattle orthophoto maps using GIS software (ArcGIS v.8.3, ESRI, Redlands, CA), then location by time was recorded. Recording involved magnifying the map many times to determine the outline of the homes, then drawing a buffer around each home so that points inside were differentiated from points outside. The same procedure was used for buildings other than the home into which the child entered. Being in transit was determined by the child's GPS path velocity. Elapsed time of movement at a velocity above that possible on foot was coded in transit. Only the hours between 9 am and 9 pm were included in analyses. Some morning periods shortly after 9am and evening periods shortly before 9pm had no GPS data, either due to reception, early bed time, or sleeping in. Since the child did not wear the vest while sleeping, it was sometimes necessary to insert proxy GPS data for early evening and morning hours if the child went to bed early or slept in. For all children, it was verified that the child did not leave the home without the vest on, and that the GPS-PAL was turned on before leaving the home. These missing time periods were coded as 'Inside at Home' unless the first logged point was far away from the home.

A key assumption made in this study is that the GPS-PAL method is what will be defined here as a 'best practical standard'. 'Best practical standard' in this case means the GPS-PAL affords good resolution and reception while still being completely portable and wearable for children. Based on a previous validation study (Elgethun et al. 2003), this is defensible provided the child keeps the vest on, and that parents are compliant with the protocol. Comparisons between the two methods were made by time-location category and by subject.

Criteria for Inclusion

Subjects were included in analyses if their GPS logged more than 6 hours during the 12 hour period from 9am to 9pm on the day of participation. 31 subjects met these criteria and were included in the analyses. This criteria excluded participants who did not follow directions (i.e. did not put the GPS on in the morning), or who stayed inside a building that blocked GPS reception for most of the day.

Statistical Analysis

Kappa measurements along with z test for significance were performed to compare the two methods. Kappa itself is a measurement and not a statistic. Kappa is based on 2 proportions: proportion of concordance expected if methods are completely unrelated, and proportion of concordance observed between the two methods. A misclassification matrix is constructed such that the five time location categories by each method are listed perpendicular to one another, creating a 25 square grid (Tables 3.4 and 3.5). This matrix allow for a frequency of agreement to be calculated for each possible combination of reporting by the two methods. Cells that fall along the diagonal from upper left to lower right are in concordance (both methods rated the same). These determine the proportion of concordance observed (P_o).

The formula for the Kappa measurement is:

$$\text{Kappa} = \frac{(P_o - P_e)}{(1 - P_e)}$$

where P_o is the proportion of observed agreement, and P_e is the proportion of agreement expected.

The influence of differences in gender, age, first language spoken, housing factors, family demographics, and income on reporting concordance was tested for two types of data. The first type of data was sequential scoring concordance (Kappa or proportion measures). This was tested by linear regression two ways: by using frequency of reporting correctly in each time location category as the dependent variable, and by using overall Kappa value as the dependent variable. The second type of data was overall time (sum) in each category. This was tested using Spearman rank correlation.

Results

Demographics

Two children and their families (English-speaking) were excluded from data analysis. One family participated on a weekday instead of a weekend, the other forgot to turn on the GPS. All parents reported that children kept the GPS vest on for the duration of the study day. Children's mothers completed the diary for all but one family. Demographics of the 33 children included are shown in Table 3.1. Several families earned above 150% poverty level because their household income had risen since the time of child's enrollment in Head Start. Table 3.2 shows where children spent their time during the 24 hour weekend period, by both methods. This is also shown in Figure 3.1. The NHEXAS diary responses under reported time spent inside at home, and over reported time spent in other places when compared to the dGPS measurement. There was a wide distribution in the range of time spent in each location by children. Two of the 33 children and their families (one English-speaking, one Spanish-speaking) were excluded from statistical analyses (Tables 3.3-3.7) since they did not meet the criteria for minimum number of GPS-logged hours between 9 am and 9 pm.

Sequential Reporting Concordance (Kappa Results)

Table 3.4 contains data for 31 included subjects analyzed by 15 minute time interval. Table 3.5 contains data for 31 included subjects analyzed by 1 hour time interval. The numbers logged in the matrix are counts: the number of times the 31 subjects classified time-location into a certain category by diary and the number of times they were classified by GPS (Table 3.4 and Table 3.5). Next to each counts value, in parentheses, is the proportion of the total number of counts. The test for significance is a one-sided z test with the null hypothesis Kappa = 0, and the alternative hypothesis Kappa > 0. (Negative values for kappa have no significance). Guidelines for the evaluation of Kappa (Rosner 2000) are:

$k>.75$ excellent reproducibility

$.4<k<.75$ good

$0<k>.4$ marginal

The p value for a z test of the kappa measurement can be significant whether or not the kappa value denotes appreciable reproducibility.

For both 1 hour and 15 minute data the Inside at Home time was the largest proportional to the total sampling time period (12 hours). Consequently, Inside at Home had the greatest impact on Kappa. The greatest proportion of overall counts fell in the INHOME/INHOME cell. Since this was one of the concordance cells, it influenced the overall kappa value more than any other cell. This was also seen to be true in 2x2 tables analyzed for each subject (Table 3.6).

While significance (p less than .000001) of the z test was observed for both 1hr and 15 minute data, the kappa values were .35 and .33, respectively. According to Rosner (1995), this implies *marginal* reproducibility. Notably the kappa was almost the same regardless of the time interval resolution. This was likely due to the fact that there is sufficient lack of concordance regardless of time subdivision, or to a lesser extent due to the fact that few subjects logged time-location in the diary at sub-hour intervals

Table 3.6 shows the kappa values generated by a simplified 2 x 2 matrix, where each location is compared to the aggregate of the other 4 categories. Inside at Home has the highest Kappa value of .443, considered 'good' reproducibility. Outside at Home has the lowest Kappa value of .160. As stated above, it follows that Inside at Home has the greatest positive influence on the overall Kappa, particularly since the most time was spent overall in this category. Outside at Home has less influence on overall Kappa in the negative direction since little time was spent on average in this category.

Results by Individual Child and Household Factors: Sequential Reporting Concordance, Linear Regression

Very few demographic variables were found to be predictors of concordance when tested using a linear regression model (Table 3.7). Mothers who stayed at home or worked an unskilled labor job had higher concordance between methods when Kappa was tested as the dependent variable. Access to a car was also a predictor of higher Kappa. Fathers who stayed at home were not a predictor of higher overall Kappa, but did influence reporting concordance in the Inside at Home category based on regression analysis of the Inside at Home frequency of concordance (proportion of agreement). A child with siblings was predictive of higher overall concordance in the Outside at Home category based on regression analysis of the Outside at Home frequency of concordance.

Results by Individual Child and Household Factors: Total Time, Rank Correlation

Table 3.4 shows the correlation between methods for total time spent in time-location category by child and household factors (Spearman rank sum). Note that the rank correlation only measures difference in total time in category, and is not a measure of sequential concordance of responses. Spearman rank sum correlation was performed because it is a non-parametric, distribution-independent metric of correlation. Non-parametric analysis was indicated due to the small sample size used in comparisons performed here. An asterisk indicates significance of correlation ($p<0.05$).

Given the assumption that the GPS method is testing the NHEXAS diary timeline, it can be said that subjects with the factors listed below reported *total time in location* for the whole day more accurately than other subjects. This does not directly relate to concordance of sequentially correct answers. The following is a summary of the child and household factors that showed the *highest number* of significantly correlated time-location categories: English speaking household, 3 categories; Male child, 2 categories; Child with siblings, 4 categories; Not in daycare on weekdays, 3 categories; Home with fenced outdoor area, 3 categories; Parent owns or uses a car, 4 categories; Mother's occupation unskilled labor, 3 categories; Father's occupation unskilled labor, 2 categories; Household income >$4000/mo (highest bracket), 2 categories.

English speakers reported total time in home, out at other, and especially total time in transit more accurately than Spanish speakers. Parents reported boys' total time more accurately outside at home, and inside at other places. Parents reported girls' total time in transit more accurately. Parents with more than one child consistently reported total time in location more accurately. Even though this study took place on a weekend, parents of children who were in weekday daycare reported total time more accurately in three of five categories, versus one of five for parents of children in weekday daycare. Parents reported total time spent outside at home more accurately if they had a fenced area, while parents without a fenced outside area reported total time spent inside the home more accurately. Parents who did not own or use a car reported total time spent in transit more accurately, but less accurately in every other time-location category. For both mothers and fathers, parents who worked unskilled labor jobs were most likely to report total time accurately. This was less unique for fathers, since two of the other occupation categories also had one significant correlation each. Parents in the highest income category reported total time by location accurately more often than other parents, but significant correlations were also found in two other income categories.

Demonstration of Continuous GPS-PAL Data

Results thus far have been based on categorical analysis. However, it is not necessary to reduce GPS-PAL data into categories. Greater temporal-spatial resolution can be achieved if continuous distance and direction from a point of interest (such as a contaminant source or a monitoring station) are recorded, as shown in Figure 3.3. 25 of the 31 subjects were outdoors during the hour between 2-3 pm, and their 1-hr averaged distance and direction from an air monitoring station in Seattle are represented by one line for each child for this time period. The air monitoring station used here was Beacon Hill. Based on data from the Puget Sound Clean Air Agency (PSCAA), this time of day on weekends during the study months of April and May 2003 had the highest 2.5 um particulate matter (PM2.5). The 6 subjects who were indoors the entire hour are not recorded on this figure, as exposure to ambient PM2.5 only is measured by the Beacon Hill station, and no measure of indoor contaminants was made. Using the continuous GPS data, it is possible to decide how representative the air data is for each child. The further away a child is, the less representative the Beacon Hill station data would be for estimating exposure. Similarly, distance from a source can be observed in Figure 3.3. Interstate 5 runs North-South less than 0.5 km West of the air station and is the major source of PM2.5 measured at the Beacon Hill station. Children closer to this line source or more directly downwind from it may be expected to receive greater PM2.5 exposure than children further away or upwind. Continuous GPS data provides the distance and direction information needed to make such estimates of exposure.

Discussion

The population studied here was chosen for three reasons: first, to consist both economically and culturally of a lower income demographic; second, to reflect a socioeconomic profile likely to have greater risk of exposure to pesticides; and third, to include Spanish-speaking families, since much of our research involves Hispanic families. Other studies by our group, such as the aerial spray drift study included in Chapters 4 and 5, have focused on similar income groups who live in agricultural communities. The per capita diversity of this study was limited by the under-representation of Asian families. Recruitment fliers were distributed in Vietnamese, as advised by the Early Head Start officials, but no Vietnamese subjects signed up. The theory that a lower income population might be expected to have lower compliance with a diary was marginally supported. Families in the highest income bracket (>$4000 per month) had the highest rank correlation for total time. This was not true for sequential reporting, however, as income was not a predictor of kappa or frequency of concordance by regression analysis. .

Compliance is a problem with all time-location data collection methods. The problem with a diary method is that the subject's parent may forget to fill in the diary as instructed, and may later fill in the time-location as an estimate or 'best-guess'. Even if the parent fills in the diary as instructed, recall of specific time-location may be challenging. Parents can have difficulty if the child is extremely active and goes between many locations or spends very short time periods in each location. This is not unusual behavior, especially in the 3-5 year old age group studied here (Zartarian et al. 1997). Illiteracy also confounds the successful completion of a diary, even when the researchers thoroughly rehearse the procedure with parents, as was the case in this study. Compliance with the GPS-PAL method is simply limited by parents remembering to turn on the unit, and by children continuing to wear the unit while it is turned on. The former is obvious, since the GPS time-stamps the turn-on time. The latter is less obvious, but can be checked by asking parents to report if this happened, as was done in this study. This still introduces a potential recall problem, a problem that could be overcome in future studies by wiring a simple switch that trips if the vest is removed. On the whole, the GPS-PAL method is not limited so inherently by recall bias, nor is it limited by illiteracy or by other language barriers.

Overall, children spent a large portion of their weekend day inside the home. The NHEXAS diary responses under-reported time spent inside at home, and over-reported time spent in other places when compared to the dGPS measurement (Table 3.2, Figure 3.1). An integral part of this over reporting is the default length of the diary time-location category. A child may only be in the car for 5 minutes, but the parent either consciously or unknowingly rounds up to 15 minutes when reporting on the diary. Parents were encouraged to record every 15 minutes, but the format of the NHEXAS diary does not promote such vigilant recording. The numbers listed on the diary timeline are whole hours, even though the last column has a designation for hours and minutes. The wide range of times spent in each location for all children (for both methods) emphasizes the problem with using proxy time-location distributions such as the US EPA Consolidated Human Activity Database (CHAD) (McCurdy and Graham 2003). It should be noted that for the aims of NHEXAS, higher time resolution was possibly not necessary.

While it is interesting to examine correspondence by total time (since time is often summed over a day when day-weighted environmental readings are available) as was performed here using the Spearman Rank test, this does not test correspondence of the sequential recording of category. The Kappa measures (Tables 3.4, 3.5 and 3.6) show that overall agreement of methods can be considered marginal, and that time spent inside the home has the greatest influence on the overall Kappa for two reasons. First, the most time during the day is spent inside the home. Second, some of the time recorded as inside at home by GPS method is in fact proxy, since reception was often blocked until the subject left the home. These are both notable limitations of the GPS-PAL. The need for proxy data could be overcome by having the GPS time stamp when it is turned on, regardless of reception. A switch could also be wired such that the GPS would time stamp when the vest is zipped shut and zipped open so that removal of the vest would be logged by the GPS.

Compared to the Spearman rank data, few demographic variables were found to influence concordance measured by Kappa or by frequency of concordance within individual category. This is likely because concordance is already sufficiently low that few if any variables will change it significantly. Sample size is also a limiting factor. It follows that having one or the other parent staying at home full time increases concordance, since these parents could be more accustomed to watching their child. It is not clear why access to a car improved Kappa. Access to a car was not related to income, as income had no effect on Kappa by itself or when combined with the car variable. Having siblings was predictive of improved concordance for outside at home reporting, perhaps because the parent relies on a sibling to help remember where the subject was, or because multi-child parents have more experience monitoring their children.

Timelines such as the NHEXAS diary timeline still have utility for time-location data collection. One point of this study was to show that GPS can be used to illuminate for which people the diary works least well. This is important because GPS is not yet affordable enough to use in large-scale exposure assessments. For example, in this study, 'Outside at Home' had the lowest Kappa, and 'Inside at Other' was found to be least well correlated with the GPS for total rank sum of time. Perhaps parents could be coached to set a timer during the times the child goes out the back door, or when they go into stores. It should be noted that while not affordable now, GPS will likely be affordable enough for large-scale studies in the future. Thus, evaluating diaries with GPS is a practical stopgap measure until technology catches up and becomes more affordable. At the moment, diaries also have the advantage over GPS of being less time-consuming to process.

Other weaknesses in the diary timeline were found when child and household factors were examined for comparisons of total time in location (Spearman rank correlation, Table 3.3). Spanish speaking households were less likely than English speaking households to reply accurately, perhaps due to cultural differences. The fact that male children's time-location was reported more accurately at home suggests parents in this cohort paid more attention to male children. On the other hand, parents were maybe more cautious for female children when outside away from the house. Parents of only children reported less accurately than parents with more than one child. Apparently having more than one child improved a parent's awareness of child time-location, or made the parent more accustomed to keeping an eye on children. Similarly, a parent who did not put her child in daycare during the week was found to be better at reporting her child's time-location on the weekend. As expected, having a fenced outdoor space at the home improved parent's reporting accuracy for the 'Outside at Home' category, given the defined boundary within which to watch the child. Parents who never had access to a car and thus primarily used public transportation were very accurate in their reporting of time spent in transit, likely because their travel was dictated by bus schedules. These same parents reported less accurately in every other category, however, but this result is confounded by the association between higher income and access to a car. It is not clear why both parents being unskilled laborers improved reporting accuracy. In terms of improving the reporting accuracy of the NHEXAS time/activity diary, all of these problems could possibly be addressed by changing the way the question is asked, changing how the researcher rehearses and trains the parent to fill out the diary, or providing some adjunct aid such as a timer to help the parent report accurately. Some combination of these three methods might be feasible.

Figure 3.2 shows GPS data averaged to represent time and location for one hour, but with GPS it is not necessary to average (as done here) or to categorize time location. Instead, GPS allows for delineation of hundreds or thousands of very small exposure environments and exposure intervals of only a few seconds. This means that peak, transient exposures can be recorded by specific time and location rather than being absorbed into a time-weighted average. While a diary could record time spent outside for the day for relating to the Beacon Hill PM2.5 data, the diary could not have captured the children's proximity to the monitoring station. Contaminant concentration is not uniform in all distances and directions from a monitoring station. With GPS, two advancements have been made. First, inherent problems with human-reported data are minimized, yielding higher resolution data. Second, proximity of the moving human receptor to contaminants can be measured. With the automated collection of near-continuous (once every 5 second) dGPS data, researchers can now pinpoint where subjects are in relation to contaminants. This is particularly important in the case of a transient, spike release such as a pesticide spray event. Continuous sampling (once every second) is in fact possible with the GPS-PAL and other dGPS instruments if it is required for a specific application. The only limitation on sampling interval is memory (byte) space. As personal logging dosimeters for air toxics improve in resolution and decrease in size and weight, it is logical to expect that tandem time-synched contaminant monitoring and dGPS positional monitoring will become standard procedure.

Conclusions

This study has been a comprehensive comparison of the dGPS GPS-PAL instrument to the NHEXAS diary timeline. Clearly, differing results are generated by the two methods. Overall, the timeline misclassified child time-location approximately 48% of the time in comparison to the GPS-PAL. This study has demonstrated that dGPS can be used to evaluate a diary timeline such as that used in the NHEXAS studies, and to illuminate which categories fail to elicit accurate responses or which people are most likely to have trouble reporting using a diary. The most important finding of this study is that concordance between GPS-PAL and NHEXAS diary timeline was poor. dGPS testing could be invaluable for researchers pilot-testing a time/activity diary. In the future, a larger study is recommended to provide more statistical power and thus better dissect which types of subjects fail to respond accurately to particular diary questions. Most exciting is the ability of dGPS tracking to collect continuous rather than categorical data by way of automated rather than human reporting. With the elimination of categories and the automation of data collection, the resolution of time-location data dramatically improves. This represents a major shift in the collection of time-location data.

It can be concluded that though concordance between methods was poor, it was demonstrated that dGPS affords a tool for illuminating weaknesses in a diary and thus could be used to focus improvements on specific categories and specific people. dGPS testing of time-location diaries can aid researchers for the next several years until the technology evolves further. Diaries continue to be more cost-effective and time-efficient than GPS-GIS methods. However, current trends suggest that GPS will be affordable enough within the next five to ten years to be used in studies with thousands of subjects. Similarly, data processing will likely become more efficient, broadening the appeal of GPS methods.

Table 3.1. Demographics of participating families

Household Language	
English	58%
Spanish	42%
Participating Child	
Female	52%
Male	48%
Only Child	21%
Median # of Siblings	1
Median Age	4 years
Median Income per Mo	$1,100
Mother's Occupation	
Stay at Home	40%
Unskilled Labor	42%
Trade Labor	9%
White Collar	9%
Father's Occupation	
No Father in Home	30%
Stay at Home	11%
Unskilled Labor	33%
Trade Labor	11%
White Collar	15%

n=33 families

Table 3.2. Time (minutes) spent in each location category by dGPS and NHEXAS diary methods for one 24 hour weekend period

	INHOME	INOTHER	OUTHOME	OUTOTHER	TRANSIT
dGPS					
Mean	1108	131	51	81	69
Range	642-1397	0-690	0-442	0-301	0-186
NHEXAS Diary					
Mean	922	172	89	182	75
Range	420-1260	0-600	0-420	0-840	0-180
Difference	186	-41	-38	-101	-6
% Difference	17	-24	-43	-55	-8

n=33 children
Age 3-5 years

Table 3.3. Spearman rank correlation between methods for total time in time-location category by child and household factors (n=31)

	INHOME	INOTHER	OUTHOME	OUTOTHER	TRANSIT
Household Language					
English	0.448*	0.305	0.415	0.532*	0.692*
Spanish	0.365	0.240	0.127	0.404	-0.034
Child's Gender					
Female	0.223	-0.040	0.215	0.425	0.581*
Male	0.450	0.530*	0.519*	0.467	0.292
Age					
3	0.277	-0.235	0.604	0.368	0.427
4	0.363	0.354	0.218	0.268	0.589
5	0.700	0.872	0.783	0.667	0.205
Siblings					
No	0.720	0.071	-0.490	0.536	-0.255
Yes	0.496*	0.319	0.469*	0.462*	0.514*
In Daycare, Weekdays					
No	0.421*	0.300	0.345	0.480*	0.465*
Yes	0.543	-0.203	0.893*	0.232	0.618
Home w/ Fenced Area					
No	0.648*	0.110	-0.045	0.519	0.184
Yes	0.363	0.328	0.507*	0.460*	0.516*
Parent Uses a Car					
No	0.174	-0.369	0.679	0.589	0.955*
Yes	0.482*	0.477*	0.436*	0.603*	0.338
Mother's Occupation					
Stay at Home	0.180	0.154	0.049	0.239	0.315
Unskilled Labor	0.695*	0.595*	0.592*	0.460	0.055
Trade Labor	id	id	id	id	id
White Collar	id	id	id	id	id
Father's Occupation					
No Father	0.036	-0.283	0.129	0.556	0.845*
Stay at Home	-0.500	-1.000	id	-0.500	0.866
Unskilled Labor	0.440	0.734*	0.176	0.644*	0.086
Trade Labor	0.500	-0.866	0.866	0.500	0.866
White Collar	0.051	0.700	0.800	-0.100	0.975*
Income per Mo					
<$1000	0.344	0.306	0.067	0.497	0.842*
$1000-$2000	0.529	-0.050	0.477	0.428	0.196
$2000-$3000	-0.500	0.500	0.866*	id	-1.000
>$4000	0.949*	0.800	0.632	0.775	0.949*

id=insufficient data
*Values are significantly correlated at p<0.05

Table 3.4. Frequency (proportion) matrix for all subjects comparing GPS-PAL method to NHEXAS diary method for 15 minute time intervals (n=31)

		GPS-PAL					
		INHOME	INOTHER	OUTHOME	OUTOTHER	TRANSIT	
NHEXAS	INHOME	459 (.308)	33 (.022)	19 (.013)	10 (.007)	20 (.013)	541(.364)
	INOTHER	80 (.054)	124 (.083)	16 (.011)	24 (.016)	28 (.019)	272 (.183)
	OUTHOME	120 (.081)	18 (.012)	38 (.026)	20 (.013)	12 (.008)	208 (.139)
	OUTOTHER	109 (.073)	62 (.042)	30 (.020)	115 (.077)	43 (.029)	359 (.241)
	TRANSIT	32 (.022)	29 (.019)	5 (.003)	10 (.007)	32 (.022)	108 (.073)
		800 (.538)	266 (.179)	108 (.072)	179 (.120)	135 (.091)	**1488**

proportion of concordance expected if methods unrelated = .274
proportion of concordance observed = .516
Kappa = .334
p = .0000

Table 3.5. Frequency (proportion) matrix for all subjects comparing GPS-PAL method to NHEXAS diary method for 1 hour time intervals (n=31)

GPS-PAL

		INHOME	INOTHER	OUTHOME	OUTOTHER	TRANSIT	
NHEXAS	INHOME	119 (.320)	7 (.019)	3 (.008)	1 (.003)	7 (.019)	137 (.368)
	INOTHER	17 (.046)	30 (.081)	3 (.008)	8 (.022)	9 (.024)	67 (.180)
	OUTHOME	28 (.075)	6 (.016)	12 (.032)	5 (.013)	3 (.008)	54 (.145)
	OUTOTHER	28 (.075)	16 (.043)	7 (.019)	29 (.078)	8 (.022)	88 (.237)
	TRANSIT	9 (.024)	6 (.016)	0 (.000)	4 (.011)	7 (.019)	26 (.070)
		201 (.541)	65 (.175)	25 (.067)	47 (.126)	34 (.091)	**372**

proportion of concordance expected if methods unrelated = .276
proportion of concordance observed =
.530
Kappa =
.350
p = .0000

Table 3.6. Trends determined by 2x2 kappa matrix analysis of 15 minute data

	KAPPA	*Proportion of Concordance
INHOME	.443	.574
INOTHER	.342	.466
OUTHOME	.160	.352
OUTOTHER	.318	.642
TRANSIT	.199	.237

Overall Kappa = .334 (Table 3.4)
Total number of counts in all categories = 1488.
Number of subjects = 31.

For all Kappa measures, p <0.00001 (Z test).

*Proportion of Concordance = number of counts coded the same for both methods divided by the number of counts total by GPS-PAL (see Table 3.4).

Table 3.7. Trends determined by regression analysis of 15 minute data
Both frequency of concordance in each time-location category and Kappa used as dependent variables. All demographic factors tested as independent variables (listed in Table 3.4). All significant variables listed such that they have positive effect on beta (increase beta value).

Significant Independent Variable	Dependent Variable	Sig	Slope term
Mother's Occupation			
Stay at Home or Unskilled Labor	Kappa	.02	-.468
Access to a Car			
Yes	Kappa	.05	.386
Father's Occupation	Freq. Of Concordance		
Stay at Home	InHome	.03	.416
Siblings	Freq. Of Concordance		
Yes	OutHome	.05	.523

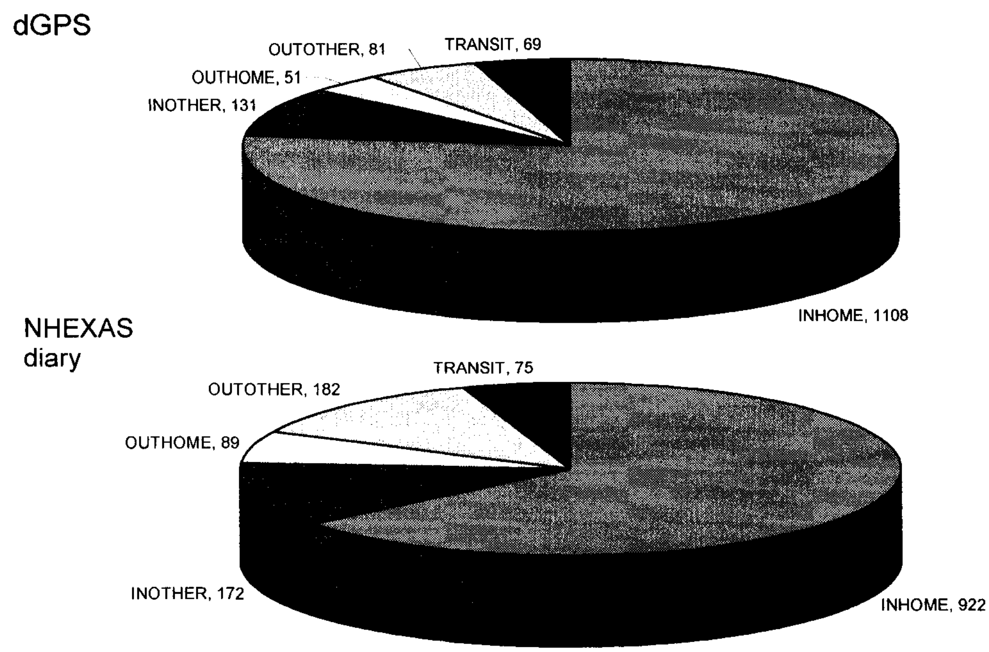
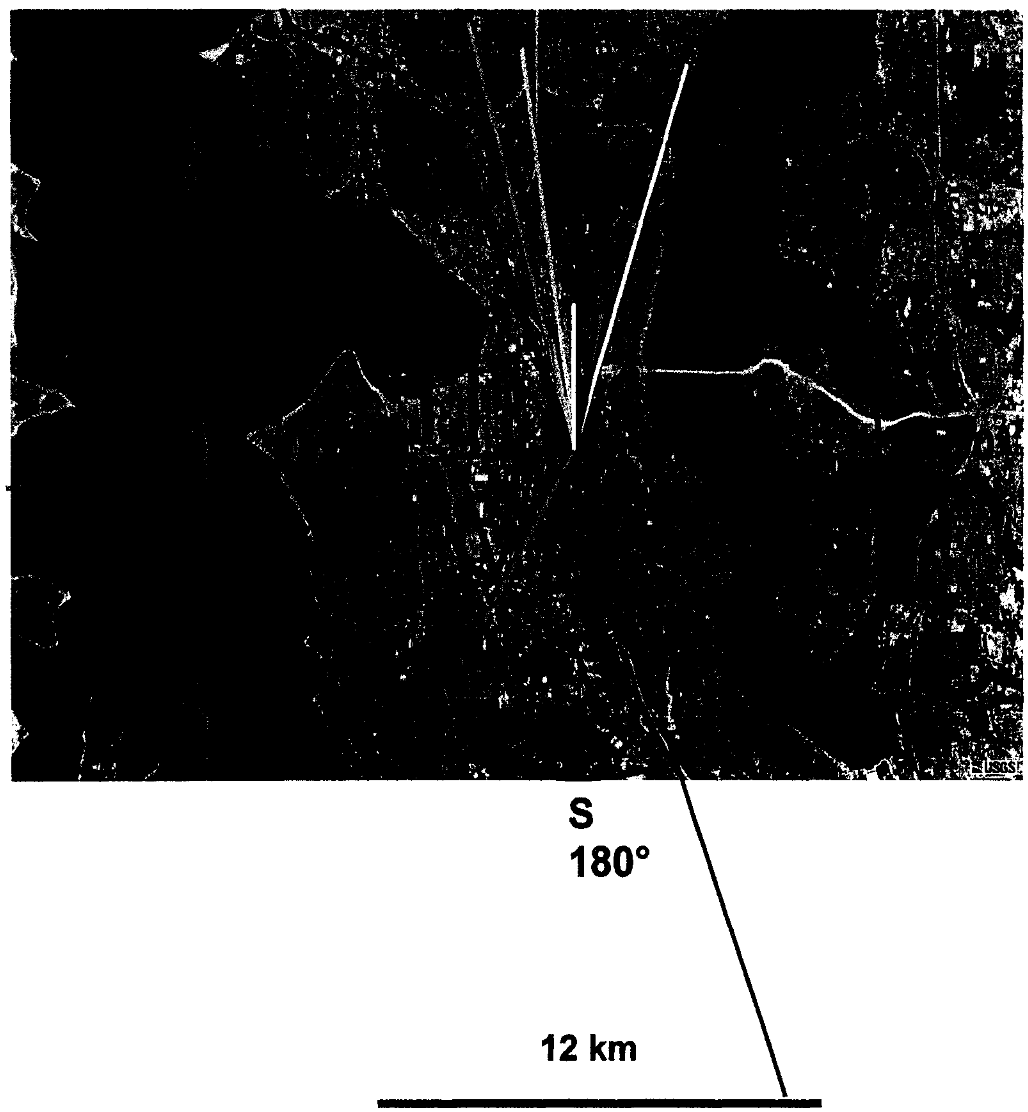


Figure 3.1: Time spent outside by dGPS and NHEXAS diary method

Figure 3.2. Mean distance and direction from an air monitoring station in Seattle during the peak hour of PM2.5 concentration

All subjects shown (n=25) were outdoors. 6 subjects were indoors where there was not GPS reception and are not shown. Time period over which mean values were calculated is 2-3 pm on a weekend day in April or May, 2003. This is the time of peak PM2.5 in Seattle for April and May on weekends. Distance and direction can be used to calculate exposure relative to PM2.5 readings from this station. The main source of PM2.5 is Interstate 5, which runs North-South approximately 0.5 km West of the air monitoring station.


USGS
S
180°
12 km

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Chapter 4

The Washington Aerial Spray Drift Study: Descriptive Data and Summary

Introduction

This chapter in its entirety will not be submitted as a publication. This chapter incorporates GPS tracking data and data from a submitted paper (Weppner et al. 2003).

Potatoes are one of the most important cash crops in Washington State. Washington is the second largest producer of domestic potatoes, and Washington farmers harvest the world's highest yield per acre (Washington State Potato Commission, 1998). Pesticides are applied to potatoes to increase per acre production. Insecticides in particular are necessary to control aphids and beetles that attack potatoes, and several hundred thousand dollars are spent each year in the state on chemical control of pests (Hinman et al. 2001). Pesticides are present in air during and after aerial and ground applications, sometimes resulting in off-target pesticide movement and potential exposure to workers and individuals near sprayed fields (Clark et al., 1991; Richter et al., 1992). A recent study demonstrated off-site drift as far as 500 meters downwind (Woods et al. 2001). Distance from source, wind direction, and wind speed are primarily responsible for off-target movement (Richards et al. 2001 and Barnes et al. 1987). Ground cover, including human-made structures, also affects drift (Riley et al. 1989).

Studies have identified an association between proximity to sprayed fields and elevated pesticide residues in nearby residences. Simcox et al. (1995), Lu et al. (2000)

and Koch et al. (2002) found decreasing levels of organophosphate (OP) pesticide residues in housedust and yard soil with increasing distance from treated fields. Higher levels of OP pesticide metabolites also were found in urine of young children living in close proximity to orchards where OP pesticides had been applied (Loewenherz et al., 1997, Koch et al., 2002).

Pesticide drift studies have characterized the movement of the pesticide spray using a variety of techniques, including tracer dyes, deposition and air sampling, foliar residues and modeling techniques (Draper et al. 1981; Barnes et al. 1987; Gilbert and Bell 1988; Riley et al., 1989; Clark et al. 1991; Salyani and Cromwell 1992; Woodrow et al., 1997; Garcia et al. 2000; Richards et al. 2001; Woods et al., 2001). Symptoms and health effects attributable to pesticide drift most often have been gathered through questionnaires after an exposure event (Goldman et al., 1987; Ames et al., 1993). Few studies have examined human exposures and environmental sampling when assessing children's potential for exposure to pesticide drift. One factor that has been difficult to measure in the past has been children's time-location and activity level in relation to pesticide drift. One approach that can address this difficulty is tracking children using differentially-corrected global positioning systems (dGPS) technology, a method refined by our group (Elgethun et al. 2003). In this study, children wore a tracking device during waking hours of the entire study, and both time-location and velocity were measured for each child. Velocity can later be normalized and used as a metric of children's relative activity level to modify breathing rate in exposure calculations.

The current study investigated the role of off-target drift as a pathway for human exposure in a nearby community. This study design combined drift characterization with environmental and biological sampling and child time-location and activity data. This study is too complex to be presented in a single paper, and will instead be presented as several related papers. This dissertation chapter focuses on descriptive data for the following: children's time-location and velocity measured by dGPS, off-site deposition patterns, residues on indoor and outdoor residential surfaces, residues on children's hands, and ambient air concentration patterns. This dissertation chapter combines the data presented in a submitted paper (Weppner et al., submitted 2003) with data on children's time location and velocity and with additional appendices and figures as appropriate.

Methods

Site Description and Study Population

The field site was a farm community of approximately 100 residents in east central Washington (Figure 4.1). The terrain is mostly flat surrounding the community for approximately 5 km in all directions. All participating families lived in farm housing surrounded by potato, corn and wheat fields (crops rotated yearly). Participating households were within 800 meters of each other and were within 15 to 200 meters of the nearest treated field.

Location of houses, coordinates of the edges of the sprayed fields, and location of deposition and air samplers were measured using GPS. These GPS coordinates were then mapped and used to inform drift modeling and exposure estimations.

Spray Synopsis

Cultivated potato fields adjacent to the residences were scheduled for aerial application of methamidophos (O, S-dimethyl phosphoramidothioate) at an unspecified date in late July to control green peach aphids. The structure of methamidophos is shown in Appendix 4A. A picture of the potato fields is shown in Appendix 4B. The timing of the pesticide application was dependent upon the aphid pressure and therefore field staff and study participants were informed of the spray day only 24 hours prior to application. According to the farm operator, methamidophos was not applied to neighboring potato crops earlier in the growing season. A single 1340S2R Thrush aircraft with a 400-gallon tank flying at approximately 180 km/hr (110 mph) and a maximum 3 meters (10 feet) above the crop canopy sprayed 5 fields for a total of 700 acres. The aircraft was equipped with 60 ASAE medium-sized whirl jet nozzles (20-22 psi) oriented 180 degrees from direction of flight and 2-3 feet below the wing. The spray boom was located forward of wing and was 75% of the aircraft's wingspan. Swath width was approximately 45 feet. Methamidophos in liquid formulation (40% O, S- dimethyl phosphoramidothioate, 60% inert ingredients, trade name 'Monitor®'), was applied at a rate of 0.45 kilogram (1 lb) active ingredient per acre beginning at 5:00 am on the day of application. The spraying pattern is illustrated in Figure 2 (adapted from Tsai et al., submitted 2004). Four fields located to the north, southwest, west and east of the community were sprayed from 5 am to 9:30 am. Spray was suspended due to wind speeds greater than 8 km/hr (5 mph) at 9:30 am. The wind abated and spraying recommenced in the afternoon at which time the south field was treated. The second spray began at 2:00 pm on the day of application and continued until 3:00 pm.

Fields located to the north, west and east of the community were sprayed while the prevailing wind blew from the south-southwest and fields to the south were sprayed while winds blew from the north-northwest, effectively carrying the primary drift away from the community.

Recruitment of study population

In May, every family in the community was invited to attend an informational meeting/picnic to be held in the playground. A poster and flyer advertising the meeting was posted and put in residents' mailboxes (Appendix 4C). Bilingual staff and researchers were present to explain the study purpose and to answer questions.

Following the community meeting, six families were recruited in to participate in the study. To be eligible for the study, participating families were required to reside in the study community, to stay near or within the community during sampling periods and to have at least one child between 2 and 12 years old living at home. Participating children had to be toilet-trained. Ten children (5 female / 5 male) aged 2-12 years were enrolled. Two participating children dropped out after baseline samples had been collected. Both children did not participate in sample collection during the spray application because they were out of town for the duration of the sample collection period.

Sampling Plan

Sampling was designed to capture potential exposures from a series of aerial applications. The timeframe for sampling and the types of samples collected are presented in Table 4.1. Baseline spot urine samples, housedust samples, and hand and surface wipe samples were collected at the end of May approximately six weeks prior to the first seasonal application of methamidophos. Baseline indoor and outdoor air samples, playground equipment, toy and apple wipes were collected in July, two days prior to the spray.

Indoor and outdoor residential air samples and outdoor community air samples were collected during and following the spray. Outdoor air samplers were set up in the yard of each participant as well as five sites in the community, including one site upwind from sprayed fields. Silica gel chromatography deposition plates were set up throughout the community. Two days after the spray event house dust samples were collected from carpeted living rooms.

Spot urine samples were collected the evening immediately preceding the spray. Complete 24-hour urine voids were collected starting the morning of the spray and three spot urine samples were collected the day following the spray.

Hand wipe samples were collected three to four times a day, at meals and bedtime on the day of and the day following the spray. Playground equipment wipes were collected the evening prior to the spray and twice during the day of the spray. The same playground equipment surfaces and surface areas were wiped each time. Clean plastic balls, 20 cm in diameter, were placed in the yard of each participating household two evenings prior to the spray and were wiped on the day of aerial application following the spray. Apples purchased from local stores were placed in the kitchen of each participating household two evenings before the actual spray event in order to assess the contribution of spray deposition to ingestible food residue.

Interview questions were asked of parents in Spanish or English as appropriate. Parents were asked about home and occupational pesticide use, particularly methamidophos and acephate since acephate degrades in the environment and metabolize in the body to methamidophos. Parents were asked to report their child's hand-to-mouth behavior including eating with hands and the frequency of hand washing.

Each child wore a small geographical positioning system personal acquisition logger (Entertech GPS-PAL) in a vest or pair of overalls during hours they were awake on the day of and the day following aerial application in order to record the time-location paths of participating children. Table 4.1 summarizes the time-location (GPS) and environmental (deposition, air and wipe) sample collection plan for the entire study.

Meteorological Data Collection

Wind speed and direction data were drawn from the Washington State University Public Agricultural Weather System. This system has a measurement station ~2 kilometers south of the study site, and provides data as 15-minute averages. The terrain in this part of the state is flat, and the station's reports were considered a good representation of wind conditions at the study site. Appendix 4D is a photograph of the community playground looking south toward the weather station.

Differential Corrected Global Positioning Systems (dGPS) Instrument: GPS-PAL

One purpose of this study was to use the novel GPS-PAL dGPS instrument to track children's time-location during a pesticide spray event. Our previous work in agricultural communities has suggested that where young children spend their time can play a critical role in how, and to what extent, they are subject to pesticide exposure (Lu et al. 2000). Time-location is not used as a proxy of exposure, rather as a way to map exposures at the intersections between humans and contaminated microenvironments.

Children wore GPS-PALs integrated into nylon vests (see Chapter 2, Figure 2.2). The clothing allowed for proper horizontal positioning of the antenna, and both allowed for secure attachment of the antenna cable inside the garment. The battery and GPS unit were concealed in closed pockets on the front of the garments. Positioning of battery and GPS unit was chosen to minimally encumber normal range of motion. A new design for the GPS-PAL was introduced by the manufacturer right before the start of the spray drift study. The new design was lighter weight due to a plastic rather than metal case, and incorporated the batteries inside the same case as the electronics. Both new and old design GPS-PAL units were used in this field study. For both, the antenna was placed on the top of the shoulder to optimize signal reception. This design allowed research staff to simply hand the clothing to the parent or child, and prevented tampering or instrument removal.

Each child wore a small geographical positioning system personal acquisition logger (Entertech GPS-PAL) in a vest or pair of overalls during hours they were awake on the day of and the day following aerial application in order to record the time-location paths of participating children. Our group has pioneered the use of this technology for monitoring time-activity patterns of children (Elgethun et al. 2003). Of the eleven children originally recruited, eight participated throughout the duration of the spray study. The GPS-PAL was used to record time-location for 3 days: pre-, during, and post-spray. Analysis by GIS (ArcView v.3.2 / ArcGIS v. software) was used to visualize GPS paths and quantify time-location (discussed in *Analytical Methods)*.

The use of the GPS-PAL represents an advance in studying the time-location patterns and activities of children. The GPS-PAL provides high temporal (~5 sec) and spatial (2 m) resolution for continuously recording time-location data of mobile subjects, and has sufficient resolution to distinguish movement between indoor and outdoor environments, or to locate subjects within rooms of a residence. This device offers the advantage that no input or recall on the part of the participant or the parents is required to record activities. In contrast, activity diaries which have been widely used, require high compliance by participants and may not accurately reflect actual activity patterns.

<u>*Personal (human) sample collection*</u>

Hand wipes

Pre-cleaned gauze pads were wetted to near saturation with 10% pesticide grade isopropanol from a spray bottle. One gauze pad was used to thoroughly wipe the palm of each hand and a second pad was used to wipe the palm side of the fingers, so that the entire palm side of the hand was wiped. Both hands were wiped and a total of four gauze pads were used and placed in a prelabeled jar and treated as one sample. If the child was unreceptive to collection of the handwipe procedures, hand wipe samples were not taken at that time. In one case, a parent collected a handwipe sample from his child while researchers observed.

Environmental sample collection

Deposition Samples

Location of deposition plates is shown in Figure 4.6. Silica gel chromatography deposition plates (20 cm x 20 cm) were mounted on stands 25 cm above the ground. Deposition plates were set up along a transect starting near the edges of two potato fields and spaced approximately 15 meters (50 feet) apart. Deposition plates also were set up on a transect along the length of the community soccer field and in participants' yards nearest to one of the sprayed field. Two sets of deposition samples were collected. The first set of plates were set up prior to the application on the north, west, east and southwest fields. The second set of plates was set up prior to application in the south field. Following collection, deposition plates were immediately wrapped in tin foil, placed in ziploc bags and put on ice until transport to the WSU-FEQL.

Playground Equipment wipes

All the gauze pads were purchased from the University of Washington stores (Johnson & Johnson, 3" x 3" 100% cotton) and were precleaned by Soxhlet extraction before field use.

Playground equipment wipes were collected from surfaces on the playground equipment where children are most likely to put their hands. These areas included monkey bar cross bars and side bars, a tire swing, a baby swing, and swing chains. In order to standardize the sampling method, the entire surface area of the equipment (such as the entire surface area of two cross bars on the north side of monkey bar set) was sampled. See Table 4.2 for descriptions and surface area estimations of equipment sampled. Playground equipment wipes were collected from the same surface once prior to and twice following the start of the spray event; approximately 6 hours and 11 hours after aerial application began. Two cotton pads wetted to near saturation with 10% isopropanol were used for to wipe each area.

Community Air Sampling

Five medium and high volume samplers were distributed across the community. Samplers required electricity and were very noisy. This somewhat limited where they could be positioned. Pump numbers 9 and 10 were Staplex medium flow samplers equipped with two polyurethane foam (PUF) cartridges in tandem (split sample) (Figures 4.7 and 4.10). Pump numbers 7 and 8 were Anderson high flow samplers with one PUF cartridge. Pump number 6 was an oil dampened vacuum pump that was positioned upwind approximately 1km from the nearest field (off the map on Figure 4.7). A pre-spray background sample was collected on both 7-10 and 7-11, since the spray was originally scheduled for 7-11. Two spray day samples were collected to prevent breakthrough. As it happened, two distinct spray periods occurred due to changing wind conditions. Thus each of these spray samples were collected during and after the separate spray events. One more post spray sample was collected from the evening of the spray (7-12) to the morning of 7-13. One more sample should have been collected on 7-13, but PUF were expended due to the extra day of background pre-spray on 7-11.

The sampling train for Staplex and vacuum pumps consisted of simple Tygon tubing supported by a metal ring stand, leading to the glass cartridge holding the PUF media. Glass remained with the PUF as a single unit (glass was not reused). Anderson samplers do not require a sampling train. The glass and PUF are enclosed inside a metal housing. Pumps were flow checked at the beginning and end of each sampling period, and mean flow rate was used to adjust sample concentrations. Anderson samplers were calibrated in the field using the attached calibrator, and flows were measured in the field using a magnehelic gauge. Liter per minute (lpm) flow rates were calculated later using atmospheric pressure adjustments as necessary.

PUF cartridges were always handled with new, clean latex gloves. PUF cartridges were sealed in glass jars, and kept in the refrigerator of the mobile lab (RV) at approximately 1C until transport on ice to FEQL in Richland. Samples were not kept at 1C longer than four hours. Samples were extracted upon arrival to the lab, and the extracts frozen at –80C until analysis. See Appendices for further details on the lab procedures.

<u>*Residential sample collection*</u>

Toy and Apple wipes

Wipes samples were collected from pre-cleaned balls (855 cm^2) and pre-cleaned apples (195 cm^2) prior to and following pesticide spray application in order to measure surface contamination of toys, foods and non-flat surfaces due to pesticide drift. Balls and apples were cleaned in warm soapy water, rinsed with distilled water and allowed to air dry in the laboratory prior to transport to the study site. Two days prior to the spray event, all balls and apples were wiped using two clean gauze pads wetted to near saturation with 10% pesticide grade isopropanol, placed into a plastic bag and stored in a cooler with ice until use.

Two nights before the actual spray event, a clean ball was placed in each participant's yard in an area where their child most often stored or played with his/her toys. One ball was placed in a central located soccer field near the community playground. Participating children were asked not to play with or take the ball inside. Toy wipe samples were collected six hours after the spray had begun.

A clean apple was placed on the top of each participant's refrigerator and a small flag was inserted in the apple for identification. It was explained to the participants that the apple would be wiped later to determine if any pesticides had settled on it due to drift from sprayed fields and all participants were asked to avoid touching, playing with or eating the apple. Wipes were collected from the apple surfaces approximately 36 hours after the spray had begun. Toy and apple wipe samples were collected in the same manner as those collected prior to the spray event.

Indoor Residential Surface wipes

Surface wipes were collected from kitchen tables and counters. A 10 cm by 10 cm plastic template was placed on the surface and the outside corners were taped down with masking tape. Two clean gauze pads wetted to near saturation with 10% isopropanol were used to wipe the entire area inside the template. Surface wipes were collected the evening following the spray, 15 hours after the spray began, and the day following the spray, approximately 36 hours after the spray began. Shortly after sampling, wipe samples were brought to the Washington State University Food and Environmental Quality Laboratory (FEQL) in Richland, WA where samples were stored at -15 to -20°C until residue analysis for methamidophos.

Indoor Residence Air Sampling

SKC medium flow pumps equipped with a sampling train identical to that described above were used. Pumps were placed outside the kitchen window of residences, and the Tygon tubing was run through the window, with the PUF cartridge supported on the window sill. Windows were sealed with duct tape around the tubing to prevent outdoor air from entering the houses. Pumps were kept outside to minimize noise pollution for the families. Only one spray sample was collected, since breakthrough was not a concern indoors. PUF were handled and processed as described above.

Outdoor Residence Yard Air Sampling

SKC pumps were used, as described above These are labeled 1-5 in figure 4.10. Pump and sampling train were placed in the participating families' yards in an area where children were known to play. PUF cartridges were 1m from ground level to approximate child breathing space. PUF were handled and processed as described above.

Analytical Methods

GPS download and post-processing

Methods were the same as described in Chapter 2 (2.2), except that the differential correction data were collected from a different CORS station that was closer to the spray drift field site. This station was located in Appleton, WA, approximately 100 km from the field site. Ideally a closer station is desirable, but this is the closest station for that particular section of Washington State.

Geographic Information System(s)-GIS construction and analysis

A new GIS was constructed for the drift field study. ArcView v.3.2 and ArcMap / ArcGIS v.8.3 were used to integrate data and map layers. USGS Digital Ortho Quarter Quads (DOQQs) were obtained as .bil files on CD-ROM from USGS. Resolution of these maps is given as 1 meter. Ortho Quad maps of a more regional scale were also obtained from Microsoft Terraserver website in .jpg format (www.terraserver.microsoft.com) for comparison purposes. Terraserver maps were used to obtain an overview of the region, and were not used in any final maps or analyses.

Laboratory analysis: deposition, wipe and air samples

Development of analytical methods and laboratory analysis of samples were performed by the Food and Environmental Quality Lab, with assistance from the author, at Washington State University, Tri-Cities in Richland, WA.

All samples were transported to the Washington State University Food and Environmental Quality Laboratory in Richland, WA, and stored at -15 to -20°C until residue analysis for methamidophos. All the gauze pads (Johnson & Johnson, 3"x 3" 100% cotton) were pre-cleaned by Soxhlet extraction with acetyl acetate before field use. Each wipe sample (consisting of 2 to 4 gauze pads) or deposition plate was submerged in ethyl acetate and sonicated. Two sequential ethyl acetate extractions of the gauze pads were performed followed by suction filtration. The two suction-filtered solvent extracts were combined. The total solvent extract volume was reduced to just dryness by rotary-evaporation under reduced pressure at 40°C. The sample extract was re-dissolved in ethyl acetate and quantitatively transferred to a pre-conditioned 500-mg carbograph SPE column. The sample extract was eluted using ethyl acetate under slight negative pressure. The sample eluent volume was reduced under nitrogen at 35°C to a desired final volume for residue determination.

Extracted samples were analyzed by gas chromatography employing a Varian Star 3400CX with 8200CX Auto Liquid Sampler using pulsed flame photometric detection (PFPD) in phosphorus mode. A fused silica megabore EC-1 (100% methyl silicone phase), 15 m x 0.53mm i.d.x 1.20 μm film thickness column was used with a flow rate of 10-13.5 mL/min. The PFPD detector temperature was set at 310°C. Injector port temperature was programmed from 200°C to 250°C at 250°C per minute. Oven temperature was programmed to increase from 80°C to 270°C at 20°C per minute and hold at a final temperature for five minutes. Injection volume was 2 μl.

Data was considered to be acceptable if variation between bracketed single point calibration standards was < 15% (averaged during run) and linearity as measured by the regression r^2 was > 0.995. A limit of quantitation (LOQ) for wipes and deposition plates was established based on the lowest reproducible level of quantification to be 0.1 μg per sample with an estimated limit of detection (LOD) of 0.02 μg per sample (~4X of the background chromatographic signal). The limit of quantification for air samples (PUF) was 0.10ug per PUF, and the limit of detection was 0.02 ug per PUF.

Recoveries of methamidophos from gauze pads, deposition plates and PUF were determined by fortifying the sample media with a known amount of methamidophos. Analytical sets usually consisted of 6 to 8 wipe samples followed by 2 quality control (QC) samples and 4 to 6 deposition or PUF samples followed by 2 QC samples. Blanks (pre-cleaned gauze and non-fortified deposition plates and PUF) were also extracted and analyzed per analytical set to serve as background controls.

Gauze wipes were routinely fortified with 0.1 to 20 μg of methamidophos during residue analyses. Average fortified percent recovery for wipes was 101 $\pm$ 13%. Average fortified percent recovery for silica gel deposition plates was 81 $\pm$ 8 %.

Average fortified percent recovery for PUF was 91 $\pm$ 8 %. No detectable residues were recovered from blank samples. Residues detected above the LOD but less than the LOQ are reported but are not quantified.

Statistical Analysis

Parametric and non-parametric tests were performed to determine if post-spray environmental, house, and indoor samples were significantly different from baseline values. Mann Whitney U tests were used to compare intraindividual hand wipe values and urine values (for each child). Mann Whitney U test were also used to compare air samples by individual pump, which is the same as individual residence for residential samples. Wilcoxson Rank Sum tests were used to compare playground deposition values on the same surfaces before, during, and after the spray event and to compare air concentration values before, during, and after the spray event.

Results

GPS/GIS Time-location

See Figure 4.1 for a detailed map of the community and surrounding fields. All data presented here are for the spray day and the day after. Children's total time spent outside, by child, is shown in Table 4.4. Children's linear velocity (a metric of activity level) is summarized in Tables 4.3 and 4.4. Children spent an average of 22 minutes longer (14 % more time) outside on the day after the spray compared to the spray day. However, some individual children spent more time outside on the spray day than on the day after (Tables 4.3 and 4.4). On the day after the spray, GPS paths of 6 of the 8 children showed they congregated in one location in a field on the southeast side of the community (>150 m from the nearest upwind sprayed field) for about 1.5 hours, possibly for a picnic or birthday party.

Children's linear velocity, as measured by GPS, was slightly higher on the spray day than on the day after the spray. Differences by day were not statistically significant. From this information, activity level of children can be determined. This will be discussed and applied in Chapter 5. Data was collected for two children traveling in a car on the spray day. These children were taken by a parent to a neighboring community for several hours while the spray was occurring. Three other children were seen to travel several miles away from the community, but their paths were not logged during transit. GPS reception is often blocked in vehicles due to the shielding properties of metal (the Farraday Cage effect). Logically, children must have been transported via a vehicle. The GPS time log backs this assertion. There was approximately 15 minutes between the last logged GPS point in the community, and the next logged GPS point in the other community. This trip is approximately 12 miles. An approximate velocity for this vehicle trip is thus 48 miles per hour.

Detailed maps showing children's paths overlaid on orthophoto maps are shown in Appendices 4F through 4BB. Each individual dot represents a sampled time-location. The dots are color-ramped to show the gradient of time of samples throughout the day. Large regional maps are shown for children who left the community, in addition to community area maps. The first set of maps shows time-location throughout the day. The second set of maps has color-ramped dots that show the linear velocity of each child throughout the day. Time spent on bicycles, for those children who rode bicycles, is separated from time on foot.

Wind Data

Figure 4.2 (adapted from Tsai et al., submitted 2004) is a scale diagram of the community and surrounding fields showing the order and direction the spray was applied by the crop duster. Also shown is the prevailing wind direction during the time each field was sprayed. Figure 4.3 (adapter from Weppner et al., submitted 2003) illustrates wind direction, magnitude and frequency with a wind stick graph during and after application. Figure 4.4 illustrates the same winds with a wind rose plot. During the morning spray period winds were generally from the south-southwest. Wind direction shifted between 9:00 and 10:00 am, and winds were from the north-northwest for the rest of the day. Fields located to the north, west and east of the community were sprayed while the prevailing wind blew from the south-southwest, and fields to the south were sprayed while winds blew from the north-northwest, effectively carrying the primary drift away from the community in each case. Figure 4.5 shows winds on the day after the spray (7-13-02). Overall trends are similar, though the wind blew more toward the community from the direction of the southern treated field on this day.

Deposition Samples

The locations of deposition plates are plotted on an aerial photo (Figure 4.6, adapted from Weppner et al., submitted 2003), and methamidophos residues found on deposition plates are summarized in Table 4.6. Plates 1-10 were placed along the edge of the community's park, 68-75 meters from the North field, and 217-325 meters from the South field. Plate 11 was placed one meter inside the North field. Plates 12-22 were placed in a line extending from several of the homes to the edge of the East field, with Plate 22 placed one meter inside the East field. Morning deposition plates were set up at 5:30 am and were in the field for approximately 6 hours. Afternoon plates were set up between 12:00 and 1:00 pm and remained in the field approximately 5 hours.

Mean plate loading following morning application of methamidophos on fields north, west and east of the community was 12.8 ng/cm^2 for plates 1-10 and 24.4 ng/cm^2 for plates 12-21. Plates 11 and 22, in contrast, had substantially higher deposition levels (7990 and 20400 ng/cm^2, respectively). Mean plate loading after the afternoon application on the field south of the community was 10.3 ng/cm^2 for plates 1-10 and 1.47 ng/cm^2 for plates 12-21. Residue level on Plate 11 was substantially higher (77.9 ng/cm^2) than levels on Plates 1-10. Residues on Plate 22 were also higher (5.3 ng/cm^2) than levels on Plates 12-21.

Playground Equipment wipes

All pre-spray playground equipment wipes had low but measurable methamidophos residues (Table 4.2). Median playground equipment concentrations at baseline, and 6 and 11 hrs following the start of application were 0.04, 0.57 and 1.04 ng/cm^2, respectively.

Methamidophos residues on playground equipment were significantly higher than pre-spray levels at both 6 hours and 11 hours after aerial application began ($p=0.04$ in each case, Wilcoxon Signed Rank test). No significant difference was found between playground equipment samples at 6 hrs and 11 hrs.

Toy, Apple and Indoor Surface Wipe Samples

No detectable methamidophos residues were found on pre-spray toy samples (Table 4.6). Three of the six post-spray toy wipe samples had measurable methamidophos, with one sample at detectable residues below the LOQ. Concentrations ranged from 0 to 0.37 ng/cm^2 with a median concentration of 0.14 ng/cm^2. One toy that was found inside the home was reported by parents to have been inside the home for the duration of the spray, and so was not included in the data set. There were no detectable residues in any of the apple wipe samples, or in any of the indoor residential surface wipe samples.

Child hand wipe samples

Participating residences are shown in Figure 4.7. Occupants of residence 2 left town for vacation midway through the study, and these data were not included in analyses. None of the pre-spray hand wipes contained detectable methamidophos, except for one sample in which the level was above the LOD but below the LOQ (Table 4.7). Sixty-two percent of the hand wipe samples collected after baseline had measurable methamidophos residues; approximately 44% these were below the LOQ but above the LOD. One hand wipe sample contained methamidophos levels 10 times higher than the median of the hand wipe samples, and was considered an outlier. This sample was collected by a parent in privacy at their child's request. It was not possible to determine if this sample had been handled properly, so it was excluded from statistical analysis.

Table 4.7 summarizes methamidophos residues from children's hand wipes both by sampling time and as daily sums for each child. We attempted to collect a total of seven hand wipe samples from each child during the field study. Three children were absent during one sampling event, and one of the three children declined two sampling events by research staff. Differences in total samples collected per child should be taken into consideration when comparing cumulative hand residues. The median value for each sampling event was either between the limit of detection and the limit of quantitation, or was non-detectable. Hand wipe levels were plotted by collection time to illustrate change over the two sample days (Figures 4.8 and 4.9). Figure 4.8 illustrates the assumption made that residues were completely removed from hands at each hand wipe event. It was also assumed that collection on hands was linear, and that no other washing events occurred in between samples. The sum of methamidophos residue removed from children's hands are presented on the right side of Table 4.8. The maximum cumulative methamidophos residue found on a child's hands on the day of the spray was 0.49 μg (n=3). The same child had the maximum cumulative post-spray residue of 0.30 μg (n=3). A total of seven hand wipe samples were attempted during the field study.

Samples collected at 4 pm and 8 pm on the spray day, and at 1 pm on the post-spray day were significantly higher than baseline samples (p=0.006, p=0.026 and p=0.017, respectively; Mann-Whitney test). The median values for all hand wipe samples collected on the spray day and on the post-spray day were 0.06 and 0.04 μg/sample, respectively. These levels were significantly higher than baseline levels (p=0.008 and p=0.031 respectively, Mann-Whitney tests), but were not significantly different from each other.

Air Samples

Arrangement of community and residential air samplers is shown in Figure 4.10. Samplers 1-5 were in the yards of participating residences. Samplers 6-10 were in public places. Data from air sampling conducted in and near the community are shown in Tables 4.8 and 4.9 and in Figures 4.11 and 4.12. Two residential yard air samples and 2-3 community air samples were collected on the spray day to prevent overloading and subsequent breakthrough of the sampling media (PUF). Several of the residential samplers were closer to the treated fields than the community samplers. The range of spray day pesticide concentration was notably higher for the residential samplers. Several of the residence yards were very close to the nearest upwind treated field (NUTF), within 10-20m. The NUTF was the field labeled 'North field' in Figures 4.6, 4.7 and 4.10. Nearest upwind treated field (NUTF) comparisons are made from the location of the child, object or residence to the nearest edge of the circular field.

Two of the community samplers consisted of one pump with two separate PUF cartridges in tandem (Table 4.9). These 'split samples' allowed for internal comparison of sampling consistency at a single location. In Figure 4.11, community Pre1 and Pre2 samples were combined into one category. Likewise community Post1 and Post2 samples were combined into one category. This allows for comparison over comparable time periods between the community and residential yard outdoor air samples.

The highest residential yard air sample was 0.984 ug/m3 at residence #4 during the Spray 2 period. The lowest non-baseline residential yard air sample was 0.062 ug/m3 at residence #5 during the Post spray period. The highest community air sample was 0.678 ug/m3 at pump #10 during the Spray 2 period. The lowest non-baseline community air sample was 0.002 ug/m3 at pump #6 during the Post spray period.

For all outdoor air samplers, air concentration followed the trend of increasing from baseline on the spray day, then decreasing during the evening, night and morning following the spray. All spray and post-spray samples were higher than baseline. For the community values, these differences were statistically significant (Wilcoxon signed rank, $p < 0.05$). The residential samplers captured the trend of higher concentration in the afternoon and early evening compared to the morning of the spray day. The community sampler furthest from the NUTF (#6, 1.5 km upwind) had the lowest concentration during and post spray. Spray and post-spray concentrations from community air samplers close to residences (samplers #7-10) were all significantly higher than the upwind sampler (#6) (Mann Whitney U, $p<0.05$). The community air sampler (#10) closest to the NUTF had the highest concentration during and post spray. The other samplers had concentrations proportional to their proximity to the NUTF except #9. . There were no trees or houses between this sampler and the NUTF to block drift. A proximity trend was also evident in the residential yard samples. Residence 4 was closest to the NUTF (less than 10 m away) and had the highest air concentration during and after the spray (Figure 4.12, Table 4.8). There were no trees or fence between this yard and the NUTF.

Residence 3 (the second highest yard concentration) was within 20 m of the edge of the NUTF, but was shielded by dense trees. Residences 1 and 5 were duplexes on the other side of the community at a distance of approximately 300 m from the edge of the NUTF.

Indoor air concentration ranged from non-quantifiable to above the LOQ by a factor of 1-2 (Table 4.10). Thirty percent of samples were non-quantifiable. During and post spray samples were not significantly different from baseline (Wilcoxon signed rank, $p>0.05$), and indoor air samples were at concentrations of 1×10^7 or more lower than any outdoor samples during the spray and post spray periods.

Discussion

Rationale for farmer interest in the study

Despite assurance of anonymity, farmers would likely be wary of participating in such a study. It is clear that pesticide drift onto human living areas carries a certain liability that farmers would not find desirable. However, in 2001, EPA proposed new label statements that could essentially ban any and all drift, a requirement known by agriculturalists to be essentially impossible. Appendix 4E contains a summary of the document "Draft Guidance for Pesticide Registrants on New Labeling Statements for Spray and Dust Drift Mitigation" (EPA, 2001). Researchers in this study were able to go to a large commercial farm corporation and offer them the opportunity to help generate and share data that would show realistically what drift occurs from a conscientious aerial spray. The farm corporation agronomist and the field manager both agreed that such a demonstration could show EPA that a requirement of no drift was unrealistic and unfair. The comment period for this legislation generated such a maelstrom of controversy that the no drift regulation was abandoned in favor of the less restrictive 'minimize drift to sensitive areas' shortly after this study was conducted.

dGPS (GPS-PAL) Sampler Data

Time spent outside and activity measured by velocity are shown in Tables 4.3 and 4.4. Children spent varying amounts of time outside on both days. Some children spent more time outside on the spray day than the day after, which was surprising (Child 1, 2, 4 and 6). In particular, Child 2 and Child 4 spent proportionally more time outside on the spray day than on the day after the spray. Children 7 and 8 (who are siblings) had parents at home that advised them not to go outside (as they told us), because they said they knew the spray could be harmful. When asked if they were behaving differently because researchers were present, these parents said no. Children who went outside on the spray day may have been told to stay inside, but were not supervised. Not all parents were home during the spray.

Children also varied in their activity level, as measured by linear velocity from the GPS. Older children were active outside for longer periods of time, while younger children had shorter bursts of speed. The two children who rode bicycles were seen riding, thus we knew to account for this. However, it was apparent from the map of the GPS path that the velocity was consistently too fast for foot travel, so a researcher need not know this a priori.

Deposition

Methamidophos residues found on deposition plates, playground equipment, toys, and children's hands confirmed that drift occurred in this community following aerial application. The most striking finding from these samples, however, was the disparity between residue levels on samples placed just within the boundaries of the treated fields compared to levels on adjacent samples outside the treated areas. The residue level from the North field sample was nearly three orders of magnitude higher than levels on deposition plates approximately 70 meters from the field (7990 vs. 12.8 ng/cm^2). Similarly, the residue level measured in the East field was more than a thousand times higher than the level measured 15 meters from the field boundary (20400 vs. 20.3 ng/cm^2). These data indicate that the aerial application was very well controlled, and that nearly all of the material applied reached the targeted fields, at least along those boundaries where measurements were taken. It is not clear whether the presence of our field investigation team had an influence on the data collected.

However according to the farm operator, the pilot scheduled for the aerial application observed our field sampling apparatus from the air and chose to return to base. The application did not commence until the next day.

Hand Wipes.

The source of methamidophos found on participants' hands is not known, but the absence of methamidophos on indoor surfaces suggests that exposure occurred outdoors. The increase in methamidophos residues on playground equipment following the spray suggests greater opportunity for children to come in contact with pesticides when playing outdoors within 12 hours of an application. Detectable residues found on three of six toys placed outside during the spray also suggests an increased opportunity for children living near treated fields to come in contact with applied pesticides following a spray event.

The data reported – surface residue and hand exposure levels – do not represent a complete picture of the exposure opportunity for the study children, and are insufficient to estimate risk. Chapter 5 reports a more holistic dermal exposure assessment using modeled deposition values (calibrated from data shown here) coupled with the GPS time-location and activity data presented here. While not much more can be said about hand loading in Chapter 4, in Chapter 5, hand loading values play in important role because they are used to calculate a surface-to-dermal transfer rate for this cohort.

Several studies have indicated that exposure to contaminants can occur from ingestion of foods that have come into contact with indoor surfaces (Akland et al.

2000; Cohen-Hubal et al. 2000; Melnyk et al. 2000.) Although we did not find methamidophos residues on surfaces inside homes, one recent study of propanil drift from rice fields to homes less 150 meters away found detectable levels of propanil on sampling surfaces within 3 of 4 houses where the prevailing wind direction was toward the home (Richards et al. 2001). The investigators noted differences in home integrity (i.e., open windows, drafts through the walls) and travel in and out of the houses that may have allowed residues to enter the home. In the current study, participants in all six homes kept their doors and windows closed and had air conditioners operating throughout the spray and post-spray day due to extreme temperatures (average afternoon temperatures during the spray day and post-spray day were 102.5°F and 101°F). It was also observed that the children in the study spent most of their time indoors on these days.

Air Samples

The NUTF was the field labeled 'North field' in Figures 4.6, 4.7 and 4.10. NUTF is used as a proximity reference for two reasons. First, it is much closer to residences and areas where children played than any other field (within 5-10m of some homes versus 150-200m for the other two fields). Second, winds blew more frequently toward the community from this field than from any other direction during and post-spray on 7-12-02 and 7-13-02 (Figures 4.3-4.5). Outdoor air sample concentration was clearly affected by two factors: proximity and land cover. Areas in which no trees, buildings, fence or other structures existed between the air sampler and the NUTF are expected to receive more drift. Land cover often influenced magnitude of concentration, but not rank of samplers, except in one case. Community sampler #9, which had downwind line-of-sight to the NUTF, had a slightly higher spray and post-spray concentration than samplers #7 and #8 which were about 80m closer to the NUTF but protected by trailer homes, trees, and a storage shed (Figure 4.10). Proximity alone determined rank for the remaining community and residential yard samplers. Residence #3 was most proximal and most exposed (least landcover), and had the highest air concentration during and post spray. Residence #5 was the furthest away from the NUTF, and had the lowest air concentration during and post spray.

As expected, concentration increased from baseline and peaked on the day of the spray, then declined during the evening, night, and early morning post-spray period. It is known from modeling of volatilization that the air concentration would have increased again during the daylight hours on the following day (Ramaprasad et al., submitted 2004). Air temperatures were in excess of 30 C for all days sampled. Methamidophos becomes highly volatile at such temperatures, with a vapor pressure of $3x10^{-4}$ mm Hg (Extoxnet 2004). Between 30 and 40 C, methamidophos vapor pressure increases approximately 300 fold. Temperatures approached 40 C for several hours on both the day of the spray and the day after. Regrettably, no sampling was possible on this day since sampling media were expended on the day when the spray was supposed to occur but did not.

Indoor air concentrations were remarkably low throughout the study period. Residents of the community kept their houses closed up during the spray day because they knew the spray was going to happen, and because of the extreme heat in the afternoon on both days. Air conditioner units were running on high in all houses observed; this re-circulates the indoor air and does not draw any fresh air from outside.

Conclusions

Results from this field study demonstrate that children were outside and active at the time and location where pesticide was present near the community, and results show that off-target pesticide drift did occur during application. It is apparent that the application was well executed as demonstrated by the large difference between in-field deposition and deposition as sites approximately 70 meters from the edge of the fields. This spray could serve the participating farm company as a realistic example of what drift will occur from such an application should they want to provide the data to EPA. The 'no drift' label statement was overruled in 2002 not long after the sampling took place.

This study is pioneering for two reasons. It is the first spray drift study to perform a rigorous exposure assessment of people in a community with high potential for drift. It is also the first exposure study to successfully apply dGPS tracking to generate high resolution time-location and velocity measurements of children.

The source of dislodgeable methamidophos residue was determined to be an outdoor source since all detectable residues were found on outdoor surfaces and none were found on indoor surfaces. This finding suggests that the opportunity for pesticide ingestion would likely be greatest when children are playing, handling food or eating outdoors.

Cumulative methamidophos residues found on children's' hands do not suggest an acute health hazard. However these residues are only a portion of potential exposure since 24 hour hand wipe sample collection was not feasible and should be viewed as such.

Methamidophos concentrations in outdoor air were influenced by proximity to nearest upwind treated field, and by land cover (i.e. the presence of buildings, fences, and trees). Methamidophos in outdoor air increased during the spray day, and decreased during the evening, night and early morning following the spray. Outdoor air concentrations were highest in the heat of the afternoon, suggesting the contribution of volatilization to measured concentration. Methamidophos is relatively volatile (~0.009 mm Hg) at temperatures observed during the afternoon hours, and can leave the target crop and be blown into a community many hours after application.

Very little methamidophos was found in indoor air, and none was found on indoor surfaces. It appears that keeping homes closed up and running the air conditioning on a re-circulate setting is an effective barrier against drift entering the home.

Table 4.1. Sample collection schedule for baseline and application (adapted from Weppner et al., submitted 2003).

SAMPLE TYPE	MAY BASELINE	JULY APPLICATION		
		Pre-application	*Application day*	*Post-application day*
GPS tracking	One hour	Evening hours	All waking hours	All waking hours
Hand wipes	One per child		Three per child	Four per child
Surface wipes	One per home			One per home
Toy wipes		One per home	One per home	
Apple wipes		One per home		One per home
Play ground wipes		One per area (5 total)	Two per area (10 total)	
Deposition samples		5 targets	2 sets of 22 targets (AM and PM)	
Indoor air samples		Two per home	One per home	One per home
Residential yard air samples		One per home	Two per home	One per home
Community air samples		One or two per location	Two per location	One or two per location

Table 4.2. Playground equipment samples: surface area and methamidophos loading.
(adapted from Weppner et al., submitted 2003).

DESCRIPTION	MATERIAL	SURFACE AREA cm^2	CONCENTRATION ng/cm^2		
			Prespray	Morning spray (11 am)*	Afternoon spray (4 am)*
Two cross bars on monkey bars	painted metal	1122	0.24	2.09	2.00
Three cross bars and two side bars on monkey bars	painted metal	3395	0.04	0.57	1.04
Entire top surface of tire swing	rubber	3098	0.03	0.36	0.98
Baby swing handles (20 chain lengths) and seat	unpainted metal and rubber	724	0.10**	2.96	5.10
Entire side bar on east of monkey bars	painted metal	5069	0.04	0.38	0.32
Median			0.04	0.57	1.04

*Morning and afternoon spray concentrations were statistically significantly different from pre-spray concentrations; Wilcoxon signed rank
**This value is less than the LOQ and greater than the LOD, therefore considered non-quantifiable.
LODs and LOQs varied for each playground equipment sample due to differing surface areas.
LODs ranged from 0.006–0.03 ng/cm^2, LOQs ranged 0.02–0.15 ng/cm^2

Table 4.3. Activity level measured as linear velocity of children (m/sec) and total time spent outside (min)

		Spray Day		Day After Spray	
		Velocity	Time Outside	Velocity	Time Outside
Child 1	On Foot				
(5 yo F)	*Mean*	0.34	199	0.20	173
	Range	0-4.82		0-5.00	
Child 2	On Foot				
(5 yo M)	*Mean*	0.18	251	0.10	76
	Range	0-3.53		0-1.69	
Child 3	On Foot				
(8 yo M)	*Mean*	0.40	148	0.25	223
	Range	0-4.83		0-4.52	
Child 4	On Foot				
(2 yo M)	*Mean*	0.44	84	0.53	45
	Range	0-4.84		0-4.99	
Child 5	On Foot				
(11 yo M)	*Mean*	0.71	169	0.56	224
	Range	0-6.91		0-5.01	
	On Bicycle				
	Mean	2.34		1.85	
	Range	0-9.57		0-9.76	
	In Car				
	Mean	17.75		nd	
	Range	0-27.93		nd	
Child 6	On Foot				
(10 yo F)	*Mean*	0.50	207	0.37	181
	Range	0-5.63		0-4.97	
	On Bicycle				
	Mean	1.72		2.03	
	Range	0-5.78		0-5.52	
	In Car				
	Mean	18.52		nd	
	Range	0-30.69		nd	
Child 7	On Foot				
(4 yo F)	*Mean*	0.31	19	0.22*	179*
	Range	0-3.66		0-5.02*	
Child 8	On Foot				
(7 yo F)	*Mean*	2.18	28	0.22	179
	Range	0-4.50		0-5.02	

*Child 7 uses Child 8 (sister) data as surrogate for day after spray. Child 7 data incomplete due to GPS malfunction. Sisters spent majority of time together on this day.

Table 4.4. Activity level (by mode of locomotion) measured as linear velocity of all children (m/sec) and total time spent outside (min)

	Spray Day		Day After Spray	
	Velocity	Foot + Bicycle Time Outside	Velocity	Foot + Bicycle Time Outside
On Foot				
Mean	0.68	138	0.32	160
Range	0-4.95		0-4.46	
On Bicycle*				
Mean	2.03		1.94	
Range	0-7.68		0-7.64	
In Car*				
Mean	18.14		nd	
Range	0-29.31		nd	

N=8

*GPS measurement for 2 children only

Mean total time outside for all children NOT significantly different by day ($p<0.05$)

Table 4.5. Deposition target loading and distance from nearest sprayed field

Location	MORNING SAMPLES* Distance to the nearest sprayed field (m)	MORNING SAMPLES* Loading (ng/cm^2)	AFTERNOON SAMPLES* Distance to the nearest sprayed field (m)	AFTERNOON SAMPLES* Loading (ng/cm^2)
1	77 [a]	12.6	217 [c]	6.80
2	76 [a]	8.50	229 [c]	16.0
3	74 [a]	12.5	241 [c]	8.30
4	72 [a]	13.4	253 [c]	8.60
5	70 [a]	3.40	265 [c]	11.3
6	68 [a]	15.4	276 [c]	10.1
7	68 [a]	15.6	288 [c]	12.2
8	70 [a]	16.8	300 [c]	12.1
9	70 [a]	14.1	312 [c]	9.50
10	73 [a]	15.4	325 [c]	7.60
11	0 [a]	7990	372 [c]	77.9
12	179 [b]	25.5	374 [c]	2.50
13	134 [b]	10.7	381 [c]	1.50
14	131 [b]	8.10	401 [c]	1.60
15	107 [b]	9.90	412 [c]	1.30
16	91 [b]	14.0	429 [c]	1.30
17	76 [b]	115	445 [c]	1.30
18	61 [b]	11.3	462 [c]	1.10
19	46 [b]	12.5	479 [c]	1.90
20	30 [b]	16.7	495 [c]	1.10
21	15 [b]	20.3	512 [c]	1.10
22	0 [b]	20400	529 [c]	5.30

*Morning samples were in the field for average duration of 6 hours 45 min. Afternoon samples were in the field for an average duration of 5 hours.

Distance measured from [a]North field, [b]East field, and [c]South field using GPS coordinates. Deposition plates #11 and #22 were placed 1 meter inside the sprayed field. LOD=0.05 ng/cm^2, LOQ=0.25 ng/cm^2

Table 4.6. Toy ball samples: location and methamidophos loading (adapted from Weppner et al., submitted 2003).

LOCATION		LOADING (ng/cm^2)	
Where placed	Where found	Baseline	Post spray
Front yard	Inside home	nd	nd
Side yard	Side yard, in sprinkler	nd	0.11*
Back yard	Backyard	nd	0.37
Side yard	Side yard	nd	0.19
Side yard	Side yard	nd	nd
Playground	Playground	nd	0.14
		*Median Concentration***	
		nd	0.14

*This value was above the LOD and below the LOQ and therefore considered non-quantifiable.
**Median is based on n=5, the toy ball that was found indoors was not used in median calculation
LOD = 0.02 ng/cm^2, LOQ = 0.12 ng/cm^2; Nondetectable residue (nd) < LOD
Toy ball surface area = 855 cm^2

Table 4.7. Methamidophos residues from children's hand wipes by sampling time and as daily sums for each child
(adapted from Weppner et al., submitted 2003)

SAMPLE TIME	N	MEDIAN µg/sample	MAXIMUM µg/sample	ND**	CHILD ID	N	SUM OF APPLICATION DAY SAMPLES µg/child	N	SUM OF POST APPLICATION DAY SAMPLES µg/child
Baseline	8	nd	0.05**	7	1-1	3	0.14	4	0.05
Spray 11 am	7	0.04**	0.09**	3	3-1	3	0.28	4	0.18
Spray 4 pm*	7	0.06**	0.15	1	3-2	3	0.23	4	0.22
Spray 8 pm*	8	0.09**	0.30	3	4-1	1	0.28	3	0.17
Post spray 9 am	8	0.03**	0.09**	4	4-2	3	0.49	3	0.30
Post spray 11 am	8	0.02**	0.12	4	4-3	3	0.16	3	0.07
Post spray 1 pm*	8	0.05**	0.10	2	5-1	3	0.03	4	0.07
Post spray 3 pm	5	nd	0.09**	3	5-2	3	0.00	4	0.09
All Spray	22	0.06**	0.30	7					
All Post Spray	29	0.04**	0.12	13					

*Statistically signicantly different from baseline concentrations ($p<0.05$), Mann Whitney
**These values were above the LOD and below the LOQ and therefore considered non-quantifiable.
LOD=0.02 µg/sample, LOQ=0.10 µg/sample; Nondetectable residue (nd) < LOD

Table 4.8. Residential yard air sample concentrations (ug/m3)

Residence #	Child(ren)	Period	Stop Time	Elaspsed Time (min)	Mass (ug)	Concentration (ug/m3)
1	1	pre	17:20	450	1.31	0.121
		spray1	10:45	325	0.63	0.076
		spray2	17:20	395	2.37	0.240
		post	21:55	275	0.27	0.041
3	2,3	pre	16:50	525	0.32	0.025
		spray1	11:00	350	1.67	0.183
		spray2	17:10	370	4.57	0.475
		post	21:40	270	1.56	0.241
4	4,5,6	pre	16:55	425	0.27	0.030
		spray1	10:52	337	3.20	0.442
		spray2	17:15	383	7.16	0.984
		post	21:50	275	1.26	0.191
5	7,8	pre	17:25	455	0.30	0.026
		spray1	10:40	315	0.83	0.110
		spray2	17:25	405	1.52	0.156
		post	22:02	277	0.41	0.062

LOQ = 0.10 ug/PUF
LOD = 0.02 ug/PUF
Limits are per sample

Table 4.9. Community air sample concentrations (ug/m3)

Sampler #	Period	Stop Time	Elaspsed Time (min)	Mass (ug)	Concentration (ug/m3)
6	pre2	21:05	645	0.14	0.006
	spray1	09:55	325	0.30	0.026
	spray2	17:55	480	nq	nq
	post	07:00	785	nq	nq
7	pre1	04:30	303	5.60	0.070
	pre2	16:30	400	5.20	0.049
	spray1	10:28	298	5.53	0.070
	spray2	16:10	332	30.95	0.364
	post1	21:20	308	8.34	0.111
	post2	09:00	700	13.29	0.075
8	pre1	04:30	305	2.49	0.036
	pre2	16:30	400	5.22	0.058
	spray1	10:25	295	5.68	0.085
	spray2	16:05	330	42.97	0.584
	post1	21:15	308	10.54	0.153
	post2	09:00	705	15.56	0.100
9	pre(A)	16:30	395	0.33	0.032
	pre(B)	16:30	395	0.40	0.044
	spray1(A)	10:20	300	0.94	0.139
	spray1(B)	10:20	300	1.00	0.148
	spray2(A)	16:15	345	2.82	0.341
	spray2(B)	16:15	345	3.30	0.399
	post(A)	09:00	1000	1.23	0.056
	post(B)	09:00	1000	3.46	0.157
10	pre(A)	16:30	405	0.45	0.043
	pre(B)	16:30	405	0.55	0.062
	spray1(A)	10:10	280	2.03	0.269
	spray1(B)	10:10	280	2.15	0.301
	spray2(A)	16:00	300	5.29	0.678
	spray2(B)	16:00	300	5.22	0.621
	post(A)	09:10	1000	2.46	0.089
	post(B)	09:10	1000	1.50	0.057

Samplers 9 and 10 utilized tandem split sampling technique. 'A' & 'B' indicate tandem samples taken at the same time using the same pump.

LOQ = 0.10 ug/PUF
LOD = 0.02 ug/PUF
Limits are per sample

All spray and post samples are significantly different from pre samples (Wilcoxon signed rank, $p<0.05$)
Sampler 7, 8, 9 and 10 (in community, near fields) are significantly different from sampler 6 (upwind from fields) (Mann Whitney U, $p<0.05$)

Table 4.10. Indoor air concentrations (ug/m3)

Residence #	Child(ren)	Period	Stop Time	Elaspsed Time (min)	Mass (ug)	Concentration (ug/m3)
1	1	pre1	5:24	719	0.20	1.63 x 10-8
		pre2	17:22	657	nq	nq
		spray	21:55	995	nq	nq
		post	8:30	635	0.14	8.65 x 10-9
3	2,3	pre1	5:30	740	0.44	3.13 x 10-8
		pre2	16:53	620	0.12	9.44 x 10-9
		spray	21:40	990	0.39	2.13 x 10-8
		post	9:00	680	0.14	1.18 x 10-8
4	4,5,6	pre1	5:28	748	0.28	1.53 x 10-8
		pre2	16:45	605	0.15	9.54 x 10-9
		spray	21:50	995	0.45	1.77 x 10-8
		post	8:40	650	0.30	1.68 x 10-8
5	7,8	pre1	5:28	530	0.12	9.24 x 10-9
		pre2	17:05	640	0.12	7.75 x 10-9
		spray	22:02	997	nq	nq
		post	8:30	628	nq	nq

LOQ = 0.10 ug/PUF
LOD = 0.02 ug/PUF
Note that these are per sample

Spray and post samples are not significantly different from pre1 or pre2 samples (Wilcoxon signed rank, $p>0.05$)

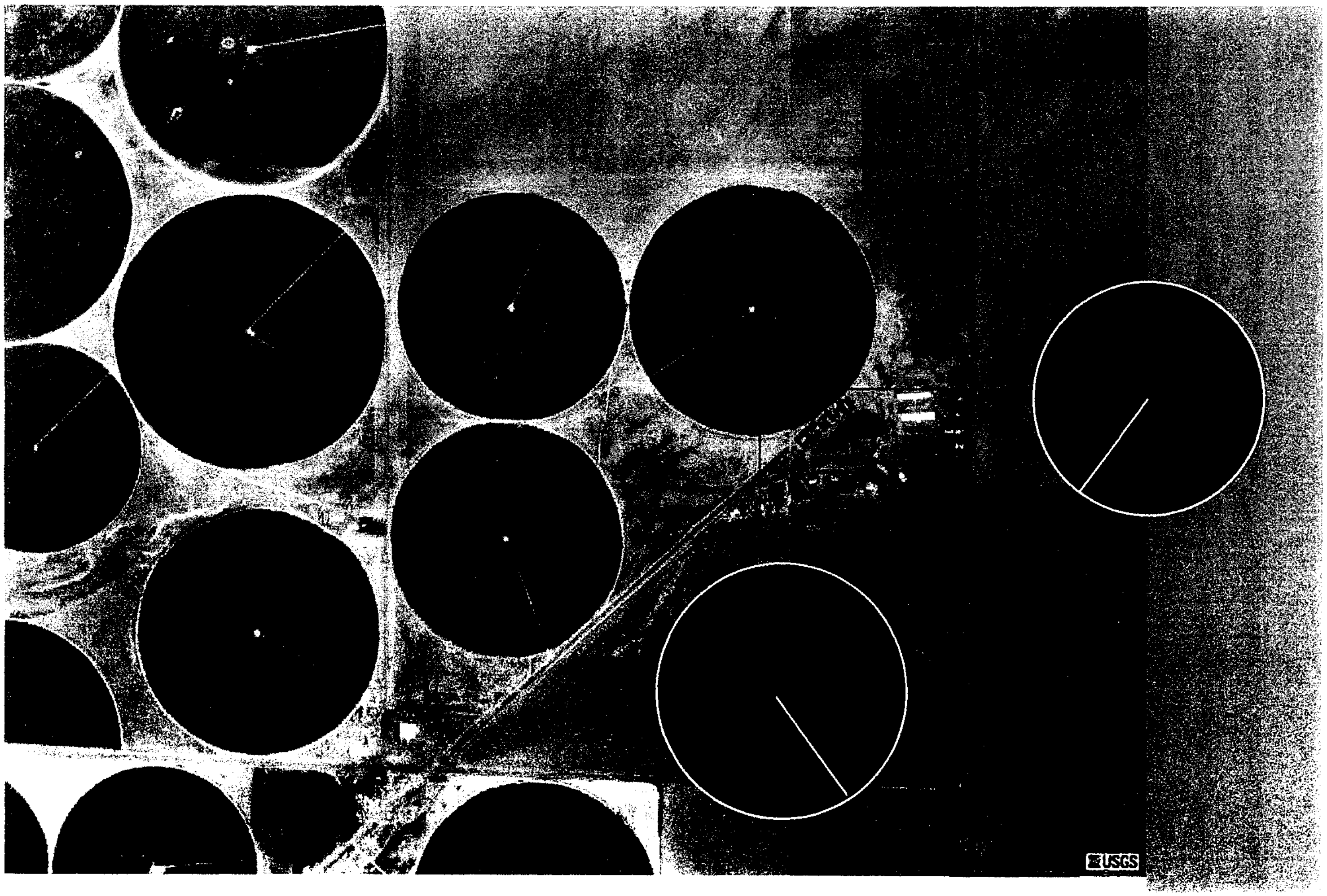


Figure 4.1: Regional aerial photo map showing the study site

Figure 4.2. Application map showing order of spray and wind direction for community and surrounding fields
The deposition samplers are numbered 1-22 and are indicated by circles within the grid area. The community area is indicated by the smaller rectangle within the grid area. There are five potato crop circles: SW, W, N, E, and S. The arrows indicate the initial 15-minute wind direction when spraying began on that particular field. The letters A-Q represent 15-minute swathes that were laid by the plane (adapted from Tsai et al., submitted 2004).

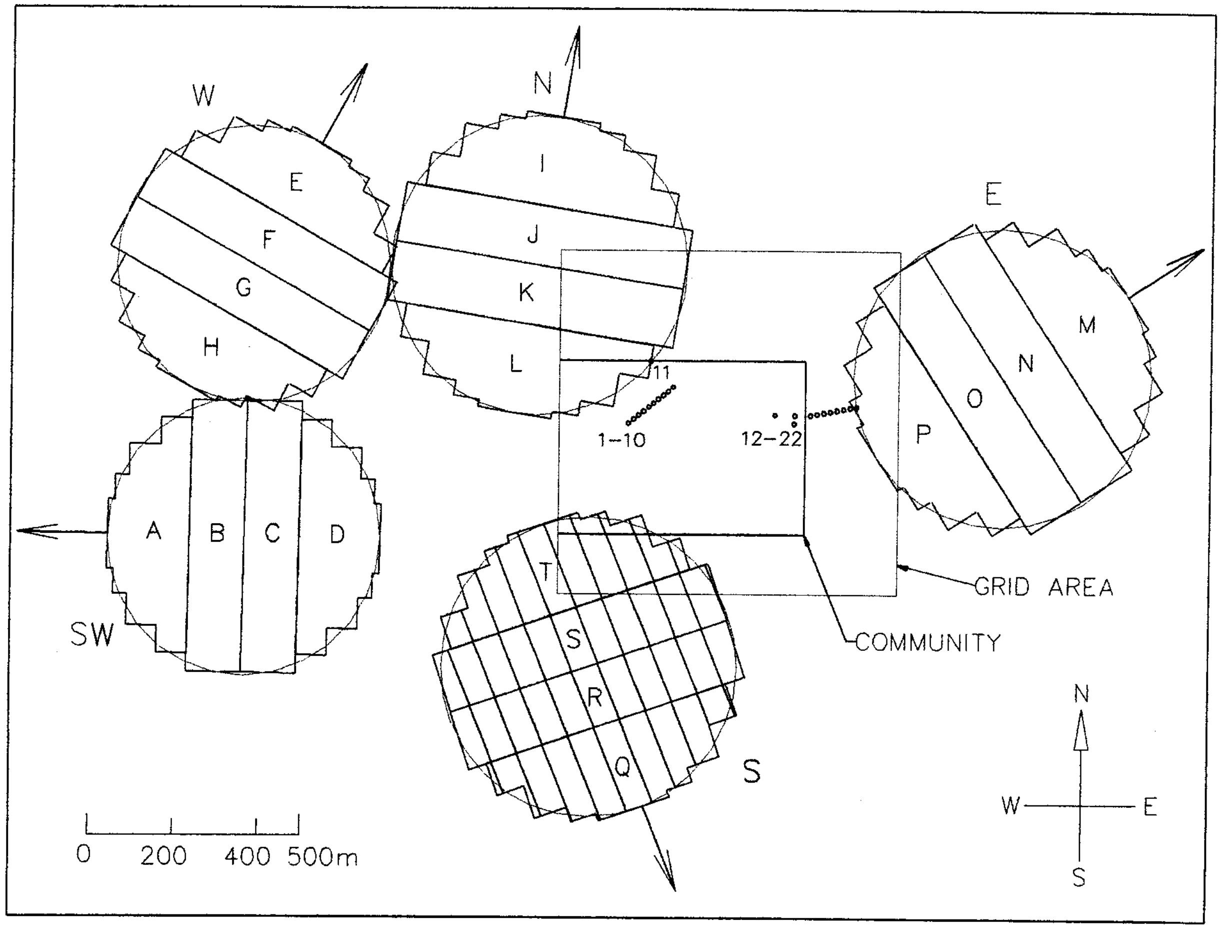
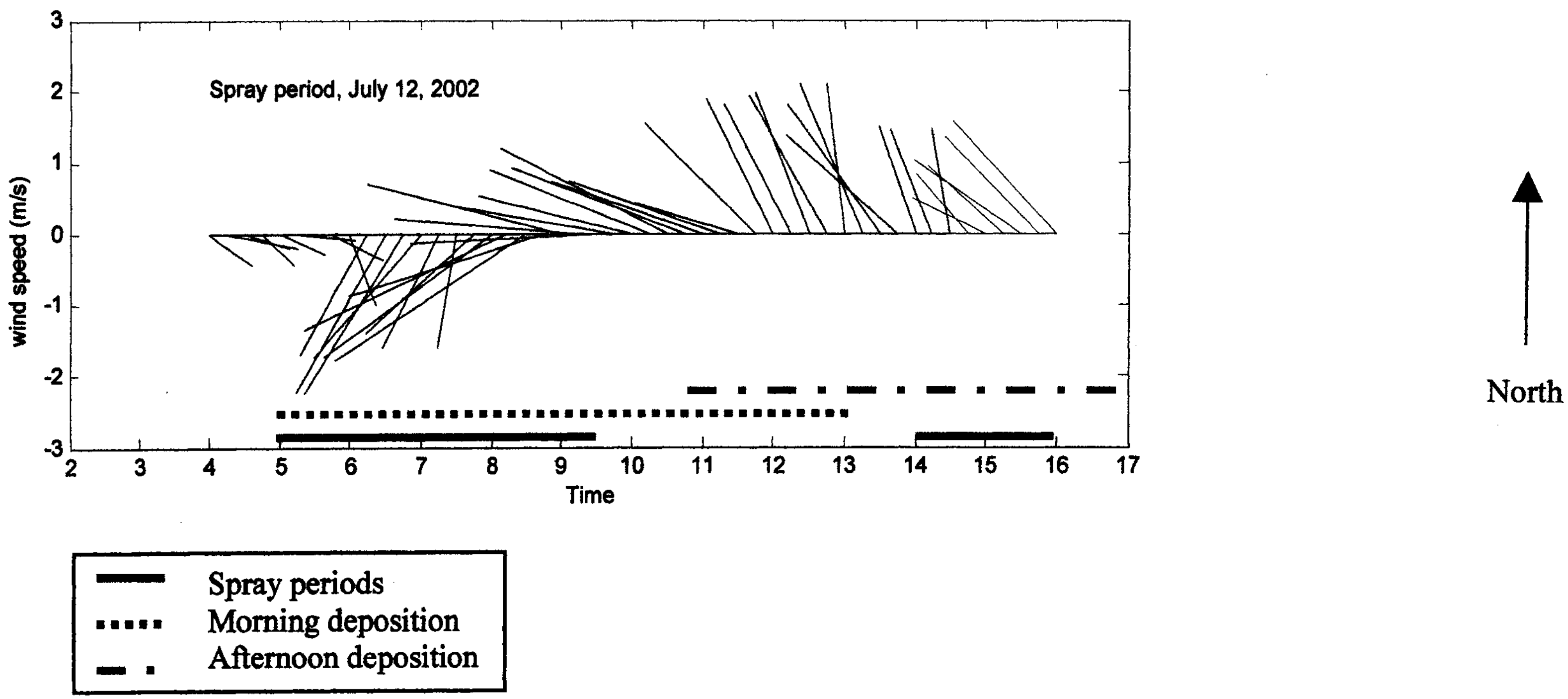

W
E
F
G
H
N
I
J
K
L
E
M
N
O
P
11
1–10
12–22
A
B
C
D
SW
T
S
R
Q
S
GRID AREA
COMMUNITY
N
W
E
S
0
200
400
500m

Figure 4.3: Fifteen-minute average wind direction and magnitude during study period
*Wind data obtained from Washington State University Public Agricultural Weather System (PAWS).

Wind sticks represent direction and magnitude along a 24-hour scale timeline. Wind direction follows the stick toward the x-axis. Magnitude is represented by stick length. All sticks are scaled equally regardless of direction to the y-axis (adapted from Weppner et al., submitted 2003).


Spray period, July 12, 2002
wind speed (m/s)
3
2
1
0
-1
-2
-3
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
Time
Spray periods
Morning deposition
Afternoon deposition
North

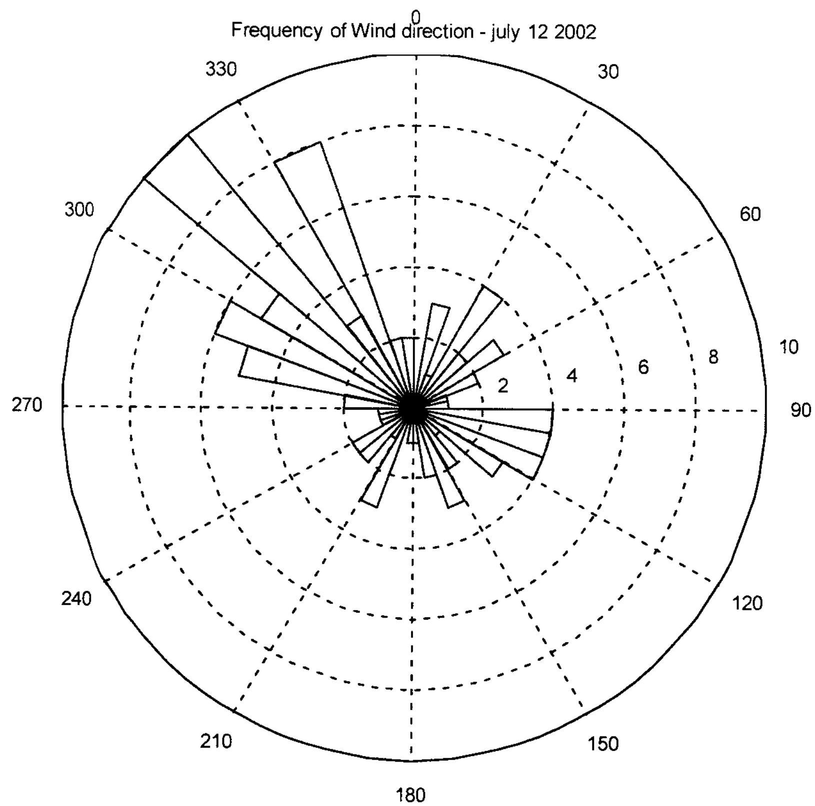


Figure 4.4. Windrose for the spray day (7-12-02)
Windroses represent frequency of observed direction of wind, and do not convey magnitude. The units of direction are 'degrees' from 0 to 360. North is at 0/360, South is 180. The units on the concentric rings are counts (number of times the wind was blowing FROM this direction during that day). The base data was 15 minute averaged direction and magnitude

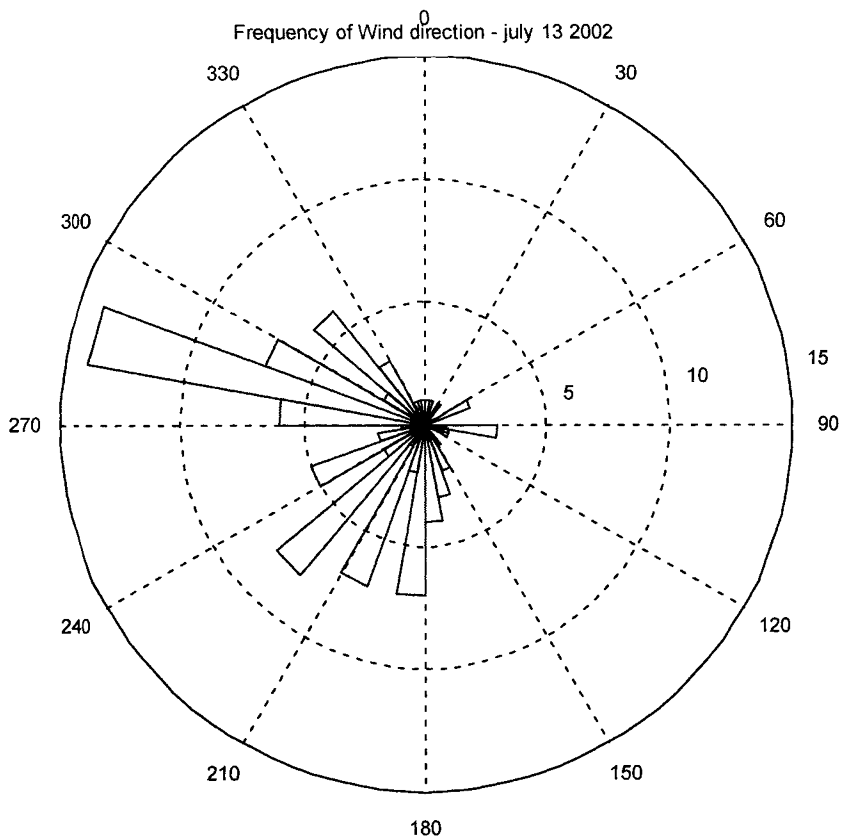


Figure 4.5: Windrose for the day after the spray (7-13-02)
Windroses represent frequency of observed direction of wind, and do not convey magnitude. The units of direction are 'degrees' from 0 to 360. North is at 0/360, South is 180. The units on the concentric rings are counts (number of times the wind was blowing FROM this direction during that day). The base data was 15 minute averaged direction and magnitude

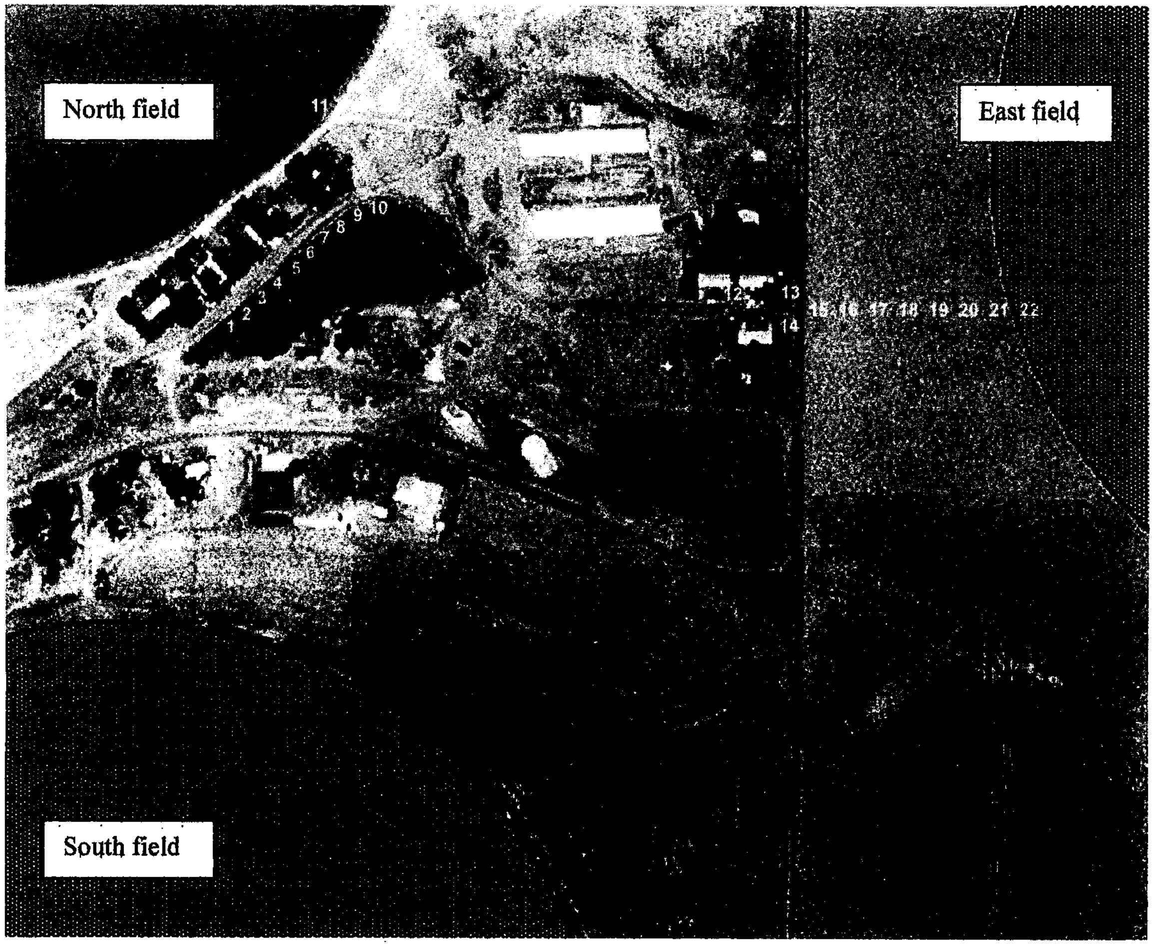


Figure 4.6: Deposition target locations
*Plates 11 and 22 were located in sprayed fields (adapter from Weppner et al., submitted 2003).

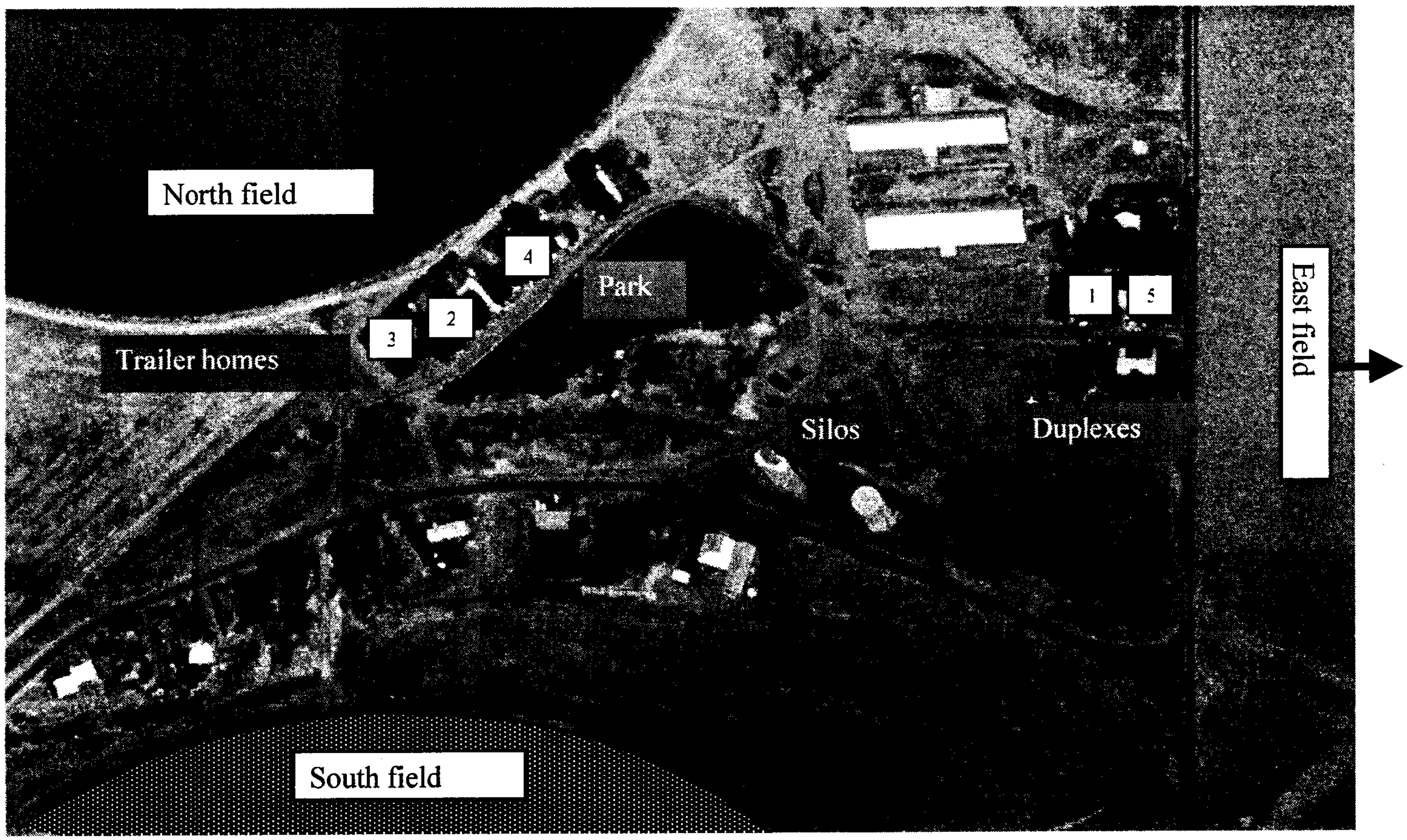


Figure 4.7: Community aerial photo map. Participating residences are numbered 1-5.

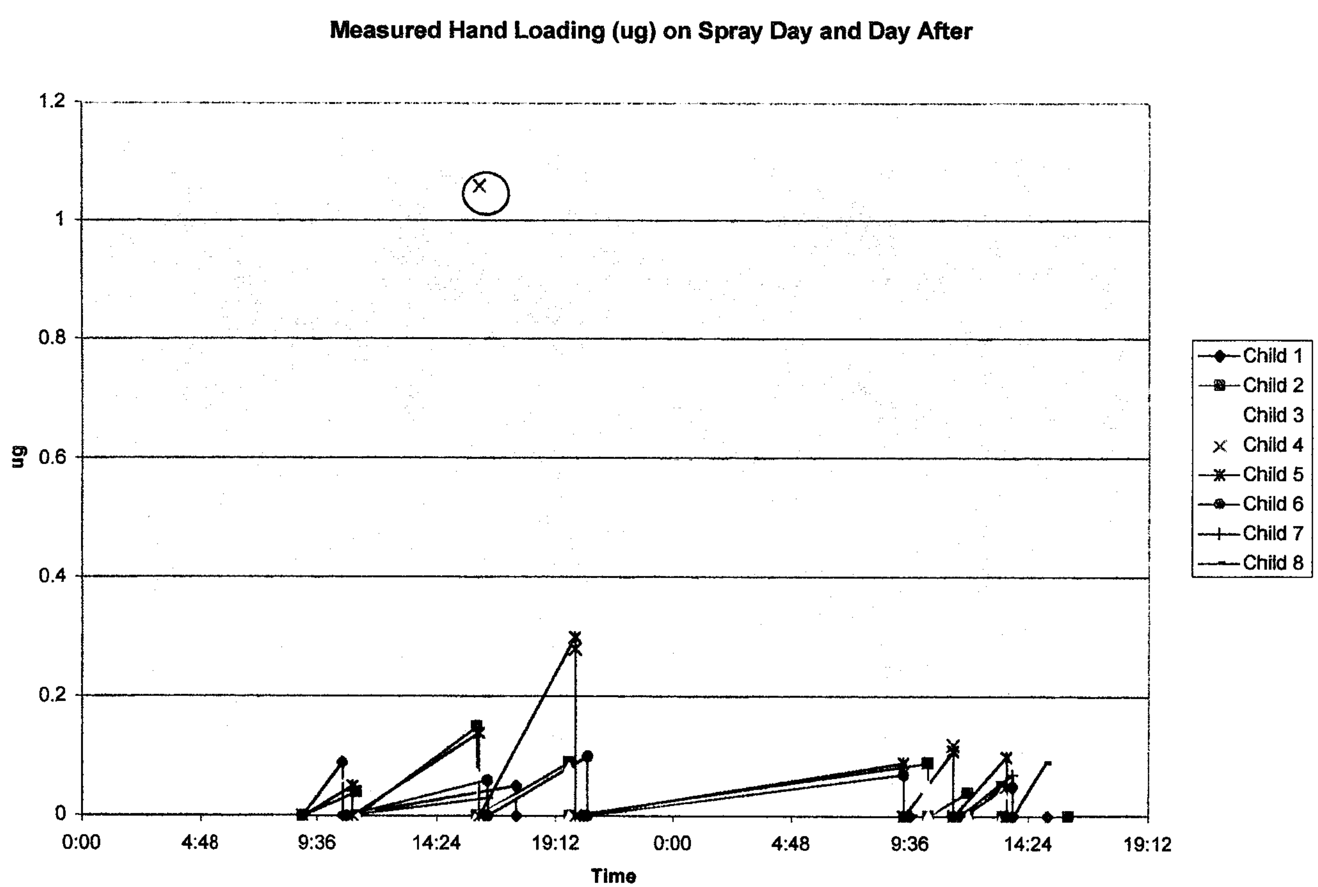


Figure 4.8: Loading on children's hands over time
Two assumptions are made in this figure: 1) Hand wiping removed all pesticide; 2) Loading was linear between wiping events. The circled value was considered an outlier and was not included in analyses. This wipe was collected by a parent, not by researchers.

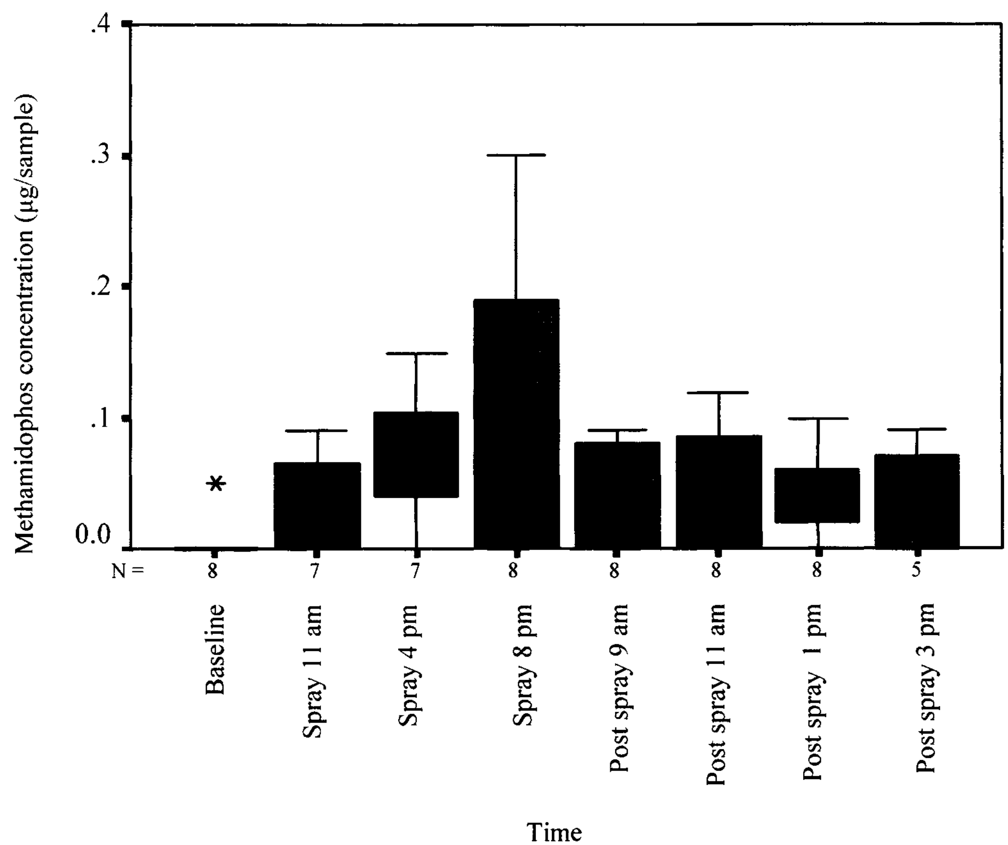
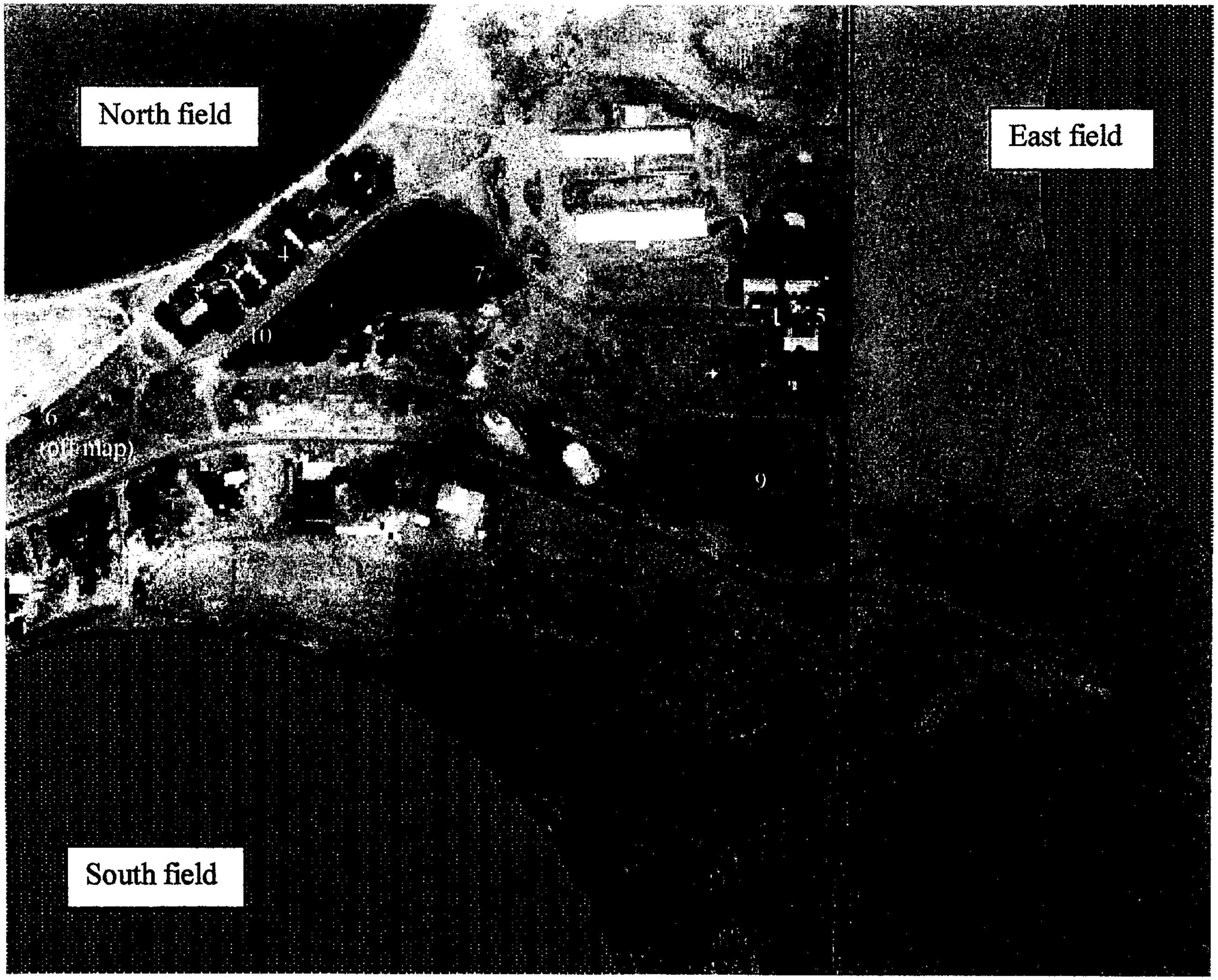


Figure 4.9: Hand wipe residues by day and time (adapted from Weppner et al., submitted 2003).



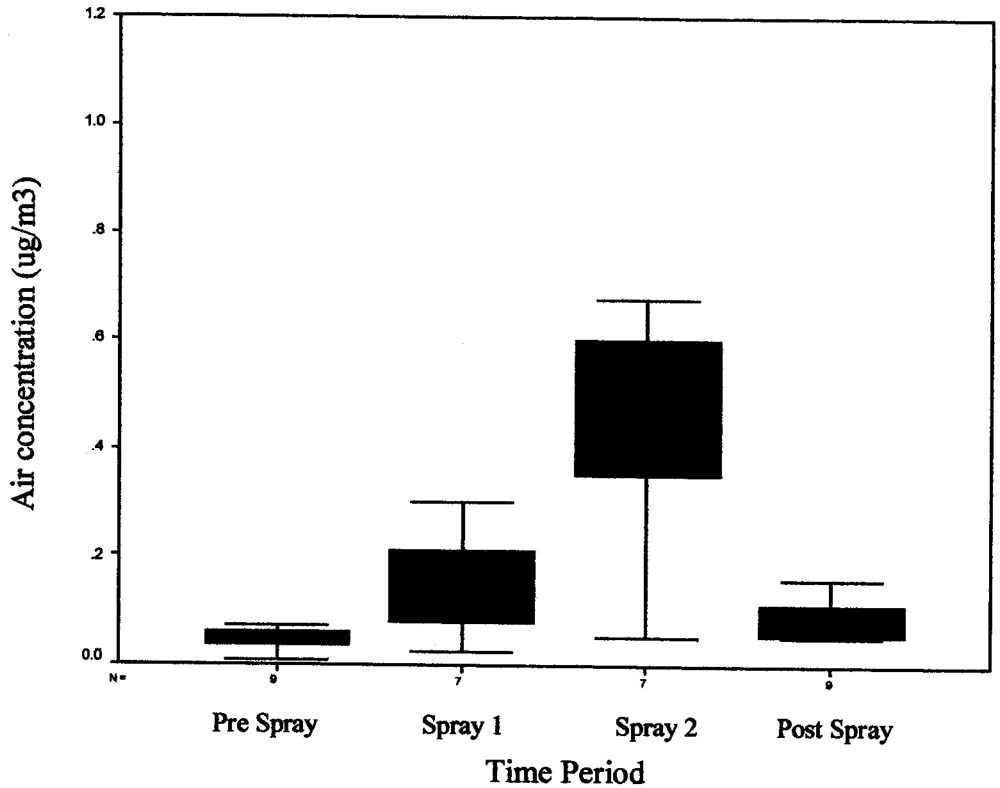
1-5
Residential
Samplers in
Yards
Approx.
20 lpm

6-10
Community
Samplers

6. 36 lpm
7. 256 lpm
8. 224 lpm
9. 24 lpm
10. 26 lpm

Figure 4.10: Outdoor air sampler locations

Figure 4.11: Outdoor air samples by time period; community samples (upper) and residential yard samples (lower)
Community samples at spray and post-spray times were significantly different from pre-spray concentrations (Wilcoxon signed rank, $p<0.05$).


1.2
1.0
.8
.6
.4
.2
0.0
Air concentration (ug/m3)
N=
9
7
7
9
Pre Spray
Spray 1
Spray 2
Post Spray
Time Period

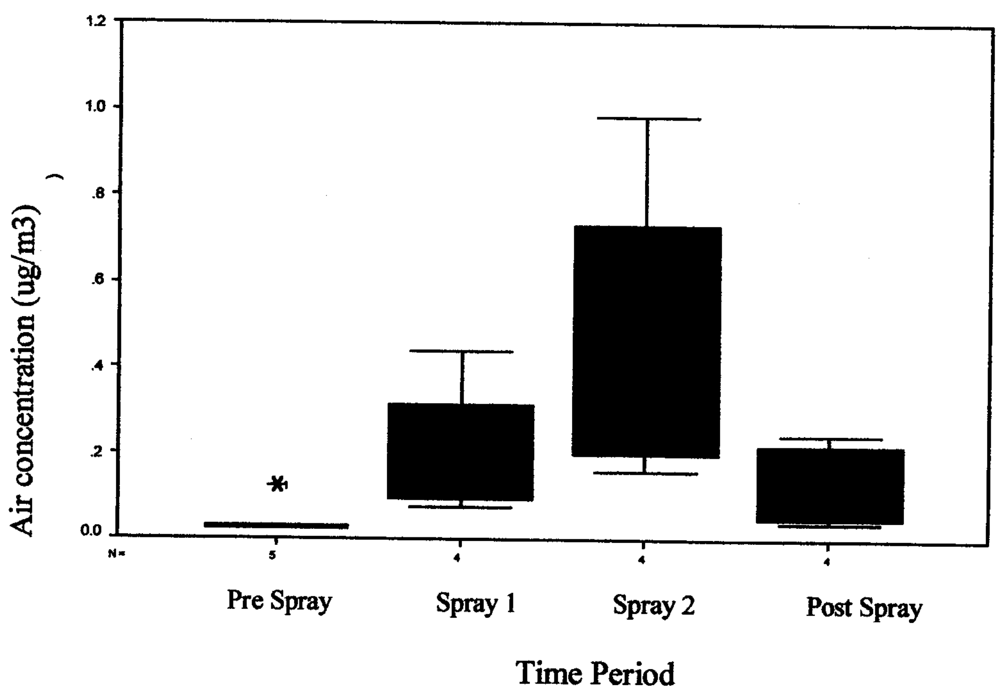
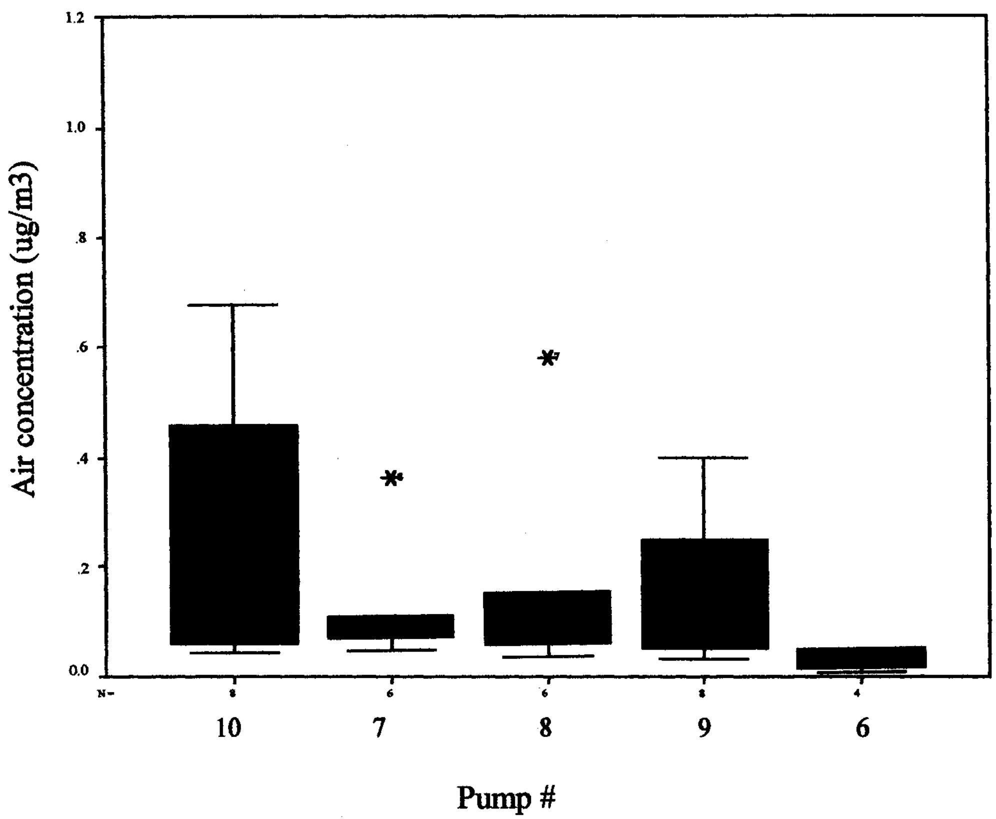

1.2
1.0
.8
.6
.4
.2
0.0
Air concentration (ug/m3)
N=
5
4
4
4
Pre Spray
Spray 1
Spray 2
Post Spray
Time Period

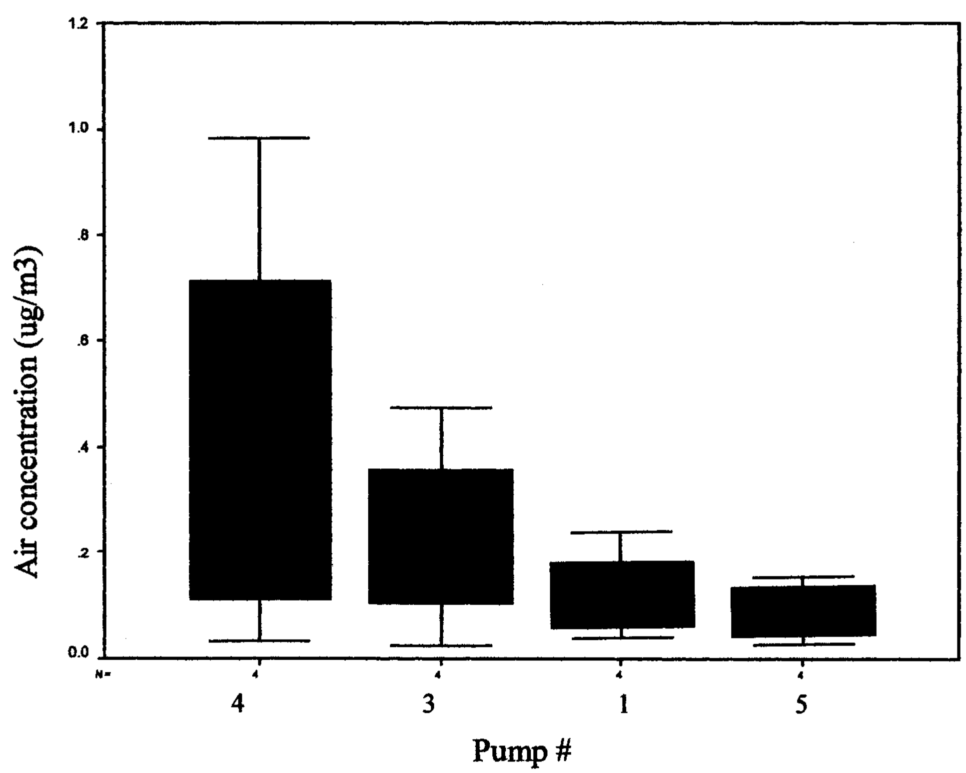
Figure 4.12: Outdoor air samples by location; community samples (upper) and residential yard samples (lower)

Residential sampler number corresponds to residence number. Locations are arranged on the plots by increasing proximity to nearest upwind treated field (NUTF) from left to right. A proximity effect is evident for all but one sample, at location #9.

Community samples in the community (7-10) were significantly different from #6, which was located 1.5 km upwind from the NUTF.

Figure 4.10 shows the location of samplers in the community.


Air concentration (ug/m3)
1.2
1.0
.8
.6
.4
.2
0.0
N=
10
7
8
9
6
Pump #


Air concentration (ug/m3)
1.2
1.0
.8
.6
.4
.2
0.0
N=
4
3
1
5
Pump #

Notes to Chapter

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Chapter 5

The Washington Aerial Spray Drift Study: dGPS-aided Exposure Assessment of Children During and After a Spray Event

Introduction

Pesticide spray drift is a concern for rural agricultural communities, both for residents who live near fields, and for farmers who must meet US EPA label guidelines for drift. Farmers who participated in the current study were particularly concerned about a proposed label statement that would have effectively banned any and all drift (US EPA 2001). Most studies of spray drift look at where drift occurs and in what concentration without focusing on the human contact component (Byer and Shepp, 1979; Byers et al. 1993, 2000; Clark et al. 1991). At the same time, most human exposure assessment studies focus on post-spray monitoring of pesticide levels in back yards, inside houses and in human subjects (biomonitoring) rather than during the spray, and without modeling the spray event of concern (Ames et al. 1993; Barnes et al. 1987; Draper et al. 1981; Garcia et al. 2000). Both approaches have yielded insight into the extent and characteristics of off-target drift and the levels of pesticide residues that can be found in and around rural agricultural residences. In this study, an organophosphate (OP) insecticide application and a cohort of children were concurrently monitored before, during and after the spray. Children's homes are surrounded by potato fields that were treated with the insecticide Monitor® (methamidophos) applied aerially. Models calibrated from measured deposition and air concentration were generated. In this study, drift modeling was combined with a new approach to exposure assessment: the use of Global Positioning Systems (GPS) tracking of human subjects (Elgethun et al. 2003). This method will be referred to as 'GPS+Model' in this chapter. This combination allowed for more refined and complete assessment of the potential exposures associated with pesticide spray drift in rural agricultural communities. Ideally, personal air monitoring also would be used with GPS, but no methods exist for OPs. Thus, modeling calibrated from ambient environmental monitoring was the best available solution.

Pesticide drift modeling is important for determining outdoor exposure to pesticides due to the variable spatial distribution of residences in relation to treated fields within a farming area. Traditional air and deposition sampling of such a large area would be prohibitively expensive. Furthermore, such methods often do not provide finely time-resolved data but are instead present an average over a relatively long sampling period. The long sampling period (2-12 hours for many methods), in relation to the relatively short spray event (an hour for an 85 acre, 34.4 hectare crop circle) does not allow the investigator to understand the evolution of any spray event. Therefore, modeling is essential to gain a high-resolution picture of the spray drift process over time.

In most spray drift studies, air and deposition samples are recorded at fixed latitude-longitude coordinates (Byers et al 1993, 2000). Such analysis is limited in that one must have many samplers in a small area to obtain a pesticide gradient measurement. The logical solution is for researchers to use air and deposition samples to calibrate models and thus obtain a spatially-referenced pesticide gradient of high resolution. The first model used was a Gaussian dispersion model (Fugitive Dust

Model (FDM)) to characterize deposition and droplet (non-gaseous) drift (detailed in Tsai et al., submitted 2004). Because the potential for multi-pathway exposure is high, particularly for children, it is important to consider deposition, air, and also volatilization to obtain a complete exposure picture. Most of the droplet fraction is deposited within a short time after a spray, but gas phase emission can continue from treated fields for several days.

The second model used was the US EPA volatilization Emission Factor Model (VEFM). Evaporation from wetted surfaces during the post-application period can lead to gas-phase releases, especially during hot and dry ambient conditions (detailed in Ramaprasad et al., accepted 2004). . Once in the atmosphere, the volatilized gases can be transported over fairly long distances. This process can contribute to atmospheric loading of the pesticide. Volatilization can potentially play a significant role when assessing risk factors associated with atmospheric exposure to pesticides. Lee et al. (2002) found that the pesticide's vapor pressure (VP) was the best predictor of the child chronic risk ranking for a pesticide and was a better predictor of lifetime cancer risk ranking than the cancer potency factor. Among the 15 pesticides evaluated in their study, vapor pressure was highly correlated with geometric mean air concentrations in rural communities. Woodrow et al. (1997) also found high correlations between vapor pressure of a pesticide and its downwind concentration. The active ingredients in most synthetic pesticide applications are volatile to a certain degree. Ignoring the effects of volatilization could significantly underestimate the ambient concentrations and risk associated with the inhaled exposure.

A key component of this study is the integration of novel spatial measurement and analysis techniques for assessing exposure. High-resolution model data becomes more useful if human time-location data are of equal (or better) resolution. In this study, children were monitored with GPS, and temporal-spatial relationships between drifted pesticides and people were analyzed using matrix analysis and GIS software. The current study is the first to combine high-resolution model data and high resolution GPS human tracking for the assessment of pesticide exposure. Rudimentary GPS time-location monitoring was first presented as part of the Oklahoma Urban Air Toxics Study (Phillips et al., 2001) where consumer-grade GPS were used, and many equipment failures occurred. Also, these researchers measured ordinal (categorical) locations rather than continuous (actual coordinate) data. The utility of using actual coordinate data to reference both pesticide model data and human movement data is that there is no dilution of precision or accuracy. In previous exposure assessment studies, human time-location and pesticide concentration in the environment have been compartmentalized into discrete groups by generalized location. For example, in the National Human Exposure Assessment Survey (NHEXAS), human time-location was grouped into one of seven categories based on responses to a diary. Chapter 3 (Elgethun et al. 2004) demonstrates the shortcomings of such diaries. By replacing ordinal time-location data with continuous measurements, this study demonstrates a new refinement in exposure analysis.

An obvious question arises: why bother with such refined GPS-modeling exposure analysis when children can be monitored for pesticide metabolites in their urine? (Fenske et al. 2000; Lu et al. 2000). Urine biomonitoring is a direct measure of exposure, but does not give evidence of where a person was exposed, or the attributable fraction of exposure routes. Urine biomonitoring is invasive, messy, and inconvenient for subjects. Compliance can be a problem, particularly with younger children. It is not practical to employ biomonitoring in a study with many subjects, nor in a study in a remote location that does not have lab facilities nearby. Limit of quantification for urine metabolite analysis can also limit the sensitivity of this surveillance method (Tomazekewska and Hebert, 2003).

The purpose of this study was to combine the best spatial measurement and analysis techniques available with environmental sampling to generate exposure profiles for children, and to compare these estimates to those produced using a 'standard' estimation method. The 'standard' method is akin to what is conventionally used in exposure assessment (i.e. diary time-location estimates instead of GPS, sampler data instead of model data). The outcome of this study will be evaluation of GPS tracking and integration with modeling for human exposure assessment, advisement of growers about the accuracy of their applications, and advisement of people in the study community and in other agricultural communities about pesticide spray drift. Spray drift data can help growers choose when and how they apply pesticides to maximize on-target coverage, can inform about compliance with EPA regulations, and can be used to demonstrate that proposed zero tolerance drift regulations were unrealistic. Spray drift data can inform residents of agricultural communities how to minimize their risk of exposure. 'Hot spots' in the community (places with high deposited or airborne pesticide) can be identified and displayed on a map. Researchers can make recommendations (i.e. Leaving town or staying indoors for a certain time period, prohibiting children from playing in certain areas until pesticide has degraded). Residents can then make informed choices about how to eliminate or reduce exposures during spray season.

Methods

Overview

This study was conducted in a rural agricultural area in Southeastern Washington State. Five potato crop circles were aerially sprayed with Monitor® containing the active ingredient methamidophos (O,S-Dimethyl phosphoramidothioate) on July 12th, 2002. Methamidophos is an organophosphate pesticide used to protect the crop against a variety of potato pests including aphids, thrips, beetles, and worms. The five crop circles surrounded a community which housed many of the farm workers and their families.

Figure 5.1 (adapted from Tsai et al., submitted 2004) shows the order in which fields were sprayed and the dominant wind direction during the time each circle was sprayed. Patches A through P were sprayed in the morning and are part of the AM-spray event. Patches Q through T were sprayed in the afternoon and are part of the PM-spray event. The application was observed to have been particularly carefully executed. A 1340 S2R Thrush flying at 110 mph (175 kph) at about 10 feet (3 m) above the canopy was used. The boom of the craft was 3/4 of the wing span (38 feet) with 60 nozzles delivering 7.7 gallons of pesticide mixture per acre over a 45 foot effective ground swath. Nozzles were Whirljets(ASAE Medium, size 12) oriented180 degrees from direction of flight and located 2-3 feet below the wing. The capacity of the tank was 400 gallons delivering the spray at 20-22 psi.

All the residences were located within 800 meters of each other and each residence was located within 10 to 200 meters of the nearest sprayed field (Weppner et al., submitted 2003). To conduct the exposure assessment, researchers collected a variety of data. Sample collection information is shown in Table 5.1. A unique aspect this study was the use of GPS systems to track the location of the eight children enrolled in the study over the course of the day (Elgethun et al. 2003; Weppner et al., submitted 2003). The environmental sampling (air, deposition) for this study is detailed in Weppner et al. (submitted 2003).

Modeling of deposition, air and volatilization concentration

Modeling was necessary for several reasons, notably the limited number of actual samplers, the lack of time resolution in actual sampling methods, and multiple exposure pathways. As can be imagined, the positions of the children far exceed the number of samplers that can be set out; furthermore, the samplers used to collect pesticide concentrations sample over long periods of time, thereby providing little if any time resolution. Drift models, after calibration with existing sampling data, allowed the prediction of concentrations in locations where no sampling data were available. The models provide time-resolved concentration data according to the resolution of the available meteorological data. Time- and location- resolved pesticide concentrations were then matched to time-location data (GPS) for each child. By modeling both deposition and air concentration and incorporating these results in the exposure assessment, the contribution of each exposure pathway can be ascertained.

Air and Deposition Modeling

Modeling of deposition loadings and air concentrations is presented in Tsai et al. (submitted 2004). In this study, modeling is particularly important for determining the exposure of each enrolled child. The Fugitive Dust Model (FDM) uses meteorological data (temperature, wind speed, wind direction, stability), a particle size distribution and source emissions as input (USEPA 1993).

The output of FDM is defined by receptor locations. The receptor grid consisted of 1024 points defining the corners of 15 square meter squares. The patches represented in Figure 5.1 were sprayed in sequence from A-T, with each patch corresponding to approximately a 15 minute time interval.

Volatilization Modeling.

. Modeling of volatilization is presented in Ramaprasad et al. (accepted 2004). Although the FDM is applied for aerosol transport it was adapted here to model gas transport by choosing a mono-dispersed particle size distribution that has a negligible deposition rate. Since very small particles follow airflow like gases, it is possible to simulate gas transport by choosing sufficiently small particle sizes. A mean size of .3 μm was used here to represent gas transport in the model. Initially an aerosol release was modeled to determine deposition. Fields were considered area sources. Emission rate was calculated from the knowledge that 7.7 gallons per acre are applied over a field of known size in a known amount of time. Emission rate was calculated to be 0.00199 g/m 2-s. To interpret the model output in terms of just the active ingredient, it is known that a gallon of unit density liquid weighs 8.32 lbs, and the active ingredient of the pesticide mixture is 1.56%. This number thus allows an estimate of the component of active ingredient in the model output. Volatilization is estimated to start after the first patch is sprayed. This patch continues to volatilize through the day while emissions from other patches are added sequentially as spraying progresses through the day. As each consecutive patch is sprayed, this new wetted area contributes to the source term for the volatilized component of the AI. Updated surface concentrations for methamidophos are calculated every fifteen minutes based on a half life of 3 days. These fluxes are used as source terms in the FDM to calculate downwind concentrations near where the air sampler data was located.

Three factors found to have the greatest influence in the volatilization of pesticides are: 1) the physical properties of the AI (e.g. vapor pressure and Henry's Law constant), 2) meteorological conditions (e.g. vapor pressure has a positive correlation with temperature and wind speeds/turbulence) and 3) environmental mobility (which is affected by parameters such as soil adsorption. A model, the US EPA volatilization Emission Factor Model (VEFM), was used to estimate the emission factor (US EPA 1994). For this study the VEFM was used to calculate only the volatilization from the wetted surfaces after the application event and not the volatilization of the particles during the spray event. The VEFM estimates an emission factor over a 30-day period. The 30 day emission factor is used to calculate a volatilization decay constant for a preferred unit of time, in this case every 15 minutes.

On the day of the spray the temperatures rose as high as 42°C (Figure 5.2) and at this temperature the VP of methamidophos is significantly higher than at 25°C. The VP of methamidophos was calculated as it varied with temperature through the day, and this was used to calculate the Emission Factor as a function of temperature (Figure 2, adapted from Ramaprasad et al., accepted 2004). When the temperature exceeded about 24° C the vapor pressure of methamidophos was over the threshold limit of 10^{-4} mmHg in VEFM, resulting in a step increase of the emission factor from 350 kg/Megagram to 580 kg/Megagram.

Meteorology.

The meteorological inputs were obtained from Washington State University's Public Agricultural Weather System (WSU PAWS) meteorological station. This station was located 2km directly south of the field site over flat land. Among the many measurements available, wind speed, wind direction and temperature were used. The finest data resolution available was 15-minute intervals. Other necessary meteorological inputs such as stability class and mixing height were estimated using Turner's method and from the literature, respectively.

GPS Child Time-location and breathing rate estimates

Each child wore a small geographical positioning system personal acquisition logger (Enertech GPS-PAL) in a vest during hours they were awake on the day of and the day following aerial application. The sampling rate was 5 seconds. This technology has been demonstrated for monitoring time-activity patterns of children (Elgethun et al. 2003). Of the eleven children originally recruited, eight participated throughout the duration of the spray study. The GPS-PAL was used to record time-location for 3 days: pre-, during, and post-spray. Analysis by GIS (ArcView v.3.2 / ArcGIS v.8.3 software, ESRI, Redlands, CA) was used to visualize GPS paths and quantify time-location.

Methods were the same as described in Elgethun et al. 2003 / Chapter 2, except that the differential correction data were collected from a different CORS station that was closer to the field site (Appendix B). This station was located in Appleton, WA, approximately 100 km from the field site. This is the closest station for SE Washington State. A new GIS was constructed for the drift field study. ArcView v.3.2 and ArcGIS v.8.3 were used to integrate data and map layers. USGS Digital Ortho Quarter Quads (DOQQs) obtained as .bil files on CD-ROM from USGS were used as base maps. Resolution of these maps is given as 1 meter. Unlike the Seattle study described in Chapter 3, time-location was not grouped into categories. Instead, horizontal linear distance (in meters) and compass direction (0°-360°) from the center of each child's home was measured for each logged point (approximately 15-20 points logged per minute, depending on reception).

The maps of GPS points were reviewed to determine the following:

1. Whether the child was inside or outside;
2. Whether the child was in the community or out of the community;
3. Whether the child was on foot, on a bicycle, or in a vehicle.

This information informed the exposure estimates. If the GPS logged one point several minutes after the previous point, the points following were scrutinized to determine if the child was inside a building, or whether the child was still outside during this time.

Periodic interference to reception is possible such that a child may be outside but the GPS may not record points. The GPS can record inside some buildings but not others (Elgethun et al. 2003). Thus it is critical to determine inside from outside by visual examination of the map, since indoor exposure is generally different from outdoor exposure.

Linear velocity for each child was calculated from dGPS data. Velocity measurements are described in Chapter 4. It was possible to determine that a child was on foot, on a bicycle, or in a vehicle by reviewing the mean velocity recorded. This was also visible when paths were mapped; faster travel is indicated by dots spaced further apart, as evident in Figure 5.3. Data points were thus grouped into foot, bicycle, or vehicle categories. Mean normal velocities for foot and bicycle were used to generate weighting factors from velocity. These velocities are 1.22 m/s for foot travel, 2.44 m/s for bicycle travel (Knoblach et al. 1996) Thus the formula for weighting was [1+ (V / V_n)], where V is the child's velocity and V_n is the mean normal velocity from Knoblach et al. (1996). A weight of '1' was applied to riding in a vehicle, since this is not expected to alter breathing rate.

Activity weights were used to multiply baseline sedentary breathing rate (BSBR) for each child (sedentary = awake, standing in place). BSBR was determined from age-specific distributions (Adams et al. 1993; US EPA 2002). The complete formula for calculating weighted breathing rate is shown in Appendix 5C, and below:

$$\textit{Weighted Breathing Rate} = \left(1 + \frac{V}{V_b}\right) * (R_{br})$$

V = velocity (m/s)

V_b = baseline velocity (m/s)
R_{br} = age specific breathing rate (m3/hr)

Modeled air concentration correction

It was determined that air estimates from the model needed to be corrected post hoc to account for differences between the model and measured air concentrations. While correlation between the modeled and measured values was good by individual day (spray period up to 16:30, spray day 16:30 through day after spray), correlation was poor for both days combined. This occurred because the slope of the regression between model and measured values changed from day to day. Slope of the line from the plot of these data was determined to use as a correction factor from data shown by Ramaprasad et al. (2004). Air concentration model output prior to 16:30 on 7-12-02 was multiplied by a factor of 4.3. Air concentration model output for the remainder of time was divided by 1.4.

Time-location-load and concentration Interpolation

Children's dGPS datasets were independently analyzed. Five-second sampling interval time-location data for each child and spatially-referenced pesticide air concentration (15 minute, 15 m resolution) data were combined using matrix analysis software (MATLAB Release 12, The MathWorks, Natick, MA). Depending on reception, dGPS time intervals varied between 5 seconds and a few minutes. A flow-chart describing the process of data combination and interpolation is shown in Appendix 5 A. In brief, time and space was matched between the datasets by a linear interpolation method. Time was interpolated from 15 minutes to actual time points logged by GPS for the deposition, air and volatilization data using a spline function. Space was similarly interpolated from 15 m grid to actual location for each child using a linear interpolation method. It was determined, for every GPS time point, the specific pesticide load or concentration encountered at a particular location. Exposures were treated as independent events of x seconds each, where x = time outside elapsed between GPS time points (Appendices 5D & F). Deposition was considered cumulative from the rates generated by the FDM model. Air concentration was not cumulative.

Exposure estimates for GPS+Model Method

GPS time intervals and model data synchronization

Elapsed time recorded by GPS was multiplied by the model air concentration or model ground load that was determined at the beginning of the respective time interval.

Inhalation

A time-weighted average encountered air concentration was calculated from dGPS and model predictions according to the following equations (Appendices 5 D & E):

1. If Within the Community Model Output Grid

$$C_E = \Sigma\ [(C_{ae} + C_{ve})*t]\ /\Sigma\, t$$

C_E = *Encountered Air Concentration (ng/m3)*
C_{ae} = *Concentration Output from Aerosol Model for that Time and Location (ng/m3)*
C_{ve}=*Concentration Output from Gas & Vapor Phase Volatility Model for that Time and Location (ng/m3)*
t = *interval time (sec)*

Σt = *sum of time over all intervals (sec)*

2. If Outside the Community Model Output Grid

Encountered Air Concentration = C_{uf}

C_{uf} = *Upwind pump fixed location concentration for that time period (ng/m3)*

The total encountered air concentration is expressed as a mean. The total inhaled mass is a summation of inhaled mass estimates over all GPS time intervals. Methamidophos is very water soluble but has a relatively moderate vapor pressure (US EPA 1998). Due to these properties, no losses are expected to occur once inhaled into the lungs (Appendix 5F). The calculation for total inhaled mass employed the weighted breathing rate data described above (Appendices 5 D & E) according to the following formulae::

$$Mi = \Sigma \left[C_{ei} * R_{brw} * \frac{1\ hr}{3600\ sec} * t \right]$$

Mi = *Inhaled mass (ng)*
C_{ei} = *Encountered Interval Air Concentration (ng/m3 per interval duration)*
R_{brw} = *Weighted Breathing Rate (m3/hr)*
t = *Interval Time in seconds (sec)*

Skin

A time-weighted average encountered ground load was calculated from dGPS and model prediction deposition rate data according to the following equation (Appendices 5 F & G):

$$L_E = \Sigma\ [M_{cd} * t] / \Sigma t$$

L_E = *Encountered ground load (ng/cm2)*

M_{cd} = *Deposition Cumulative mass per area output from model for location during that time interval (ng/cm2 per interval duration)*
t = *interval time (sec)*
Σt = *sum of time over all intervals (sec)*

Total dermal exposure was calculated using an assumed standard transfer factor (Appendices 5 F & G) as follows:

$$M_S = \Sigma \left[R_{cd} * F_t * \frac{1\ hr}{3600\ sec} * t \right]$$

M_S = *mass on skin (ng)*
R_{cd} = *Deposition Cumulative rate output from model for location during that time interval (ng/cm2 per interval duration)*
F_t = *Transfer Factor (cm2/hr)*
t = *Interval Time in seconds (sec)*

Transfer factor calculation

Children spent a substantial amount of time outdoors on turf (Elgethun, personal observation). This was also evident from examining vegetation differences on the orthophoto map of the community in relation to children's paths. Based on a review of the literature for residue transfer from turf (Vacarro 1996, Bernard et al. 2001, USEPA 2001, Williams et al. 2003) it was decided that existing transfer factors were not applicable to this study. Studies that have generated F_t have had scripted 20 minute activities (Jazzercize®) from which some assumption about what this activity means have been made. EPA considers this 20 minutes to represent 1 hour of likely turf contact, while others have considered it to represent a full 24 hour day contact. For this study, since the purpose was to compare to dermal exposure estimates, it was desirable to not make any assumptions and take the 20 minutes as a direct metric of exposure. This is a conservative approach that most likely leads to relatively high exposure estimates. Another problem with using existing transfer factors was they use dislodgeable foliar residue (DFR) as an estimate for how much pesticide is available on the turf for uptake. The current study used silica gel deposition plates to measure load, which are assumed to capture 100% of the deposited pesticide, generally more than a DFR. In light of these factors, a new estimation was made using the most recent published dataset on organophosphate pesticide exposure from treated turf (Bernard et al. 2001). The formula used for transfer factor (F_t), expressed as cm2/hr, was as follows:

$$F_t = \frac{E_d}{20 \text{ min}} * \frac{1}{D_p} * \frac{60 \text{ min}}{1 \text{ hr}}$$

E_d = dermal exposure (from Bernard et al 2001, 1600 ug)

D_p = application rate (measured on deposition coupons) (from Bernard et al. 2001, 12 ug/cm2)

The application rate as measured on deposition coupons was selected for use in the denominator because both deposition coupons and silica deposition plates are assumed to capture 100% of the deposited pesticide. The transfer factor (F_t) was estimated from these calculations to be 400 cm2/hr.

The strength of this new transfer coefficient is that both time and ground load are treated at face value. Since no data were collected in the current study for DFR, it is difficult to rationalize using a transfer coefficient that is based on DFR. 400 cm2/hr is lower than the transfer factor used for EPA risk assessments (US EPA 2001) but higher than the value suggested by Bernard et al. (2001) and Williams et al. (2003).

<u>*Exposure estimates for 'Standard' Method*</u>

Time-location estimation

A standard method would likely use a categorical diary to record time-location. However, a diary was not administered during the study period. A diary proxy was considered to be the categorization of the GPS data into 1-hour categories. Time-location was coded into four categories: inside in the community, outside in the community, inside out of town and outside out of town. Coding was based on a 'majority vote', such that the location where the child spent the most cumulative time in that hour received the vote. This is in keeping with how subjects are asked to complete the NHEXAS time-location diary.

Inhalation

Encountered air concentration was constrained by the resolution of the air sampling, which ranged from 7-17 hours. Co-located samples from the same pump were averaged and considered as a single value. The upwind pump outside the community was excluded for within community analyses. For the final sampling period (9:30-18:30 on 7-13-02), mean air concentration was predicted by linear regression from preceding data since no measurements were taken then. This was necessary for comparison because the model predicts air concentration through this time period. For each air sampling period, air concentration from all pumps in the community was averaged (arithmetic mean), and this average was multiplied times an age/gender specific breathing rate taken from the EPA Child Exposure Factors Handbook and by the duration of the sampling period (Appendices 5 D & E) as follows:

1. If Within the Community Model Output Grid

Fixed Air Concentration $= C_{cf}$

> C_{cf} = *Mean community concentration at fixed locations for all pumps for that time period (ng/m3)*

2. If Outside the Community Model Output Grid

Fixed Air Concentration $= C_{uf}$

> C_{uf} = *Upwind pump fixed location concentration for that time period (ng/m3)*

Inhaled mass was then calculated as follows:

$$Mi = C_f * BR * T$$

> Mi = *Inhaled mass (ng)*
> C_f = *Fixed Air Concentration (ng/m3)*
> BR = *Breathing Rate (m3/hr)*
> T = *Time Outside in hours (hr)*

Skin

Encountered ground load was considered to be the mean fixed location concentration for all deposition plates in the community for a given time period. Two deposition plates in the first row of treated crop (not in the community) were excluded from this mean. For each period, mean deposition load was multiplied by the transfer factor (400 cm2/hr, see explanation above) and by the duration of the time period (Appendices 5 F & G) as follows:

Fixed Ground Load $= D_{gf}$

D_{gf} = *Mean deposition plate fixed location load for all deposition plates in the community for that time period (ng/cm2*

$M_S = D_{gf} * F_t * T$

M_S = *mass on skin (ng)*
D_{gf} = *Mean deposition plate fixed location load for all deposition plates in the community for that time period (ng/cm2)*
F_t = *Transfer Factor (cm2/hr)*
T = *Time period in hours (hr)*

. For the final sampling period (9:30-18:30 on 7-13-02), mean air concentration was predicted by linear regression from preceding data since no measurements were taken then. This was necessary for comparison because the model predicts air concentration through this time period.

Statistical Analyses

Comparisons both between and within methods were made. Comparisons were made using a 2-tailed paired samples t-test. For within method comparison, exposure estimates for each child were compared such that n=8 children in each analysis. For between method comparison, exposure estimates for each child for each day (spray day and day after spray) were compared such that n=16 child-days for each comparison.

Results

GPS+Model Results
Comparison between days

The following are differences by day for each child determined using the GPS+Model method (Tables 5.2, 5,7, 5.10).

Child 1: Child 1 spent 13% more time outside on the *spray day*. 63% more mass was predicted inhaled on the spray day. 61% more mass on skin was predicted on the spray day.

Child 2: Child 2 spent 70% more time outside on the *spray day*. 97% more mass was predicted inhaled on the spray day. 98% more mass on skin was predicted on the spray day.

Child 3: Child 3 spent 34% more time outside on the *day after the spray*. However, 91% more mass was predicted inhaled on the spray day. 38% more mass on skin was predicted on the day after the spray.

Child 4: Child 4 spent 46% more time outside on the *spray day*. 78% more mass was predicted inhaled on the spray day. However, 71% more mass on skin was predicted on the day after the spray.

Child 5: Child 5 spent 25% more time outside on the *day after the spray*. However, 81% more mass was predicted inhaled on the spray day. 50% more mass on skin was predicted on the day after the spray. Child 5 had the highest total mass on skin estimate.

Child 6: Child 6 spent 13% more time outside on the *spray day*. 90 % more mass was predicted inhaled on the spray day. However, 54% more mass on skin was predicted on the day after the spray. Child 6 had the highest total inhaled mass estimate.

Child 7: Child 7 spent 89% more time outside on the *day after the spray*. 94% more mass was predicted inhaled on the day after the spray. 99% more mass on skin was predicted on the day after the spray. Child 7 had the lowest exposure estimates by both pathways.

Child 8: Child 8 spent 84% more time outside on the *day after the spray*. 57% more mass was predicted inhaled on the day after the spray. 97% more mass on skin was predicted on the day after the spray.

Table 5.2 shows time spent outside for each child. Child 2 (5 yo M) spent the most time outside on the spray day (251 minutes), while child 3 (8 yo M) and child 5 (11 yo M) spent the most time outside on the day after the spray (223 and 224 minutes, respectively). Mean time spent outside for all children was approximately 14% greater on the day after the spray. Comparison of greater amount of time spent outside, by day, showed an even split between children. Child 1, 2, 4, and 6 spent more time outside on the spray day. Child 3, 5, 7, and 8 spent more time outside on the day after the spray.

Mean encountered air concentration by GPS+Model method by time period for the four sampling time periods ranged from 0-3523 ng/m3 (Table 5.4). Total inhaled mass ranged from 0-3039 ng. Total inhaled mass (Table 5.7) for all children was significantly greater on the spray day compared to the day after (n=8 children, paired samples t-test, p=0.04). Mean total GPS+Model inhaled mass for all children was approximately 76% higher on the spray day (1570 ng versus 214 ng) (Table 5.7). Child 7 and child 8 did not follow this trend, however. These two girls, who are siblings, scarcely left the house on the spray day, but were outside a considerable amount on the day after the spray. Both children had higher inhalation exposure on the second day. Even though child 2 spent the most time outside on the spray day (Table 5.2), his inhaled exposure was much lower than that of child 5 and child 6 (Table 5.7). Child 2 had a much lower activity level and breathing rate than child 5 and child 6

(Table 5.3). Child 5 and child 6 also live closer to the NUTF, have no trees or fence between their home and the NUTF, and consistently went closer to the treated fields than did child 2 or the other children. Figure 5.7 (a) illustrates how much time child 6 spent in proximity to the fields.

GPS+Model estimates for mean ground load and total mass on skin, by sampling time period, for each child are shown in Table 5.8. Total estimates, by day, are shown in Table 5.10. Mean ground load encountered ranged from 0.00- 16.8 ug/cm2 by individual time period. The highest ground load was encountered during period 2 on the spray day. Total daily mass on skin ranged from 0 ug to 17400 ug, or approximately 17.4 mg (child 5, 11 yo M) (Table 5.10). Child 5 and child 6 had the highest mass on skin, both on the day after the spray. Mean mass on skin for all children was approximately 30% higher on the day after the spray compared to the spray day. As stated for the air data above, Child 5 and child 6 also live in the home closest to the NUTF, have no trees or fence between their home and the NUTF, and consistently went closer to the treated fields than did the other children. Figure 5.7 (a) illustrates how much time child 6 spent in proximity to the fields. Mean mass on skin for all children over both days was 3990 ug or approximately 4 mg, but this number difficult to interpret, since there was somewhat of a bimodal distribution of exposures. Child 1, 4, 7 and 8 had relatively low dermal exposures on both days compared to child 2, 3, 5 and 6. Child 1, 7 and 8 live in a different area of the community from the rest of the children. They live in the homes visible on the right side of the map in Figure 5.3, whereas the rest of the children live in the homes on the left side of the map. The

NUTF is located directly adjacent to the homes on the left side of the map. The NUTF is labeled as field 'N' (north) in Figure 5.1.

Mean mass on skin (Table 5.10) was not significantly different by day (paired samples t-test, p=0.47), but was approximately 30% higher on the day after the spray despite being statistically not significantly higher. The mean mass on skin estimated by GPS+Model method was approximately 4000 times higher than the mean inhaled mass over both days (Table 5.7 and Table 5.10).

Influence of breathing rate on mass inhaled

Weight factors from dGPS linear velocity and corresponding breathing rates for GPS+Model estimates are shown in Table 5.3. Weights ranged from 1-6.65 (no units). Breathing rates ranged from 0.43 to 2.15 m3/hr. Child 8 (7 yo female) had the highest mean breathing rate (1.31 m3/hr, on foot). Note that although means are shown, actual breathing rates used in calculations were specific to GPS time-location intervals. Table 5.5 compares GPS+Model method estimates when breathing rate is weighted and when it is unweighted and assumed to be constant. The same baseline age-specific sedentary breathing rates were used for both calculations and were taken from the Child Exposure Factors Handbook (US EPA 2002). (Note that the weighted value was used in all further results and discussion.) Inhaled mass calculated with and without the activity-weighted breathing rate were significantly different over both days (n=16 child-days, paired samples t-test, p=0.05, t=2.08). The mean weighted inhaled mass over both days was 914 ng when the weighted breathing rate was applied, versus 626 ng when the constant baseline rate was applied. The greatest difference was seen for those children with the greatest activity-based weight factors, specifically child 5, child 6 and child 8.

Comparison of GPS+Model Estimates to 'Standard' Method Estimates

A 'Standard' exposure estimation method was employed to generate a benchmark to which the GPS+Model method estimates could be compared. The Standard method uses all data available from air and deposition samplers located in the community. The mean of these samplers was used to yield constant concentration and load values for each time period. No weighting was applied to the breathing rates, but age-specific 'moderate' activity level breathing rates were used throughout (US EPA 2002). As with the GPS+Model method, the transfer factor of 400cm2/hr was used to estimate skin loading. For each child, the map of GPS time-location was reviewed to assess whether difference in time, difference in environmental concentration, or both were the main contributor(s) to the difference in concentration and load estimates between methods. The following are differences by method (GPS+Model versus Standard) for each child (Tables 5.2, 5,7, 5.10).

Child 1: GPS measured 79 more minutes outside on the spray day and 7 minutes less outside on the day after the spray compared to the Standard estimate. 23% more mass inhaled (mean, both days) was estimated by the GPS+Model method compared to the Standard method. 74% more mass on skin (mean, both days) was estimated by the GPS+Model method compared to the Standard method. The difference in exposure estimates is mostly due to the difference in time.

Child 2: GPS measured 11 more minutes outside on the spray day and 44 fewer minutes outside on the day after the spray compared to the Standard estimate. 53% more mass inhaled (mean, both days) was estimated by the GPS+Model method compared to the Standard method. 99% more mass on skin (mean, both days) was estimated by the GPS+Model method compared to the Standard method. The difference in exposure estimates is mostly due to the difference in concentration and load estimates between methods.

Child 3: GPS measured 28 more minutes outside on the spray day and 43 more minutes outside on the day after the spray compared to the Standard estimate. 84% more mass inhaled (mean, both days) was estimated by the GPS+Model method compared to the Standard method. 99% more mass on skin (mean, both days) was estimated by the GPS+Model method compared to the Standard method. The difference in exposure estimates is due to both the difference in time and the difference in concentration and load estimates between methods.

Child 4: GPS measured 24 more minutes outside on the spray day and 15 fewer minutes outside on the day after the spray compared to the Standard estimate. 96% more mass inhaled (mean, both days) was estimated by the GPS+Model method compared to the Standard method. 98% more mass on skin (mean, both days) was estimated by the GPS+Model method compared to the Standard method. The difference in exposure estimates is mostly due to the difference in concentration and load estimates between methods.

Child 5: GPS measured 11 fewer minutes outside on the spray day and 16 fewer minutes outside on the day after the spray compared to the Standard estimate. 76%

more mass inhaled (mean, both days) was estimated by the GPS+Model method compared to the Standard method. 99% more mass on skin (mean, both days) was estimated by the GPS+Model method compared to the Standard method. The difference in exposure estimates is mostly due to the difference in concentration and load estimates between methods.

Child 6: GPS measured 33 fewer minutes outside on the spray day and 1 more minute outside on the day after the spray compared to the Standard estimate. 80% more mass inhaled (mean, both days) was estimated by the GPS+Model method compared to the Standard method. 99% more mass on skin (mean, both days) was estimated by the GPS+Model method compared to the Standard method. The difference in exposure estimates is mostly due to the difference in concentration and load estimates between methods. It is evident in Figure 5.7 (a) that child 6 was close to the NUTF, which is an area that the model predicts concentration and load to be much higher than the mean air and deposition sampler values. Figure 5.3 illustrates high predicted model deposition near the NUTF (upper left circle).

Child 7: GPS measured 19 more minutes outside on the spray day and 1 minute less outside on the day after the spray compared to the Standard estimate. 28% more mass inhaled (mean, both days) was estimated by the GPS+Model method compared to the Standard method. 80% more mass on skin (mean, both days) was estimated by the GPS+Model method compared to the Standard method. The difference in exposure estimates is mostly due to the difference in time on the spray day, while it is mostly due to difference in load estimates between methods on the day after the spray.

Child 8: GPS measured 28 more minutes outside on the spray day and 1 minute less outside on the day after the spray compared to the Standard estimate. 55% more mass inhaled (mean, both days) was estimated by the GPS+Model method compared to the Standard method. 80% more mass on skin (mean, both days) was estimated by the GPS+Model method compared to the Standard method. The difference in exposure estimates is mostly due to the difference in time on the spray day, while it is mostly due to difference in load estimates between methods on the day after the spray.

Table 5.2 compares time spent outside measured by GPS versus time spent outside estimated for the Standard method. For all children, mean time outside was 18 minutes more on the spray day and 5 minutes less on the day after the spray by GPS compared to the Standard estimate. The mean difference in time outside, by day, was approximately 14% by GPS, and 27% by Standard estimate. Table 5.7 compares estimates for inhalation exposure. Mean total inhaled mass estimates were significantly different when generated by these two methods (n=16 child-days, paired samples t-test, p=0.03). GPS+Model total inhaled mass for all children was approximately 4 times higher than the standard method estimate. This translates into approximately 76% more mean total inhaled mass estimated by GPS+Model than by Standard method. Table 5.10 compares estimates for dermal exposure. Mean total mass on skin was markedly different between methods (n=16 child-days, paired samples t-test, p=0.01). The GPS+Model skin load estimate is over 2 orders of magnitude (181 times) higher than the standard method estimate. This translates into approximately 99% more mean total mass on skin by GPS+Model than by Standard method.

Figure 5.10 shows data from the two estimation methods plotted against each other. The better correlation between methods was found for the prediction of total mass in air ($r2=0.83$). Correlation was much lower for total mass on skin ($r2=0.33$).

Discussion

The novel facet of this study is the dGPS tracking of children using the GPS-PAL instrument. The GPS+Model method is essentially a surrogate for personal dosimetry using traditional portable air samplers, since no personal sampling methods exist for organophosphate pesticides. The GPS and model provide time- and space-resolved exposure estimates that are greater (higher exposures) than those predicted using the Standard method. The Standard method relies on self-report time-location and sampler values that are fixed in time and space. Using GPS also affords something that cannot be measured using a personal air sampler alone: the ability to attribute exposures to specific locations. A personal air sampler can record time-specific exposure peaks, but it cannot place the peaks on a spatial map. As such, this is the first pesticide exposure study to capture the influence that subtle differences in time-location make in people's exposure.

The GPS resolution, at approximately ±3 m resolution and 5 second sampling interval, allows for delineation of very small 'micro-environments'. Traditionally a microenvironment has been defined by physical boundaries such as a room or the front yard of a home. GPS allows for what can be called 'nano-environments' to be defined. A GPS-PAL nano-environment is a circle of radius 3m (actual position plus resolution error). While nano-environments were not measured continuously in this study, once per 5 seconds is fairly close to continuous data collection, and the GPS-PAL can be set to record every second if needed. While nano-environments are discrete, they are small and there are hundreds to thousands that a person encounters throughout the course of a day. Data is no longer categorized into 5 or 10 categories as it was with studies such as NHEXAS. Figures 5.4 and 5.5 illustrate the use of continuous rather than categorical data for children's time-location. Knowing distance and direction from a source (such as a treated field) at a given time is much more powerful than a one hour recall estimate of categorized location.

The limiting factor of this study was not the time-location but the model resolution, which was restricted to 15 m and 15 minutes. The 15 m output grid was selected since this was the approximate distance between sets of air and deposition samplers. Placing the samplers closer together would have allowed the grid points to be closer together. The 15 minute time interval was delineated by the meteorological data from the nearby PAWS weather station. Collecting on-site higher time-resolution meteorological data would have allowed the time interval to be shorter. Interpolation using matrix analysis allowed for the combining of the GPS and model datasets. However, interpolation is not based on actual data points, thus introducing uncertainty into the estimate. Another source of uncertainty was the correspondence between model output values and sampler values. Correlation was good for deposition (Tsai et al. 2004) but not as good for the air and volatilization outputs. For both outputs, the discordance was adjusted by using the slope of the correlation line as a correction factor. This correction was applied before the values were used in the exposure estimates. In a future paper, error analysis of both time and space will be performed to determine the magnitude of uncertainty introduced by the model and the GPS.

The benefit of using the GPS+Model in this study was that certain nano-environments were identified as 'hot spots' in which children were exposed to a very large fraction of their overall daily pesticide mass in a small area. Often time spent in these areas was short but was sufficient to elevate total exposure well beyond what was predicted by the Standard method. In particular, the area between the deposition samplers and the nearest upwind treated field (NUTF) (Figure 5.3, upper left) contained several 'hot spots'. Five of the 8 children lived in homes in this area. The deposition samplers were on the opposite side of these homes from the NUTF, and these sampler values were used in the Standard method exposure calculations. Thus encountered deposition estimates were far lower for the Standard method than for the GPS+Model method since deposition closer to the NUTF is not factored in the Standard method. The Standard method misses the 'hot spots' entirely. As shown in Figure 5.3, the deposited pesticide mass decreases sharply as one moves away from the edge of the NUTF. Several children played right next to the NUTF along the road that runs between the field and the homes. Reviewing the exposure profiles when children were in this area, it is evident that, for children who played along the road next to the NUTF, the majority of their exposure occurred there. For children living close to the NUTF (child 2, 3, 4, 5, 6), the yard or and areas close to the house were also 'hot spots', though much less so than the road behind the homes. Child 2 (5 year old male) and child 4 (2 year old male) both spent a majority of their time outside but near the home. Child 2 spent the most time outside of all children. The majority of this time was spent on the front porch or in the front yard within 5 m of the front door. Child 4, 5, and 6 are siblings and all had relatively high exposures compared to their peers who live further from this field. These children's yard is less than 10 m from the upwind treated field.

Children as a group spent significantly more time outside on the day after the spray. However, child 3 and 4 actually spent proportionally much more time outside on the spray day. Some parents were observed to be very strict about keeping their kids inside on the spray day. Most parents prohibited their children to go outside while the crop dusters were overhead, but then allowed them out shortly thereafter. As expected, exposures were higher on the spray day for inhalation. Child 7 and 8 were an exception, since they spent a great deal of time outside on the day after the spray. Dermal exposure occurred on both days, but was mostly higher on the day after the spray due to children spending more time outside on the day after the spray.

The dermal exposure estimates presented here were influenced by the transfer factor , and are in need of further refinement. However, use of a common transfer factor for the two methods did allow a direct comparison, which was the primary purpose of this analysis. There is debate about what value(s) are legitimate for transfer factors. The transfer factor of 400 cm2/hr generated for this study from existing data (Bernard et al. 2001) was lower than the EPA policy 12 numbers (9412 cm2/hr) (US EPA 2001) but higher than other published estimates (500 cm2 per day) (Bernard et al. 2001, Williams et al. 2003). It was observed that outdoor contact with turf was common (Elgethun, personal observation), and this observation is supported by knowledge of vegetation on orthophoto maps of the community. The fact that the

GPS+Model estimate for mass on skin was 181 times higher than the standard estimate was at first suspicious. Careful review of the data revealed this is attributable to the higher resolution of the GPS+Model method on all three scales: time, space, and ground load.

The difference between GPS+Model estimates and Standard estimates is a striking finding of this study. As shown in the Results, differences in some children's exposure estimates appear to be more influenced by differences in time, while others appear to be more influenced by differences in concentration or load between the two methods. Difference in time was most influential for the three children who lived in homes farther from the NUTF (child 1, 7, 8), since they generally went to areas where the model output was close to the mean sampler values. The difference and variability in outside time measured by GPS versus measured by the 1-hour proxy diary data used in the Standard method is evident in the Chapter 5 tables. For example, child 1 during period 3 logged 47 more minutes outside by GPS than by 1-hr categorical classification (Tables 5.4, 5.6, 5.8, 5.9). Intuitively this seems like an error, since the 1-hr data was derived from the GPS. However, the 1-hr data was coded in the same manner that a diary is coded. By this protocol, the location in which the child spent the most time in a given hour is designated as the correct location for the child. The 'missing' 47 minutes were absorbed by times when the child was inside longer than outside, but was nonetheless outside. This is particularly striking if a child enters and exits a building frequently, and spends only short periods of time in either place. Hypothetically, a child could be outside for 29 minutes in a given hour but not be counted as being outside. The greatest challenge of the GPS method is correctly coding inside versus outside. This process is time consuming and would be difficult to perform accurately without visiting the field site in person.

Differences in concentration or load between the two methods was most influential on differences in exposure estimates for children who lived closer to the NUTF (child 2, 3, 4, 5, 6). The Standard method did not capture location-specific peak ground loading in areas close to fields since no deposition samplers were placed there, nor did it capture the exact elapsed time a child spends in each 'hot spot'. The model predicts very high deposition in areas that are closer to treated fields compared to the mean deposition plate values in the community. The Standard method only uses data from the plates that were not as proximal and/or downwind of treated areas. While these children were characterized as spending roughly the same time outside using the GPS data as the 1-hour categorical data, short forays into and out of 'hot spots' are not captured by the categorical time-location data.

GPS+Model mean mass on skin estimates were approximately 4000 times greater than GPS+Model inhalation estimates, but it must be noted again that these dermal exposure estimates are strongly influenced by the choice of a transfer factor. A more refined analysis of these data will need to be conducted before a final estimate of dose attributable to these two routes can be ascertained. Mass on skin confers approximately 0.5% absorption per hour (Sartorelli et al. 1998). In contrast, essentially all methamidophos is expected to absorb in the lungs and airways. If removal from abrasion and washing of skin are also considered, it reasonable to assert that 1-2% of predicted mass on skin might be absorbed. This reduces the difference between dermal and inhalation to 40-80 times different, and underscores the importance of the inhalation route. While evidence of contact with surfaces is needed to definitively say dermal exposure has occurred, only evidence of being outside is needed to definitively say inhalation exposure has occurred. In this study, time outside was quantified at high resolution, but no data were collected to quantify ground contact

A surprise in this study (based on GPS+Model data) was the lingering influx of volatilizing methamidophos in the community. This is consistent with the finding that volatility of methamidophos, as demonstrated with the volatilization emission factor model (VEFM), greatly increased during times when children were likely to be outside, and that the wetted fields acted as source from which methamidophos could re-enter the air space on days following the spray. Recommendations for avoiding exposure to treated fields should take this finding into account. Exposures to volatilized fractions has been somewhat overlooked for most pesticides. One notable exception is the risk estimation paper published by authors at California Department of Health Services (Lee et al.2002) that ranked the relative hazard of various pesticides by considering their tendency to volatilize. To the best knowledge, the current study is the first field study to quantify a spray in close proximity to people and highlight the contribution of volatilization. While OP insecticides are not highly volatile at springtime temperatures (when crops such as apples are sprayed), vapor pressure increases 300-400 fold between 30C° and 42C° (the maximum temperature on both the spray day and the day after) (Ramaprasad et al. 2004). High temperatures of 40C°+ are not uncommon in areas such as Eastern Washington and Central California during the time that tuber and vegetable crops are treated with OP insecticides.

This spray event appeared to be a good scenario in terms of drift abatement. Figure 5.1 shows that the wind was blowing drift away from the community during the time that each field was sprayed. This was a remarkable coincidence, and prevented appreciable drift of larger size fractions anywhere in the community. The crop duster pilot appeared to be very careful during this spray compared to a spray later the same year when scientists were not measuring drift (Elgethun, personal observation). During the later season spray, the pilot was observed to fly higher from the crop and not turn the nozzles off immediately upon finishing the application. During the study period, spraying was halted in the morning when winds reached greater than 10 miles per hour. Spraying resumed only when winds subsided a few hours later. Winds did shift direction toward the community from the NUTF during non-spray time periods on both days (as detailed in Chapter 4). This was reflected by relative marked increases in air concentration. Air concentration in the community appears to have peaked in the early evening hours on the spray day. Very low levels of methamidophos were recorded in indoor air samples in only a few houses, and concentrations were not significantly different from baseline. Levels were mostly below LOQ, and detects were approximately 10^7 times lower than any outdoor levels. Thus time spent indoors was not considered in exposure estimates. No methamidophos was detected on indoor surfaces.

The use of velocity as a metric of activity was a novel and logical use of the dGPS data, and the analysis is quite straightforward. The breathing rates generated using the velocity-weighting factor technique were within a realistic range for children this age (US EPA 2002). From the analysis in Table 5.5, it is clear that activity level impacts inhalation exposure, as exposure estimates using unweighted breathing rates were significantly different from those using weighted breathing rates. Recommendations for reducing exposure should be followed. Two important protective factors were documented in this study. First, staying inside and keeping the air conditioner on recirculate appeared to completely or very nearly completely exclude methamidophos from indoor air. Staying inside eliminated dermal exposure as well. Second, for residences very close to treated fields, reducing or eliminating time spent near the field (i.e. in the yard or on the road next to the NUTF) reduced exposure. Children 4, 5 and 6 who lived in the residence closest to the field all had lower exposures in other parts of the community than in their own yard.

Conclusions

This was an aerial application conducted under favorable conditions Rich Fenske for drift prevention, with the exception of the high heat and subsequent volatilization. Favorable winds that blow drift away from people cannot always be expected, though they occurred during the application events shown here. Risk reduction measures such as staying inside a closed house and keeping air conditioning on recirculate (if needed) should be emphasized for people living in communities proximal to sprayed fields. Prolongation of pesticide in air should be anticipated from volatilization in hot weather, and people should consider staying inside an extra day after a spray event or leaving town for a few days. Play outside should be minimized during and several days after a spray event. Play near fields should be prevented for at least several pesticide half-lives (foliar half-life of methamidophos = 3 days). Proposed US EPA pesticide label statements mandating zero threshold for drift were revised in 2002 to state that drift should not contact people, animals and sensitive sites. It is not clear how these label statements will be enforced.

The GPS+Model prediction method generated exposure estimates that were significantly higher than those predicted by the Standard method. This underscores the importance of characterizing elapsed time in specific higher exposure areas (using GPS), and characterizing areas of peak exposure risk (using modeling). Short, intermittent periods where children go outside are captured by GPS, but are not captured by a lower resolution instrument such as a diary with 1-hr time intervals. Concentration and load in areas close to fields where no sampler data are available can be generated using modeling. The greatest challenge of the GPS method is correctly coding inside versus outside. This process is time consuming and would be difficult to perform accurately without visiting the field site in person.

The utility and resolution of dGPS tracking of human subjects was well demonstrated by this study. Nano-environments as small as 3 m in radius can be characterized using GPS and thus small pesticide 'hot-spots' can be located. The transience of drift and the hyper kinetic movement of children were both documented at high resolution. The intersection of the moving receptors (children) with the moving area-source contaminant was nicely characterized. Categorical time-location data can now be replaced with continuous high-resolution data, making dynamic microenvironment monitoring possible.

Table 5.1. Sample collection schedule

SAMPLE TYPE	JULY APPLICATION		
	Pre-application	*Application day*	*Post-application day*
GPS tracking	Evening hours	All waking hours	All waking hours
Surface wipes			1 per home
Apple wipes	1 per home		1 per home
Indoor air samples	2 per home	1 per home	1 per home
Deposition samples	5 targets	2 sets of 22 targets (AM and PM)	
Residential yard air samples	1 per home	2 per home	1 per home
Community air samples	1 or 2 per location	2 per location	1 or two per location

Table 5.2. Total time spent outside (min) measured by dGPS and by 1hr categorization of dGPS data for 'standard method'

	Spray Day 7.12		Day After Spray 7.13			
	GPS+MODEL	STANDARD	GPS+MODEL	STANDARD	*% difference	
					GPS	STD
Child 1	199	120	173	180	-13.1	+33.4
Child 2	251	240	76	120	-69.7	-50.0
Child 3	148	120	223	180	+33.6	+33.4
Child 4	84	60	45	60	-46.4	0
Child 5	169	180	224	240	+24.6	+25.0
Child 6	207	240	181	180	-12.6	-25.0
Child 7	19	0	179	180	+89.4	+100.0
Child 8	28	0	179	180	+84.4	+100.0
Mean	138	120	160	165	+13.8	+27.3

*% difference in time spent outside, by day, for each method, calculated by the formula:

$$\%\text{difference by day} = \frac{100\,(t_{das} - t_{sd})}{t_{sd}}$$

t_{das} = time outside on day after spray
t_{sd} = time outside on spray day

Table 5.3. Weight factors (unitless) from linear velocity of children and corresponding breathing rates (m^3/hr)

		Spray Day		Day After Spray	
		†Weight Factor	^Breathing Rate	†Weight Factor	^Breathing Rate
Child 1	On Foot				
(5 yo F)	*Mean*	1.28	0.510	1.16	0.460
	Range	1-4.95	0.400-1.98	1-5.10	0.400-2.04
Child 2	On Foot				
(5 yo M)	*Mean*	1.15	0.460	1.08	0.430
	Range	1-3.89	0.400-1.56	1-2.39	0.400-0.960
Child 3	On Foot				
(8 yo M)	*Mean*	1.33	0.630	1.20	0.560
	Range	1-4.96	0.470-2.33	1-4.70	0.470-2.20
Child 4	On Foot				
(2 yo M)	*Mean*	1.36	0.48	1.43	0.50
	Range	1-4.97	0.35-1.74	1-5.09	0.35-1.78
Child 5	On Foot				
(11 yo M)	*Mean*	1.58	0.740	1.46	0.690
	Range	1-6.65	0.470-3.13	1-5.11	0.470-2.40
	On Bicycle				
	Mean	1.96	0.920	1.76	0.830
	Range	1-4.92	0.470-2.31	1-5.00	0.470-2.35
Child 6	On Foot				
(10 yo F)	*Mean*	1.41	0.660	1.30	0.610
	Range	1-5.61	0.470-2.64	1-5.07	0.470-2.38
	On Bicycle				
	Mean	1.70	0.800	1.83	0.860
	Range	1-3.36	0.470-1.58	1-3.26	0.470-1.53
Child 7*	On Foot				
(4 yo F)	*Mean*	1.25	0.500	1.18	0.470
	Range	1-4.00	0.400-1.60	1-5.11	0.470-2.04
Child 8	On Foot				
(7 yo F)	*Mean*	2.79	1.31	1.18	0.550
	Range	1-4.69	0.470-2.20	1-5.11	0.470-2.40

*Child 7 uses Child 8 (sister) data as surrogate for day after spray. Child 7 data incomplete due to GPS malfunction. Sisters spent majority of time together on this day.
†Mean Standard Velocities used in Calculations: On Foot =1.22 m/s, On Bicycle = 2.44 m/s. Velocity in Car does not influence breathing rate, weight = 1 (Knoblauch et al. 1996).
Weight factor is calculated from velocity by the following formula:
1 + (measured velocity / mean standard velocity)
^Baseline Sedentary Breathing Rate: Children 2yo = 0.35 m3/hr, Children 3-5.9 yo = 0.40 m3/hr, Children 6-12 yo = 0.47 m3/hr (Adams et al. 1993; US EPA 2002). Means shown. Breathing rates used in exposure calculations were specific to each time-location / time-velocity measurement registered by dGPS.

Table 5.4. 'GPS+Model' method predicted air exposure (encountered air concentration) and mass inhaled, by time period

#	Age	Sex	◊Date/Time		* Mean Concentration (ng/m3)	Mean Inhalation Rate (m3/hr)	^Time (min) Outside *In Town*	*Out Town*	Total Mass Inhaled (ng)
1	5	F	7-12	5:30-10:30	0.00	.010	3	0	0
			7-12	10:30-16:30	0.00	.780	29	0	0
			7-12, 7-13	16:30-9:30	182	.500	167	0	236
			7-13	9:30-18:30	68.8	.460	173	0	87.0
2	5	M	7-12	5:30-10:30	2060	.440	11	0	153
			7-12	10:30-16:30	2060	.470	76	0	1140
			7-12, 7-13	16:30-9:30	48.4	.460	164	0	65.3
			7-13	9:30-18:30	71.0	.430	76	0	38.8
3	8	M	7-12	5:30-10:30	1610	.520	22	0	285
			7-12	10:30-16:30	2680	.660	97	0	2620
			7-12, 7-13	16:30-9:30	1260	.600	29	0	370
			7-13	9:30-18:30	144	.570	223	0	300
4	2	M	7-12	5:30-10:30	2030	.440	19	0	280
			7-12	10:30-16:30	0.00	**	0	0	0
			7-12, 7-13	16:30-9:30	208	.600	16	49	112
			7-13	9:30-18:30	245	.580	45	0	86.8
5	11	M	7-12	5:30-10:30	1900	.500	5	0	78.3
			7-12	10:30-16:30	3520	.860	49	0	2560
			7-12, 7-13	16:30-9:30	337	.780	62	53	504
			7-13	9:30-18:30	214	.720	224	0	586
6	10	F	7-12	5:30-10:30	2020	.490	22	0	361
			7-12	10:30-16:30	3280	.810	68	0	3040
			7-12, 7-13	16:30-9:30	473	.670	59	58	694
			7-13	9:30-18:30	210	.670	181	0	423
7	4	F	7-12	5:30-10:30	0.00	**	0	0	0
			7-12	10:30-16:30	245	.680	1	0	1.79
			7-12, 7-13	16:30-9:30	29.4	.400	2	16	3.45
			7-13	9:30-18:30	67.2	.470	179	0	86.9
8	7	F	7-12	5:30-10:30	453	.570	12	0	38.4
			7-12	10:30-16:30	244	.680	1	0	2.26
			7-12, 7-13	16:30-9:30	34.4	.400	2	13	3.41
			7-13	9:30-18:30	67.2	.560	179	0	102

◊First two and beginning of third time period = spray day 7.12; end of third and fourth time period = day after spray 7.13

*Mean concentration is the mean of all concentrations 'encountered' during that period. Out of town air concentration is included in the mean where relevant.

**Child inside, inhalation not calculated

^Time outdoors used in GPS+Model calculations measured by GPS with sampling rate of 5 seconds.

Table 5.5. Comparison of 'GPS+Model' method predicted mass inhaled (ng) with and without activity-weighted breathing rate

Child #	Spray Day 7.12		Day After Spray 7.13		MEAN Both Days	
	Weighted	Unweighted	Weighted	Unweighted	Weighted	Unweighted
1	236	203	87.0	79.5	162	141
2	1350	1240	38.8	36.2	696	638
3	3270	2590	300	252	1790	1420
4	392	348	86.8	73.5	239	211
5	3150	1790	586	375	1970	1080
6	4090	2480	423	336	2340	1410
7	5.24	4.54	86.9	80.2	46.1	42.4
8	44.1	41.4	102	94.1	73.0	67.8
Mean	1570	1090	214	166	*914	*626

*Inhaled mass with and without inhalation weight factor significantly different, p=0.05 (paired samples t-test, t = 2.08). N=16 child-days.

Table 5.6. 'Standard' method predicted air exposure (fixed air concentration) and mass inhaled, by time period

#	Age	Sex	◊Date/Time		*Fixed Conc (ng/m3) In Town	Out Town	^Time (min) In Town	Out Town	†Inh. Rate (m3/hr)	Total Mass Inhaled (ng)
1	5	F	7-12	5:30-10:30	142	.026	0	0	0.90	0.00
			7-12	10:30-16:30	415	.005	0	0	0.90	0.00
			7-12, 7-13	16:30-9:30	102	.002	120	0	0.90	183
			7-13	9:30-18:30	24.0	.001	180	0	0.90	66.0
2	5	M	7-12	5:30-10:30	142	.026	0	0	0.96	0.00
			7-12	10:30-16:30	415	.005	60	0	0.96	399
			7-12, 7-13	16:30-9:30	102	.002	180	0	0.96	292
			7-13	9:30-18:30	24.0	.001	120	0	0.96	46.9
3	8	M	7-12	5:30-10:30	142	.026	0	0	0.96	0.00
			7-12	10:30-16:30	415	.005	60	0	0.96	399
			7-12, 7-13	16:30-9:30	102	.002	60	0	0.96	97.4
			7-13	9:30-18:30	24.0	.001	180	0	0.96	70.4
4	2	M	7-12	5:30-10:30	142	.026	0	0	0.78	0.00
			7-12	10:30-16:30	415	.005	0	0	0.78	0.00
			7-12, 7-13	16:30-9:30	102	.002	0	60	0.78	1.65
			7-13	9:30-18:30	24.0	.001	60	0	0.78	19.1
5	11	M	7-12	5:30-10:30	142	.026	0	0	1.50	0.00
			7-12	10:30-16:30	415	.005	60	0	1.50	624
			7-12, 7-13	16:30-9:30	102	.002	60	60	1.50	155
			7-13	9:30-18:30	24.0	.001	240	0	1.50	147
6	10	F	7-12	5:30-10:30	142	.026	60	0	1.26	179
			7-12	10:30-16:30	415	.005	60	0	1.26	524
			7-12, 7-13	16:30-9:30	102	.002	60	60	1.26	131
			7-13	9:30-18:30	24.0	.001	180	0	1.26	92.4
7	4	F	7-12	5:30-10:30	142	.026	0	0	0.90	0.00
			7-12	10:30-16:30	415	.005	0	0	0.90	0.00
			7-12, 7-13	16:30-9:30	102	.002	0	0	0.90	0.00
			7-13	9:30-18:30	24.0	.001	180	0	0.90	66.0
8	7	F	7-12	5:30-10:30	142	.026	0	0	0.90	0.00
			7-12	10:30-16:30	415	.005	0	0	0.90	0.00
			7-12, 7-13	16:30-9:30	102	.002	0	0	0.90	0.00
			7-13	9:30-18:30	24.0	.001	180	0	0.90	66.0

◊First two and beginning of third time period = spray day 7.12; end of third and fourth time period = day after spray 7.13

*'In town' fixed concentration is the arithmetic mean of measured values from all 9 air samplers within the community for a given time period. 'Out town' fixed concentration is a value from a single air sampler upwind of the treated fields for a given time period.

^Time is measured by categorical grouping of GPS time-location data using 1 hour time blocks.

†Inhalation rates are age and gender specific estimates for 'moderate' exertion given in the US EPA Child Exposure Factors Handbook (USEPA 2002).

Table 5.7. Comparison of mass inhaled by two methods (ng)

Child #	Spray Day 7.12 GPS+MODEL	Spray Day 7.12 STD	Day After Spray 7.13 GPS+MODEL	Day After Spray 7.13 STD	MEAN BOTH DAYS GPS+ MODEL	MEAN BOTH DAYS STD	*%diff
1	236	183	87.0	66.0	162	124	-23.0
2	1350	692	38.8	46.9	696	369	-53.0
3	3270	497	300	70.4	1790	284	-84.1
4	392	1.65	86.8	19.1	239	10.4	-95.7
5	3150	779	586	147	1970	463	-76.5
6	4090	834	423	92.4	2340	463	-80.2
7	5.24	0	86.9	66.0	46.1	33.0	-28.3
8	44.1	0	102.0	66.0	73.0	33.0	-54.8
Mean	1570^	373~	214^	71.7~	914†	222†	-75.7

*%difference by method = $\frac{100\,(m_{std} - m_{gm})}{m_{gm}}$

m_{std} = mass by standard method
m_{gm} = mass by GPS+Model method

^ ~ Inhaled mass for all children (within method) significantly different on spray day compared to the day after the spray (paired samples t-test; GPS+Model p =0.04; Std p=0.04). N=8 children.

†Total inhaled mass for all children (between methods) significantly different (paired samples t-test, p= 0.03, t=2.46). N=16 child-days.

Lung absorption of methamidophos is likely complete (100%)
(at 32C, Water solubility >200g/l, VP = 0.0075 torr)
No losses or saturation is expected to occur.

Table 5.8. 'GPS+Model' method predicted deposition exposure (encountered ground load) and mass on skin, by time period

#	Age	Sex	◊Date/Time		*Mean Ground Load *In Town* (ug/cm2)	^Transfer Coefficient (cm2/hr)	† Time (min) Outside *In Town*	Total Mass on Skin (ug)
1	5	F	7-12	5:30-10:30	.005	400	3	.110
			7-12	10:30-16:30	.070	400	29	12.7
			7-12, 7-13	16:30-9:30	.110	400	167	126
			7-13	9:30-18:30	.050	400	173	54.0
2	5	M	7-12	5:30-10:30	4.19	400	11	284
			7-12	10:30-16:30	1.19	400	76	603
			7-12, 7-13	16:30-9:30	6.39	400	164	6990
			7-13	9:30-18:30	.300	400	76	151
3	8	M	7-12	5:30-10:30	.190	400	22	26.8
			7-12	10:30-16:30	2.59	400	97	1670
			7-12, 7-13	16:30-9:30	7.39	400	29	1440
			7-13	9:30-18:30	3.37	400	223	5020
4	2	M	7-12	5:30-10:30	.520	400	19	65.5
			7-12	10:30-16:30	0.00	400	0	0
			7-12, 7-13	16:30-9:30	.270	400	16	30.5
			7-13	9:30-18:30	1.11	400	45	332
5	11	M	7-12	5:30-10:30	.130	400	5	4.10
			7-12	10:30-16:30	16.8	400	49	5470
			7-12, 7-13	16:30-9:30	7.64	400	62	3140
			7-13	9:30-18:30	11.7	400	224	17400
6	10	F	7-12	5:30-10:30	.770	400	22	113
			7-12	10:30-16:30	6.44	400	68	2820
			7-12, 7-13	16:30-9:30	9.49	400	59	3650
			7-13	9:30-18:30	11.8	400	181	14200
7	4	F	7-12	5:30-10:30	0.00	400	0	0
			7-12	10:30-16:30	.250	400	1	1.09
			7-12, 7-13	16:30-9:30	.060	400	2	.760
			7-13	9:30-18:30	.120	400	179	147
8	7	F	7-12	5:30-10:30	.040	400	12	2.87
			7-12	10:30-16:30	.240	400	1	1.30
			7-12, 7-13	16:30-9:30	.060	400	2	.670
			7-13	9:30-18:30	.120	400	179	147

◊First two and beginning of third time period = spray day 7.12; end of third and fourth time period = day after spray 7.13

*Mean ground load is the mean of ground load that was 'encountered' for all GPS time intervals during that period. No out of town ground load is expected.

^A turf transfer factor of 400 cm2/hr was determined for all dermal calculations (from data by Bernard et al. 2001).

†Time outdoors used in GPS+Model calculations measured by GPS with sampling rate of 5 seconds.

Table 5.9. 'Standard' method predicted deposition exposure (fixed ground load) and mass on skin, by time period

#	Age	Sex	◊Date/Time		* Fixed Ground Load (ug/cm2) *In Town*	^Total Time (min) *In Town*	†Transfer Coeff (cm2/hr)	Mass on Skin (ug)
1	5	F	7-12	5:30-10:30	.019	0	400	0.00
			7-12	10:30-16:30	.025	0	400	0.00
			7-12, 7-13	16:30-9:30	.025	120	400	20.0
			7-13	9:30-18:30	.025	180	400	30.0
2	5	M	7-12	5:30-10:30	.019	0	400	0.00
			7-12	10:30-16:30	.025	60	400	10.0
			7-12, 7-13	16:30-9:30	.025	180	400	30.0
			7-13	9:30-18:30	.025	120	400	20.0
3	8	M	7-12	5:30-10:30	.019	0	400	0.00
			7-12	10:30-16:30	.025	60	400	10.0
			7-12, 7-13	16:30-9:30	.025	60	400	10.0
			7-13	9:30-18:30	.025	180	400	30.0
4	2	M	7-12	5:30-10:30	.019	0	400	0.0
			7-12	10:30-16:30	.025	0	400	0.0
			7-12, 7-13	16:30-9:30	.025	0	400	0.0
			7-13	9:30-18:30	.025	60	400	10.0
5	11	M	7-12	5:30-10:30	.019	0	400	0.00
			7-12	10:30-16:30	.025	60	400	10.0
			7-12, 7-13	16:30-9:30	.025	60	400	10.0
			7-13	9:30-18:30	.025	240	400	40.0
6	10	F	7-12	5:30-10:30	.019	60	400	7.60
			7-12	10:30-16:30	.025	60	400	10.0
			7-12, 7-13	16:30-9:30	.025	60	400	10.0
			7-13	9:30-18:30	.025	180	400	30.0
7	4	F	7-12	5:30-10:30	.019	0	400	0.00
			7-12	10:30-16:30	.025	0	400	0.00
			7-12, 7-13	16:30-9:30	.025	0	400	0.00
			7-13	9:30-18:30	.025	180	400	30.0
8	7	F	7-12	5:30-10:30	.019	0	400	0.00
			7-12	10:30-16:30	.025	0	400	0.00
			7-12, 7-13	16:30-9:30	.025	0	400	0.00
			7-13	9:30-18:30	.025	180	400	30.0

◊First two and beginning of third time period = spray day 7.12; end of third and fourth time period = day after spray 7.13

*Fixed concentration is the arithmetic mean of measured values from all 18 deposition plates within the community for a given time period.

^Time is measured by categorical grouping of GPS time-location data using 1 hour time blocks.

†A turf transfer factor of 400 cm2/hr was determined for all dermal calculations (from data by Bernard et al. 2001).

Table 5.10. Comparison of skin load (mass on skin) by two methods (ug)

	Spray Day 7.12		Day After Spray 7.13		MEAN BOTH DAYS		
Child #	GPS+MODEL	STD	GPS+MODEL	STD	GPS+ MODEL	STD	*% diff
1	139	20.0	54.3	30.0	96.4	25.0	-74.1
2	7880	40.0	151	20.0	4010	30.0	-99.2
3	3140	20.0	5020	30.0	4080	25.0	-99.4
4	96.0	0.00	332	10.0	214	5.00	-97.7
5	8620	20.0	17400	40.0	13000	30.0	-99.8
6	6580	28.0	14200	30.0	10400	29.0	-99.7
7	1.85	0.00	147	30.0	74.4	15.0	-79.8
8	4.84	0.00	147	30.0	75.9	15.0	-80.2
Mean	3310	15.9	4680	27.5	3990†	22†	-99.4

$$\text{*\%difference by method} = \frac{100\,(m_{std} - m_{gm})}{m_{gm}}$$

m_{std} = mass by standard method
m_{gm} = mass by GPS+Model method

Total mass on skin for all children (within method) NOT significantly different on spray day compared to the day after the spray (paired samples t-test; GPS+Model, $p=0.47$; Std, $p=0.09$). N= 8 children.

†Total mass on skin for all children (between methods) significantly different (paired samples t-test, $p=0.01$, $t = 2.86$). N= 16 child-days.

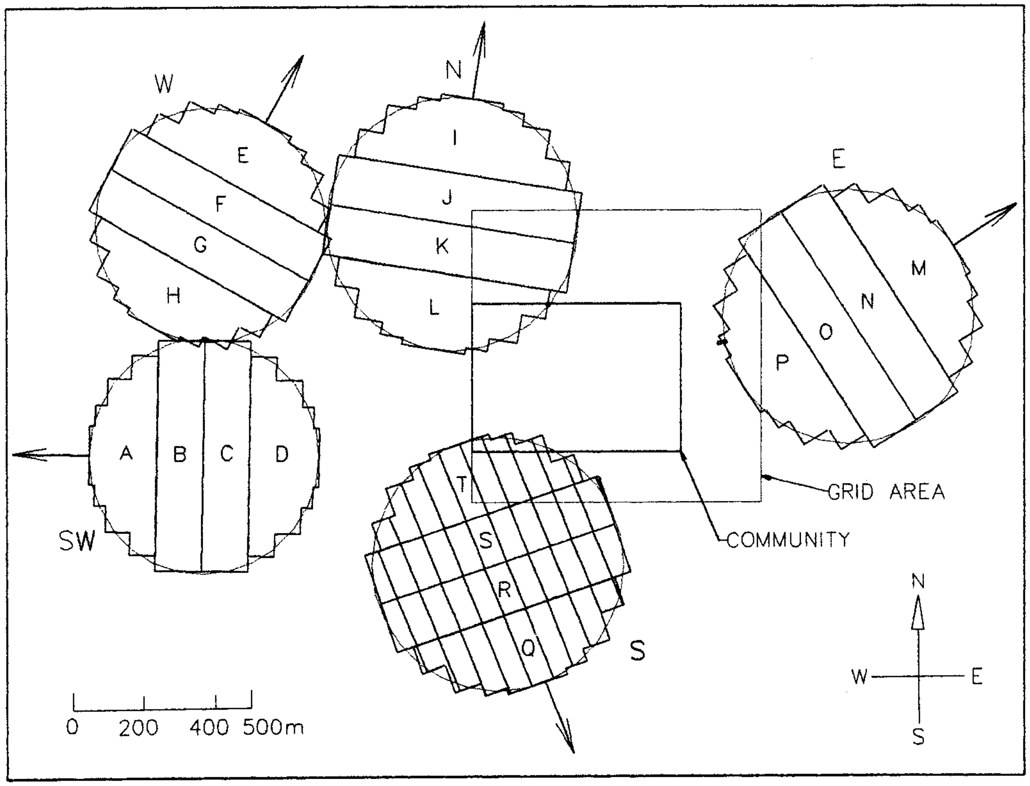


Figure 5.1. Map of community and surrounding fields showing wind direction and order in which fields were sprayed.
The community area is indicated by the smaller rectangle within the grid area. There are five potato crop circles: SW, W, N, E, and S. The arrows indicate the initial 15-minute wind direction when spraying began on that particular field. The letters A-Q represent 15-minute swathes that were laid by the plane. (Adapted from Tsai et al., submitted 2004).

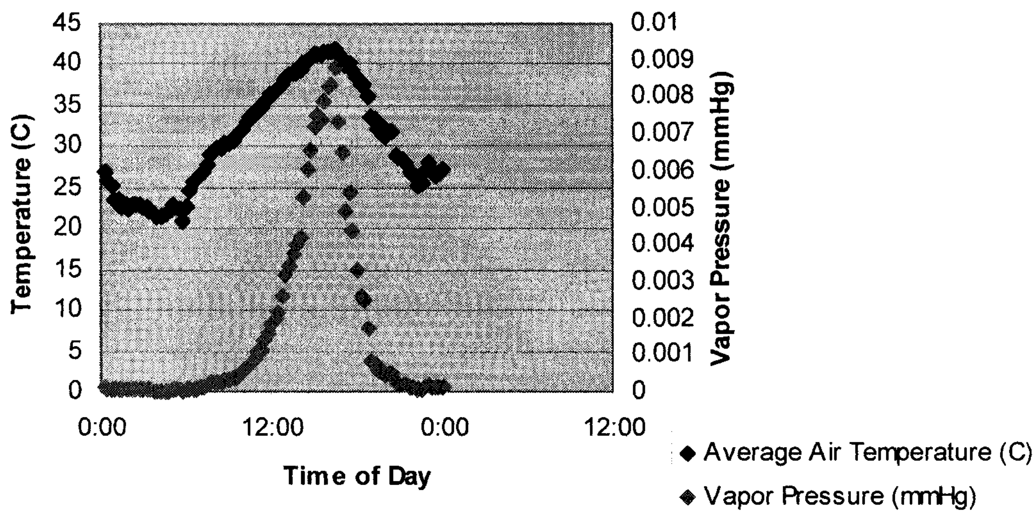


Figure 5.2: Variation in temperature and vapor pressure on the day of the spray (adapted from Ramaprasad et al., submitted 2003).

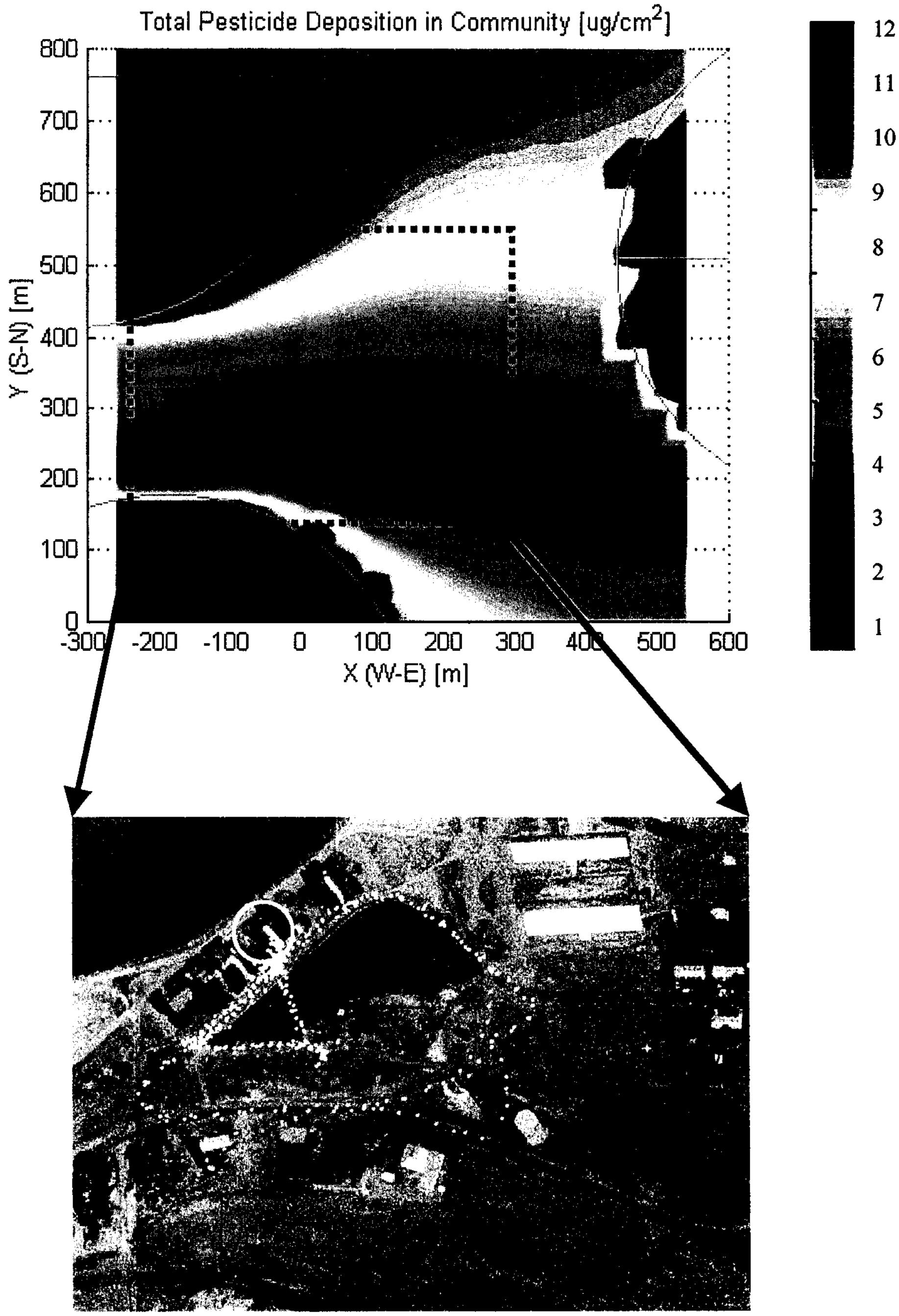
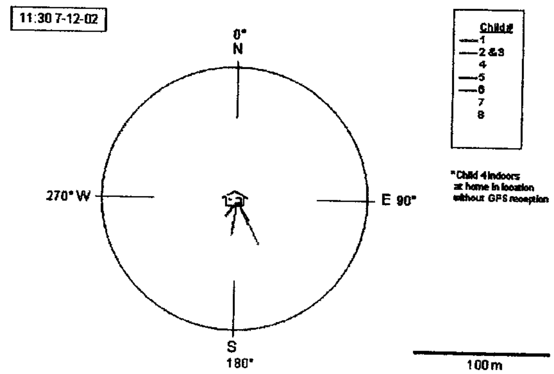
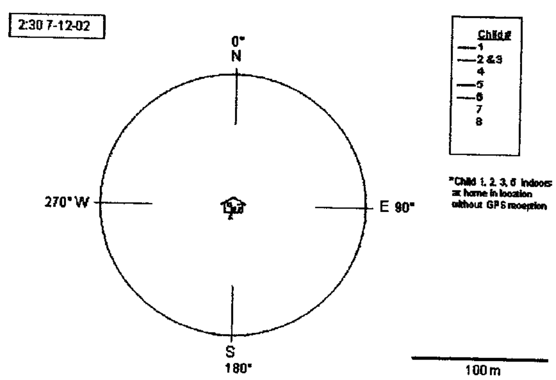


Figure 5.3. Spray day deposition contour map with pull-out detail of child's one-hour outdoor path immediately following last spray

Path traveled by child 6 (10 yo female) who spent the most total time outside; 7/12/02, immediately following 2nd spray. (Shown: 46 minutes outside between 3-4pm). Child's residence is circled.

Figure 5.4: Distance and direction from the center of the home for 8 children at 3 time points on day of pesticide spray event (7-12-2002)


11:30 7-12-02
0°
N
270° W
E 90°
S
180°
Child#
1
2 &3
4
5
6
7
8
*Child 4 indoors at home in location without GPS reception
100m


2:30 7-12-02
0°
N
270° W
E 90°
S
180°
Child#
1
2 &3
4
5
6
7
8
*Child 1, 2, 3, 6 indoors at home in location without GPS reception
100m

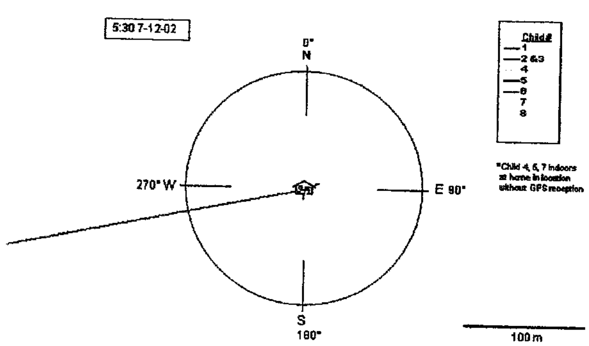
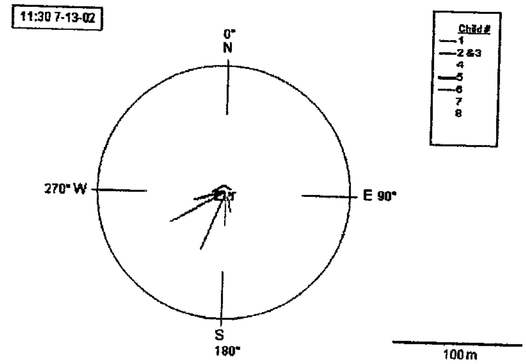
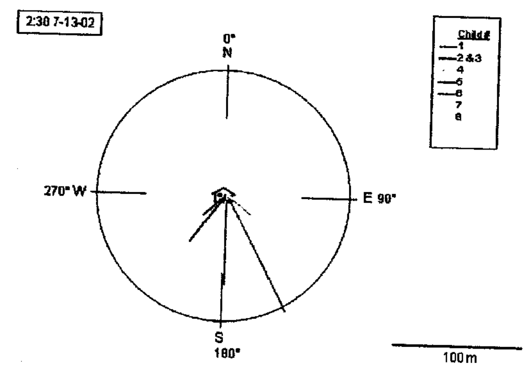
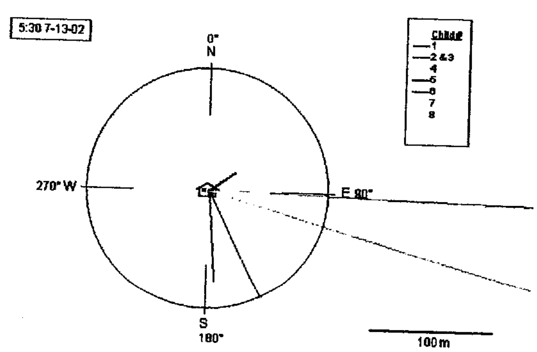

5:30 7-12-02
0°
N
270° W
E 90°
S
180°
Child#
1
2 &3
4
5
6
7
8
*Child 4, 6, 7 indoors at home in location without GPS reception
100m

Figure 5.5: Distance and direction from the center of the home for 8 children at 3 time points on day after pesticide spray event (7-13-2002)


11:30 7-13-02
0°
N
270° W
E 90°
S
180°
Child #
1
2 &3
4
5
6
7
8
100m


2:30 7-13-02
0°
N
270° W
E 90°
S
180°
Child #
1
2 &3
4
5
6
7
8
100m


5:30 7-13-02
0°
N
270° W
E 90°
S
180°
Child #
1
2 &3
4
5
6
7
8
100m

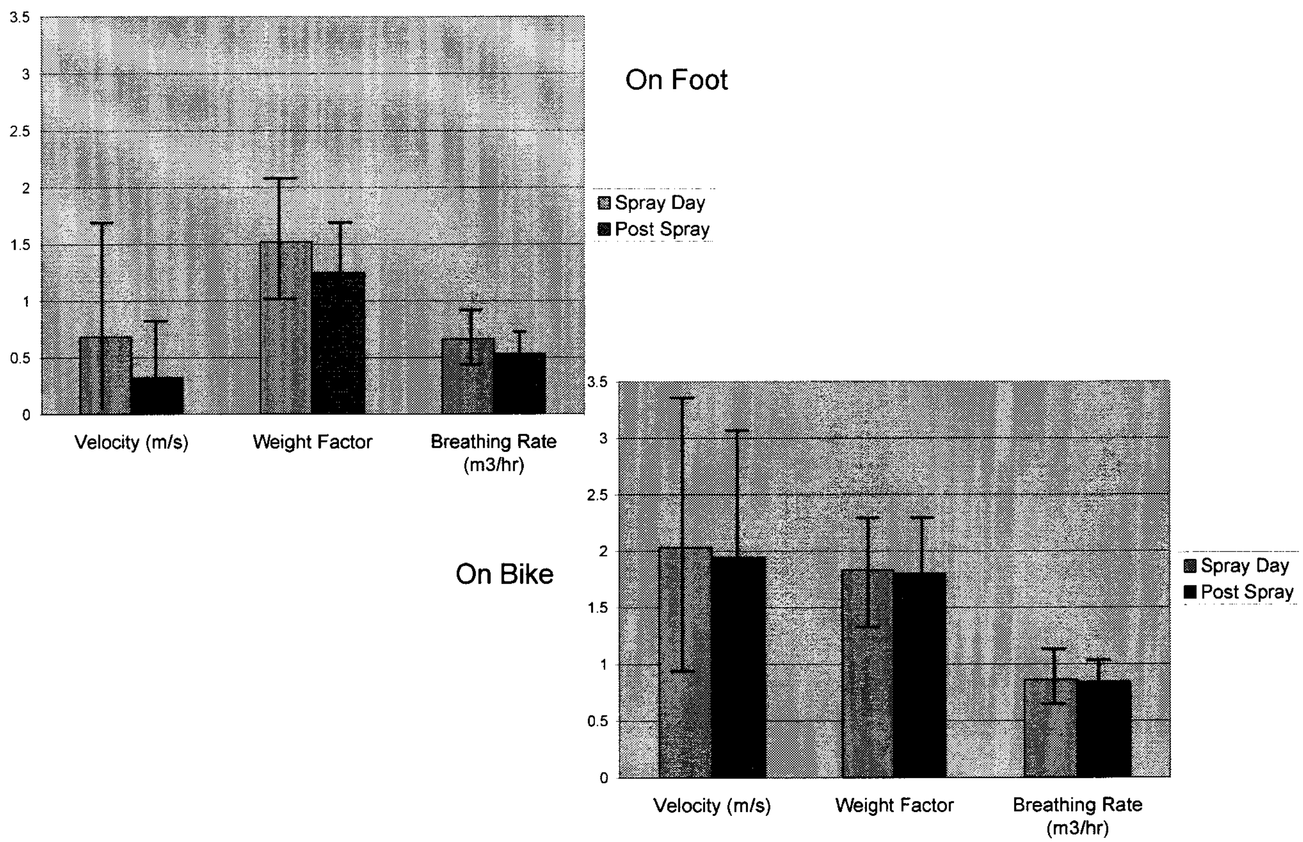
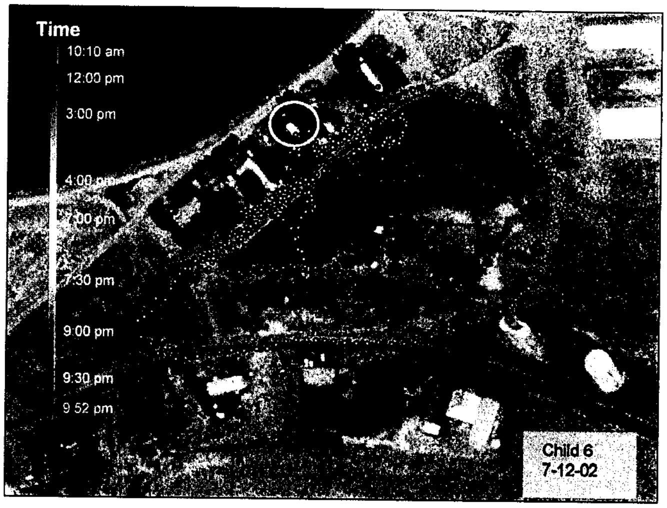
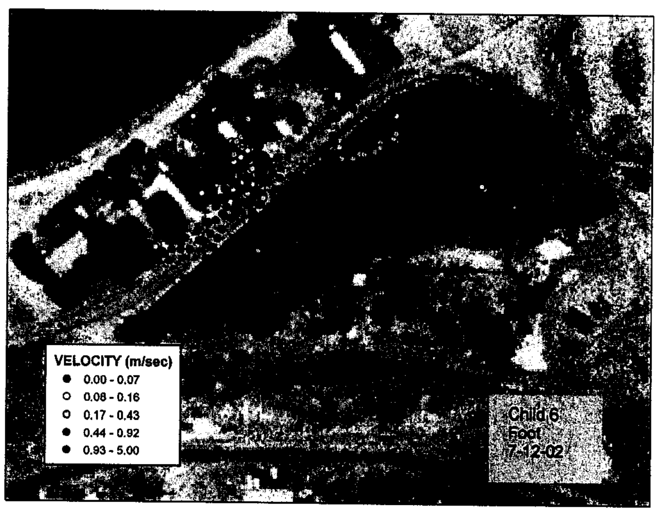


Figure 5.6: Velocity, weight factor, and subsequent breathing rate for all children

Figure 5.7. dGPS time-location (a) and velocity (b, c) for one child (child 6, 10 yo F) on the spray day
Velocity on foot (b) is separated from velocity on bicycle (c) because breathing rate is weighted differently for each activity. Child's residence is circled in (a).


Time
10:10 am
12:00 pm
3:00 pm
4:00 pm
7:00 pm
7:30 pm
9:00 pm
9:30 pm
9 52 pm
Child 6
7-12-02

(a)

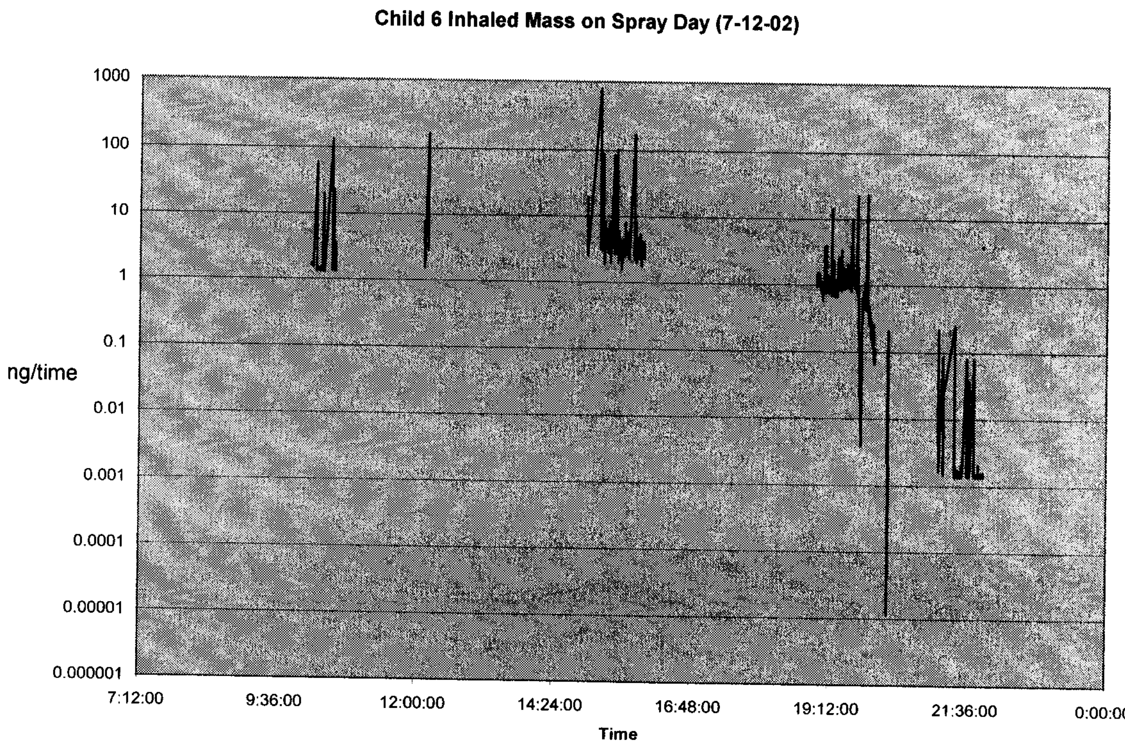

VELOCITY (m/sec)
0.00 - 0.07
0.08 - 0.16
0.17 - 0.43
0.44 - 0.92
0.93 - 5.00
Child 6
Foot
7-12-02

(b)


VELOCITY (m/sec)
0.01 - 0.74
0.75 - 1.24
1.25 - 1.60
1.61 - 2.95
2.96 - 5.00
Child 6
Bicycle
7-12-02

(c)

Figure 5.8. Log-scale inhalation exposure profiles for one child (child 6, 10 yo F) on the spray day and the day after spray.
Scale is 0.000001-1000 ng. Inhaled mass is greater on the spray day than on the day after.


Child 6 Inhaled Mass on Spray Day (7-12-02)
1000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
ng/time
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time

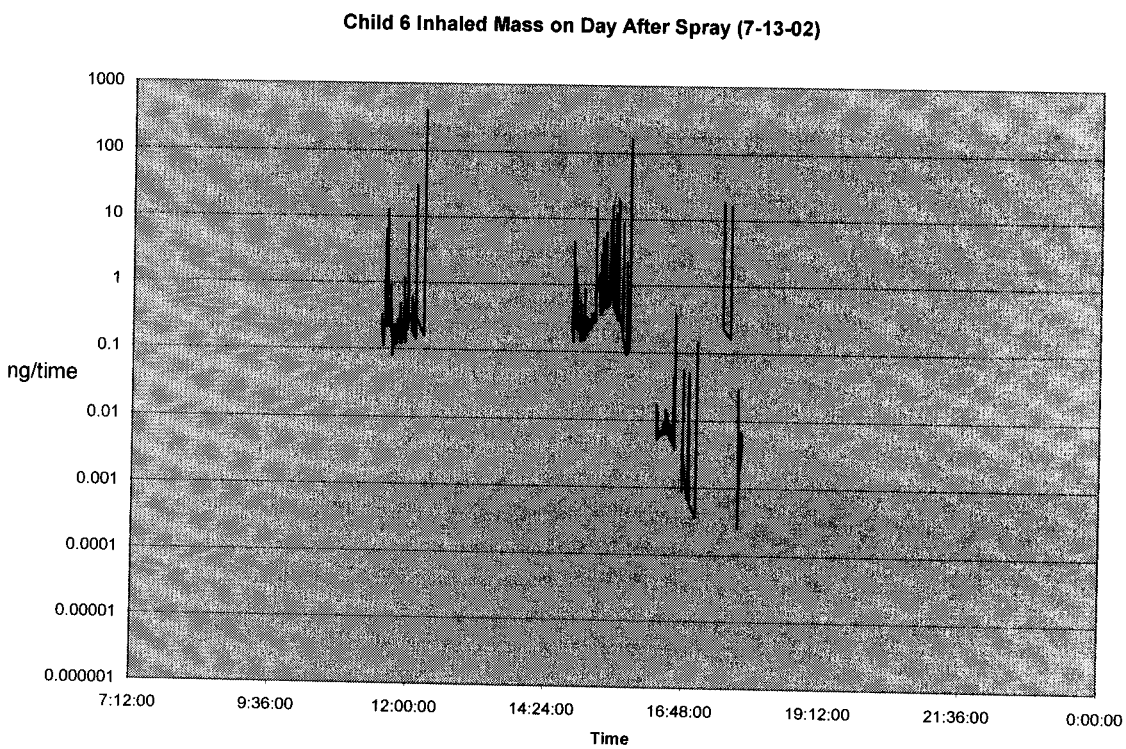
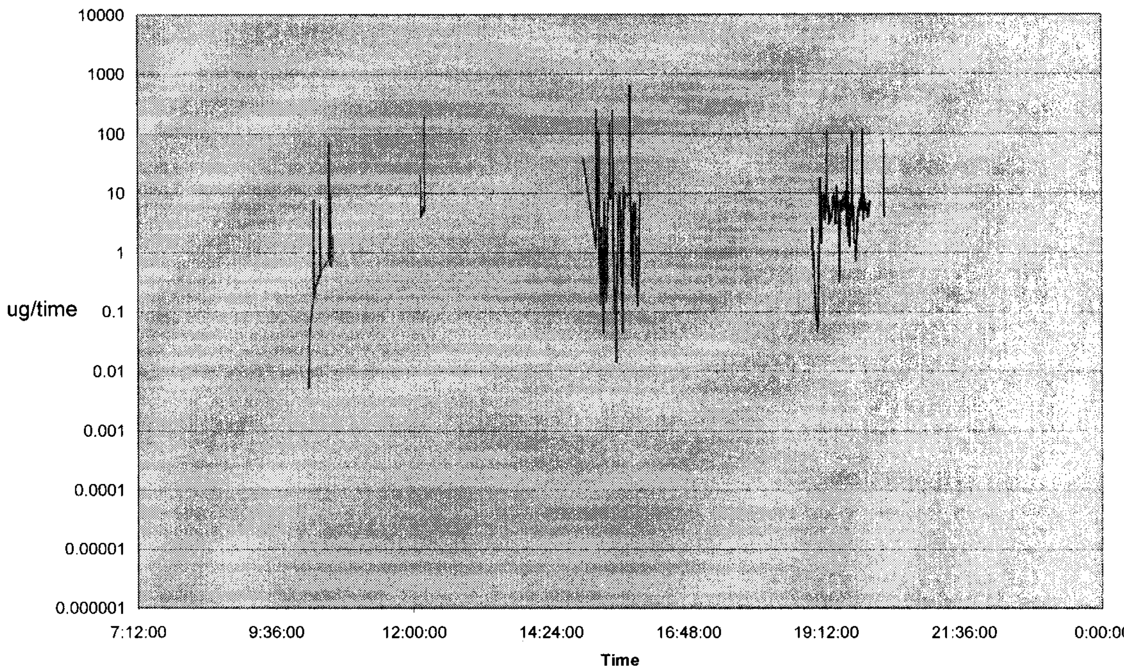
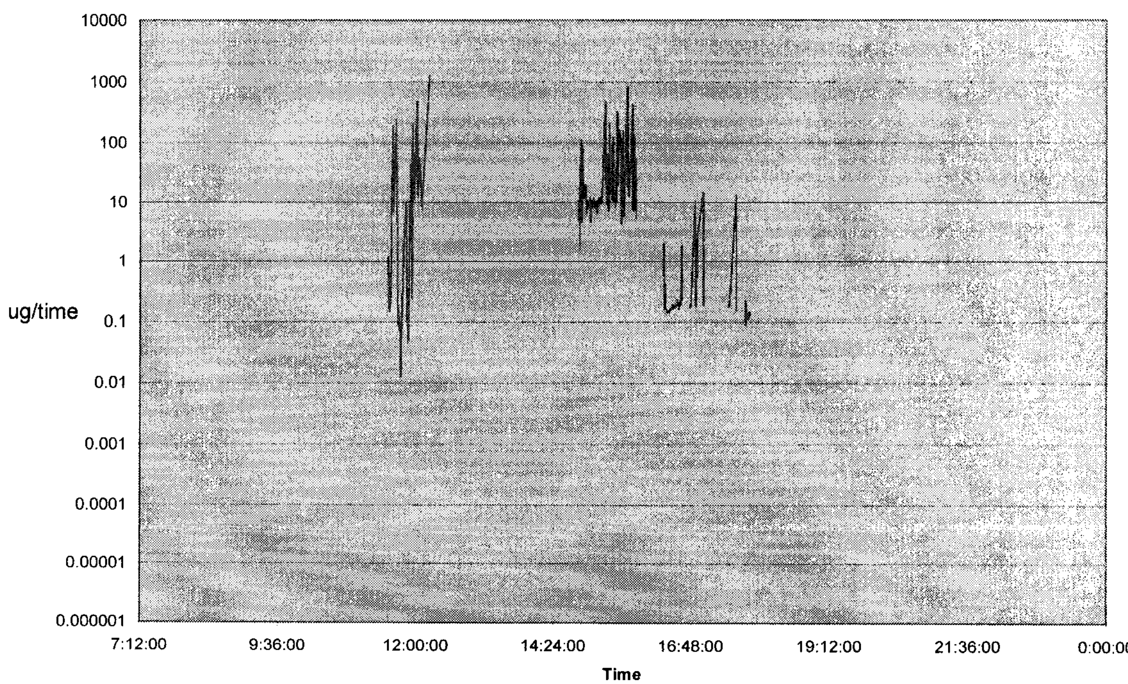

Child 6 Inhaled Mass on Day After Spray (7-13-02)
1000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
ng/time
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time

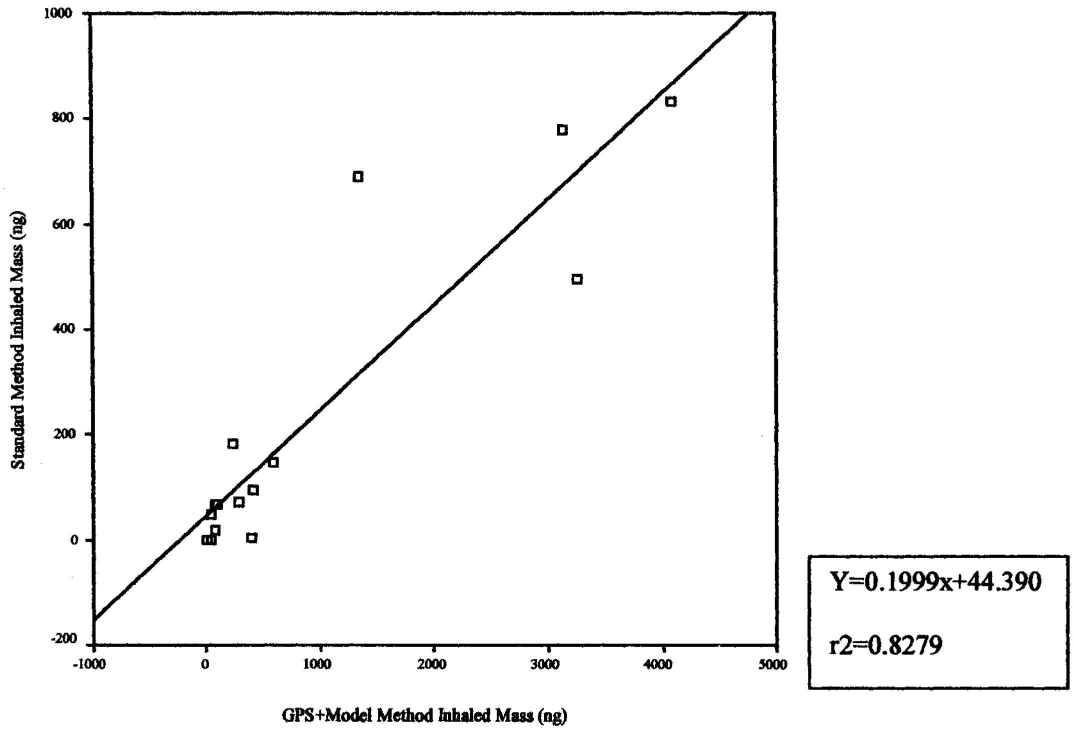
Figure 5.9. Log-scale dermal exposure profiles for one child (child 6, 10 yo F) on the spray day and the day after spray.
Scale is 0.000001 – 1,000 ug. . Skin loading is higher on the day after spray day than on the spray day.

Child 6 Skin Mass on Spray Day (7-12-02)



Child 6 Skin Mass on Day After Spray (7-13-02)





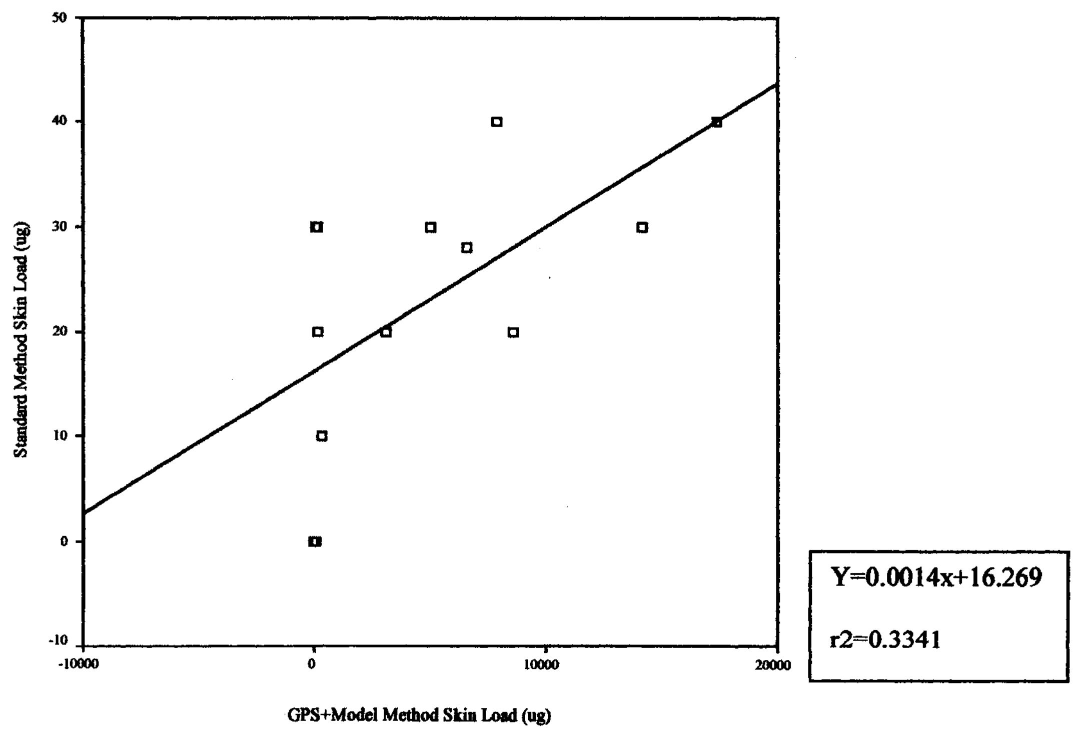


Figure 5.10: Comparison of inhaled mass and skin load by two estimation methods ('GPS+Model' method vs. 'Standard' method)

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Chapter 6

Summary & Conclusions

Children in agricultural communities can potentially be exposed to organophosphates and other pesticides by a number of pathways. This body of work focused on the drift pathway. Drift has been well characterized before, but this dissertation is unique in its calculation of the dynamic interaction between moving receptors (children) and the transient peaks in pesticides in areas proximal to treated fields. Characterization of this interaction would have been impossible without high-resolution time-location data. The novel component of this dissertation was the development, validation and use of a dGPS instrument (the GPS-PAL) to attain high-resolution, low subject burden time-location data. dGPS may very well revolutionize exposure assessment by providing continuous data in place of customary categorical data for people's time-location. GIS has already revolutionized the spatial understanding of injury and disease determinants, and is an integral part of visualizing and analyzing the dGPS data. dGPS and GIS are important facets of human spatial analysis. Epidemiology, medical geography, and environmental health will continue to benefit and progress from these technologies.

Chapter 1 provided a needs assessment and rationale for: 1) studying children's exposure to pesticides, and the drift pathway in particular; and 2) a dGPS datalogging instrument to gather high-resolution human time-location data. Children are a susceptible population in regard to toxins such as organophosphates (OPs). Children's organs are not fully developed and cannot detoxify OPs as well as adults. Children have a greater body surface area to mass ratio and a higher breathing rate to mass ratio than adults and thus can receive relatively larger doses. Children consume much more fresh fruit and juices that are more likely to consume OPs than do adults. Children have behaviors that predispose them to greater exposure, including playing on the ground and generally being more active than adults. Children also are at greater potential risk due to their continuing neural development. Evidence in animal models has suggested inhibition of neurite growth resulting from chronic exposure to OPs, which are nerve toxins of questionable toxic threshold (Dap and Barrone 1999; Slotkin et al. 2001).

In regards to the drift pathway, some drift away from fields is inevitable given the physical properties of OPs and the physics of droplets produced from spray nozzles. An important finding of this dissertation (as informed by the work of Tsai and Ramaprasad) was the relative contribution of volatilized pesticide to human exposure when OPs are sprayed in hot summer weather. OPs being moderately volatile at lower temperatures, this exposure route had not been well considered before. Proximity has been shown in past retrospective (conducted sometime after sprays occur) studies to be a factor that influences children's exposure to pesticides. For this prospective study, proximity was seen as a major factor for drift exposure during and immediately after a spray. Especially when the winds are light or blowing away from residences, the pesticide concentration gradient is steep with increasing distance from treated field. By utilizing dGPS tracking, proximity was not confined to residence-to-field measurement but was extended to child's kinetic movement relative to fields. The children studied in the dissertation drift study lived and played so close to treated fields (5-20m away) that proximity was very important for the drift pathway.

Chapter 1 introduced the idea that dGPS can provide not only time-location but also time-activity in the form of linear velocity. Velocity can then be normalized and used to adjust breathing rates. This novel approach had not been explored previously in the exposure assessment field. Velocity weighting did prove to be feasible, as shown in Chapters 4 and 5, and made a significant difference in exposure estimates. Unfortunately, no simple inference between velocity and behavior affecting dermal loading can be made. A shortcoming of the dissertation's studies was the inability to quantify *in situ* activity. Datalogging accelerometers are commercially available and can quantify this, but they were cost-prohibitive for this study. The concluding message is that technology (dGPS, GIS and accelerometry) exists to replace assumptions about time location and activity with quantifiable measures. It is logical to use and improve upon existing technology for furthering exposure assessment.

Chapter 2 contains the paper published in *Environmental Health Perspectives* in 2003. This paper validated the GPS-PAL instrument and documented the abilities and limitations of using dGPS for tracking human subjects. This paper prompted an invitation to participate in the US EPA National Children's Study planning workshop in May 2003. It is inevitable that exposure assessment will move forward with new technologies such as GPS. In summary, Chapter 2 covers three important parameters: reception, resolution, and interference. Lack of reception limits the utility of GPS inside concrete and metal framed buildings, though the time of entry and exit into the building (an important bit of data) are known. The GPS-PAL can be set to record as often as every second, which generally helps overcome limitations of moderate or spotty reception, since the mean sampling rate is still several times per minute, because many buildings allow moderate reception. Reception inside vehicles is both moderate and spotty due to metal shielding. RF interferences also can cause episodic poor reception. Total interferences other than buildings are rare, and were determined to be from powerful EMF and RF emitters. Chapter 2 was somewhat limited by its small study population.

To that end, the field studies described in Chapter 3 involved 5 times more subjects than the initial pilot in Chapter 2. 35 children participated in the Seattle study. Time-location data has typically been collected using self-report diaries, as covered in the literature review in Chapter 1. For studies of young children, a parent will fill out a diary for the child. Diaries suffer two obvious shortcomings: recall is difficult, and resolution (number of categories, length of each time interval recorded) is limited. As shown in Chapter 2, dGPS tracking of people is now feasible, and may be used as a tool to evaluate and improve time-location diaries. The concordance between the GPS-PAL and the widely-used NHEXAS diary timeline was poor. The GPS-PAL was shown to be a useful tool for illuminating where (in which categories) subjects were most likely to make reporting errors in the diary. Another finding in the Seattle study was that low literacy (both English and Spanish) was a major obstacle to the successful completion of a diary for some parents. In contrast, compliance with the GPS-PAL protocol was not affected by literacy. An important outcome of the Chapter 3 field studies was evidence that dGPS presents a new approach for time-location analysis by eliminating the need to categorize data. A person's exact position (distance and direction) relative to landmarks and contaminant sources is recorded. dGPS can be used by itself for small studies now (such as the Washington Aerial Spray Drift Study covered in Chapters 4 and 5), and could potentially improve diaries for large studies. Based on current trends in consumer and commercial GPS hardware, dGPS should be cost-permissive for large studies in the near future.

Chapter 4 presented dGPS data for 8 children in context of the aerial pesticide spraying of the potato fields surrounding their community in SE Washington State. Children and their environment were monitored intensively while methamidophos was applied to the fields. Based on GPS data, most children were noted to be active (from velocity data) and outside both days, spending slightly more time outside on the day after the spray. Potato farmers were amenable to participating in the study because they were concerned about an EPA docket (OPP-00730) entitled "Draft Guidance for Pesticide Registrants on New Labeling Statements for Spray and Dust Drift Label Statements for Pesticide Products (Appendix 4E). The proposed label statement would have imposed a 'no drift whatsoever' sanction for methamidophos, a rule thought to be unfair and unrealistic by farmers. The spray monitored for this study was executed conscientiously and under ideal weather conditions. Appreciable drift of pesticide droplets onto non-crop areas was confined to an area very close to the field, with deposition 20 m into the community 10^3 lower than deposition on the edge of the treated field. Deposition was highest in the morning, while air concentration was highest in the late afternoon and evening, 4-6 hours after the end of the initial drift period, suggesting the importance of volatilization for air exposure. The temperature exceeded 40C on the spray day and the day after, causing a higher volatilization rate than expected. Deposition was found on playground equipment and outdoor toys as well as on deposition targets, but no pesticide was found on indoor surfaces, and indoor air concentrations were not significantly different from baseline and were $>10^7$ lower than any detect outside. Based on personal observation, it is believed this was due to residents' vigilance at keeping houses closed up, and due to recirculating air conditioners. Handwipes showed detectable but relatively low skin loading on children's hands, but this was confounded by lack of information about other washing and bathing events. This appeared to be a good spray in terms of drift abatement. Winds were uncannily cooperative for the spray pilots, allowing them to spray at the exact time when wind direction blew away from the community.

A few common sense behaviors were observed that appeared to be protective. Keeping houses closed and air conditioners on recirculate appears to have been effective at blocking drift into homes. Staying at a distance greater than 50 m from the nearest upwind treated field also kept children isolated from the highest residues and air concentrations. Based on dGPS data, it was discovered that two children went to stay with relatives in the next community (about 10 km away) where there was no spraying during part of the spray day, a behavior that is advisable for children living within very close proximity to the fields. Contact with outdoor surfaces should also be minimized in the period following the spray. Leaving for the day greatly reduces inhalation exposure, but avoiding dermal exposure requires avoidance of drifted areas for at least several days. The Washington Aerial Spray Drift Study was successful at pointing out these simple behavioral changes, was successful at demonstrating the contribution of volatilization to airborne pesticide, and successful at generating exposure profiles unique to each child. Chapter 5 focused on the process and outcome of generating these profiles.

In Chapter 5, environmental samples were used to calibrate high-resolution deposition and air models. This modeling was submitted in two publications separate from the dissertation (Tsai et al. 2004 and Ramaprasad et al. 2004). dGPS and model data were combined to generate longitudinal exposure profiles, and to compute exposure attributable to dermal and inhalation routes. The models predicted that low levels of methamidophos continued to volatilize from the treated crop for many hours after the application. Deposition ended quickly following the last application. Using a transfer factor of 400 cm2/hr calculated from recent turf transferable residue data (Bernard et al. 2001), the dermal route was predicted to be a more major exposure route than inhalation by several orders of magnitude. However, given that inhaled pesticide mass is expected to absorb completely, while less than 5% might absorb from skin contact, the attributable dose from dermal contact is considerably less than the skin load. Arguably, more confidence can be placed in the inhalation estimate than the dermal estimate, since frequency and duration of contact with ground was not measured in this study. It is not certain what fraction ingestion (diet or non-dietary) might contribute to the overall methamidophos exposure.

GPS+Model estimates were 3.5 times higher for inhaled mass and 181 times higher for dermal mass than Standard method estimates. For some children, the difference in time-location recorded for each method was the main contributor to the difference in exposure estimates. For other children, particularly those living closest to the nearest upwind treated field, the difference in air concentration and ground load predicted by the model was the main contributor to differences in exposure estimates. This was because the standard method relied on sampler data, and no samplers were placed right next to the fields. These children played within 5 m of the nearest upwind treated field, slightly closer to the treated area than the nearest air sampler and much closer than the nearest deposition sampler. The findings underscore the importance of characterizing elapsed time in specific higher exposure areas (using GPS), and characterizing areas of peak exposure risk (using modeling). Short, intermittent periods where children go outside are captured by GPS, but are not captured by a lower resolution instrument such as a diary with 1-hr time intervals. Concentration and load in areas close to fields where no sampler data are available can be generated using modeling. 'Nano-environments' of approximately 3 m radius can be sampled as often as every second using the GPS+Model method. The greatest challenge of the GPS method is correctly coding inside versus outside. This process is time consuming and would be difficult to perform accurately without visiting the field site in person.

Uncertainty introduced by the model is also a shortcoming of this method. The model is limited by the temporal and spatial resolution of the available input data.

Parents were generally wise about keeping children indoors during the time crop dusters were overhead, and the winds were protective for most of the spray day. Also, crop duster pilots knew we were watching them, so the halo effect cannot be underestimated. In reality, normal drift from routine spraying of these fields might be appreciably higher, and thus deposition and air concentration would be higher. However, that is not to say that exposure is imminent. Exposure can be minimized if parents follow the recommendations noted above. Leaving the community for the day is an easy solution to avoiding the majority of the air concentration. Guiding children to play in areas sufficiently far (>100m) from the nearest upwind treated fields also makes good sense. Play near fields should be prevented for at least several pesticide half-lives (foliar half-life of methamidophos = 3 days).

This study did show that the US EPA zero tolerance for drift proposed label statement was unrealistic, and that children's exposures can be minimized by a conscientiously-applied spray. The issue of risk from this exposure level is debatable. The best policy is to do everything possible to minimize exposure regardless of projected dose. The label statement for methamidophos, as it reads right now, is still somewhat unrealistic and should be revisited. The current statement calls for no drift onto inhabited buildings, people, or sensitive areas. Inhabited buildings would have to be removed from this statement to make most farmers in compliance. Millions of arable acres would be lost, or people would need to be relocated. This is a serious dilemma if US EPA is earnest about imposing the letter of the law. Since enforcement is limited in some states, the best tact as environmental health scientists is to advise behaviors that will minimize or eliminate exposure. Since methamidophos is only sprayed on these fields 3-4 times every 3 years (crops are rotated and cover crops are not sprayed), risk communication and intervention campaigns would not be as time-intensive, and could realistically work. It was inspirational that both community members and farmers were so cooperative, and a great gratitude is owed to these stakeholders.

The importance of GPS tracking and modeling for capturing the transience of drift in relation to the hyperkinetic movement of moving receptors (children) was well demonstrated by this study. GPS, GIS and other spatial technology may become requisite tools for the environmental health scientist. The location and sequential patterns of exposure clearly matter in the overall exposure picture. The visualization of these patterns yields insight that has been lacking from the field of exposure assessment. Spatial data will likely become increasingly important for informing effective exposure prevention strategies.

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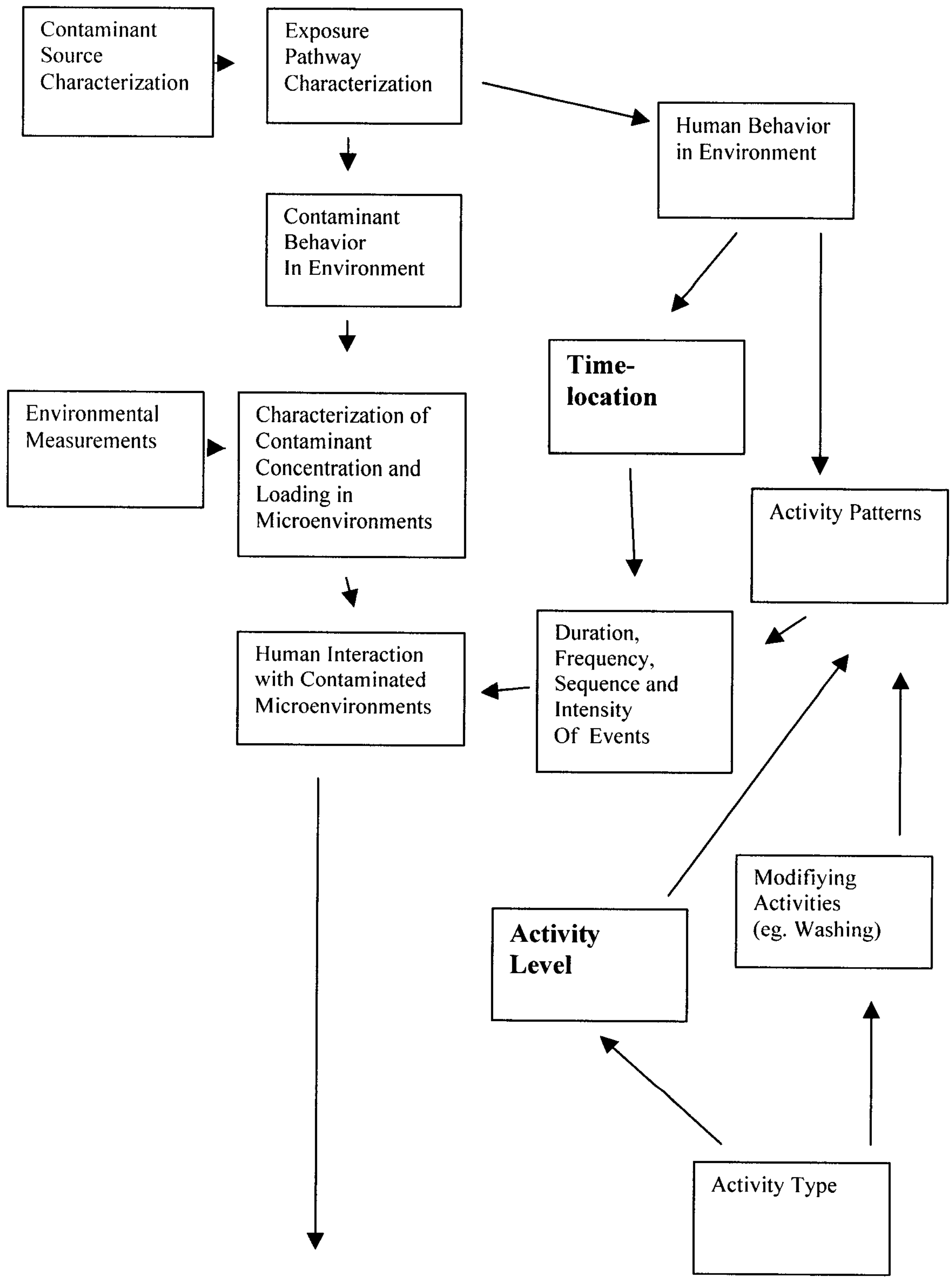
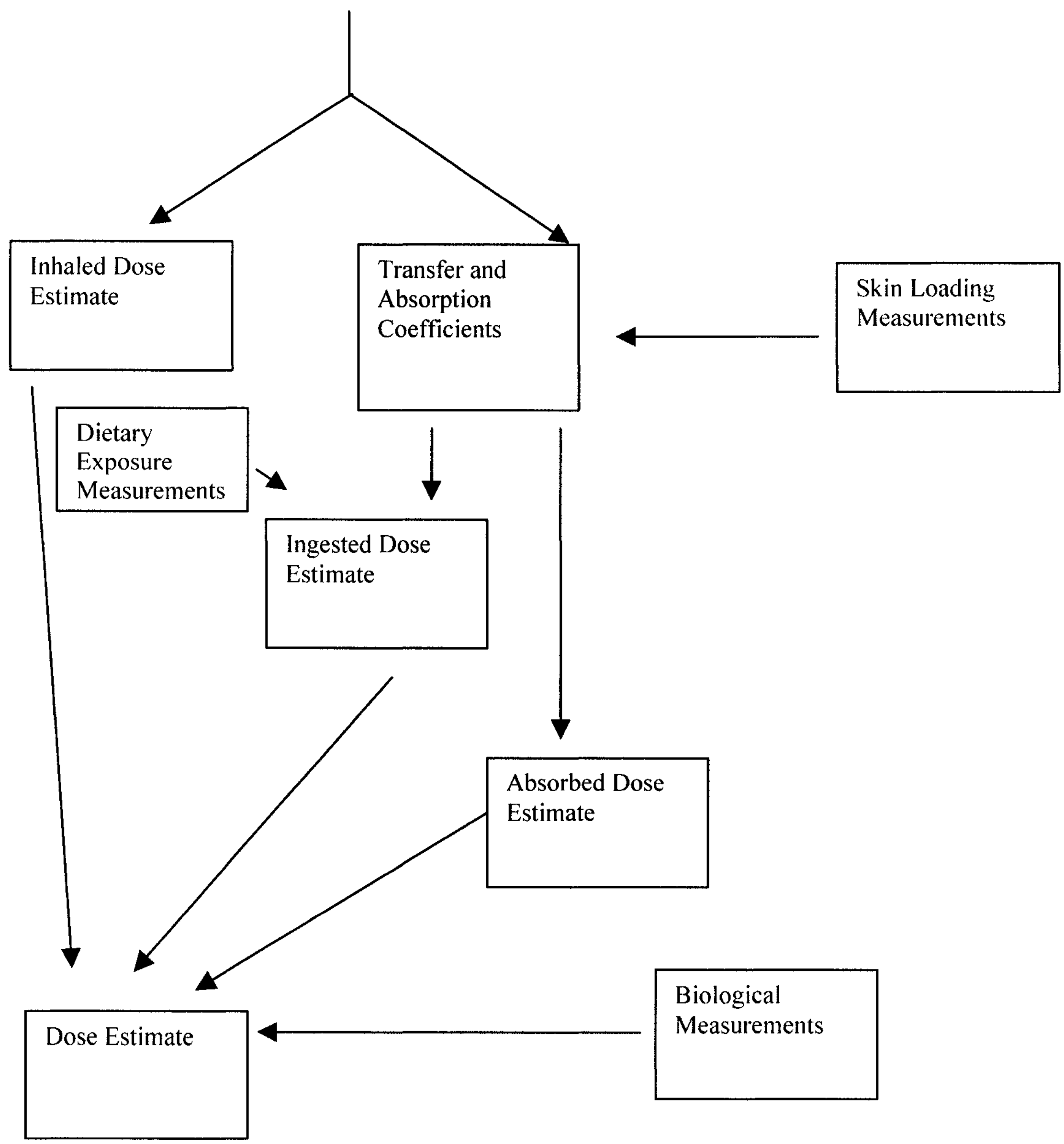
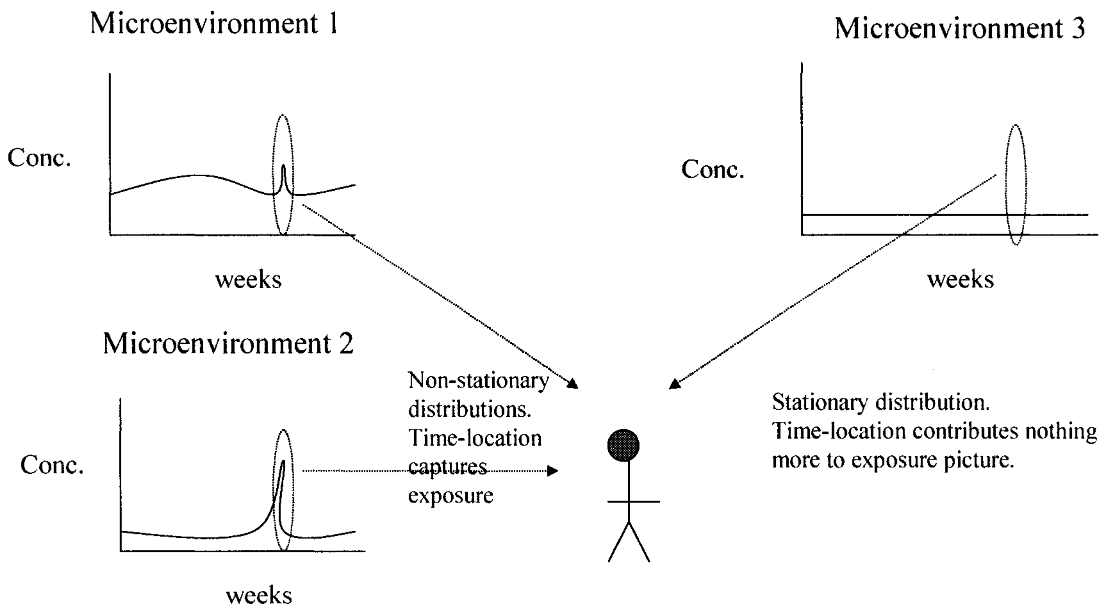
Appendix 1A
Framework:
The role of time-location and activity level analysis in exposure assessment




Inhaled Dose Estimate
Transfer and Absorption Coefficients
Skin Loading Measurements
Dietary Exposure Measurements
Ingested Dose Estimate
Absorbed Dose Estimate
Biological Measurements
Dose Estimate

Appendix 1 B

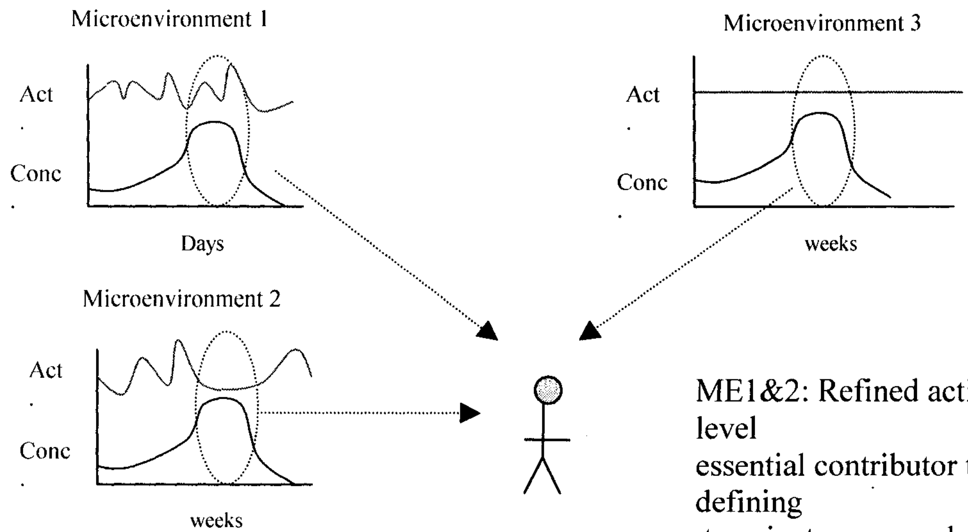
Framework:
Why is a refined time-location measure important to exposure assessment?



Moving receptor with transient contaminant release

Here a person can be considered the receptor. To capture a person's exposure to a 'spike' release such as a pesticide spray event requires high-resolution time-location measurement. In other words, a detailed account of where a person goes over a short time scale is needed to tell us his time spent in each microenvironment.

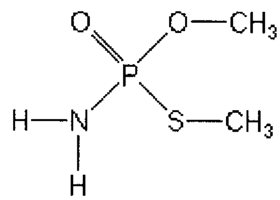
Appendix 1 C
Framework:
Why is a refined activity level measure important to exposure assessment?



ME1&2: Refined activity level
essential contributor to defining
transient exposure level

ME3: Default assumption

<u>Moving, variably-active receptor with transient contaminant release</u>
Here a person can be considered the receptor. To capture a person's exposure to a 'spike' release such as a pesticide spray event requires high-resolution time-location measurement AND activity level measurement to determine variation in breathing rate. In other words, a detailed account of breathing rate within microenvironments is needed to assess how much contaminant was inhaled.



$C_2H_8NO_2PS$

Appendix 4.A. Methamidophos
(*O,S*-dimethyl phosphoramidothioate)

Appendix 4B. Recruitment poster.

Appendix 4C. Potato crop with center pivot irrigation.

Appendix 4D. Community playground, looking south toward the PAWS weather station.

Appendix 4E

ENVIRONMENTAL PROTECTION AGENCY
"Draft Guidance for Pesticide Registrants on New Labeling Statements for Spray and Dust Drift Mitigation"

Summary of the Agency's Position on Drift

The Agency has the responsibility to ensure that the use of pesticides will not cause unreasonable adverse effects to human health and the environment. Those involved in pesticide application decisions have an important responsibility to protect people, domestic animals, wildlife, and the environment from pesticide exposures and potential harm from drift. States, tribes, and EPA have responsibilities to carry out enforcement to ensure compliance with pesticide use requirements.

EPA's position on pesticide drift is that applicators must not allow spray or dust drift to contact people, animals, and certain sensitive sites, including structures people occupy at any time, and the associated property, parks and recreation areas, nontarget crops, aquatic, wetland areas, woodlands, pastures, and rangelands. The Agency believes this is prudent public policy. It sets high but appropriate standards for applicators to protect people and the environment. Applicators must consider and use necessary application practices and measures required by states or tribes in addition to mandatory drift control measures that are stated on product labels.

EPA realizes this position sets high but appropriate standards for applicators to protect people and the environment. However, the Agency believes that this policy will not have an undue impact on agriculture or other uses of pesticides. Rather, this policy

[[Page 44143]]

and new labeling will clarify expectations of applicators and set definitive standards for application practices. The Agency also believes that in addition to improved labeling a very important component for controlling drift is training and education of applicators and others involved in pesticide application decisions about the causes and consequences of drift, control methods, and legal requirements.

D. Other Options EPA Considered for Labeling

EPA considered a variety of other options for label statements for spray drift mitigation, some of which were offered by stakeholders. These other labeling options and the Agency's reactions are discussed below. The Agency welcomes comment on these other options.

Label Statement Option-``Do not Allow Spray Drift''

This option, which EPA has required on some product labels, oversimplifies and conflicts with the Agency's conclusions of the supporting scientific data that some de minimus degree of drift will occur as part of nearly all pesticide applications. Nevertheless, recognizing the inadequacies of this statement and its appearance on numerous product labels for many years, we believe that it has been effectively and practically enforced by EPA, states, and tribes. Enforcement authorities have used their discretion to pursue violations based on their evaluation of those cases where there may have existed the potential for an effect or concern for exposures and risks to off-target people, animals, plants, and the environment.

Label Statement Option-``Do not Allow Drift to Cause Adverse Effects''

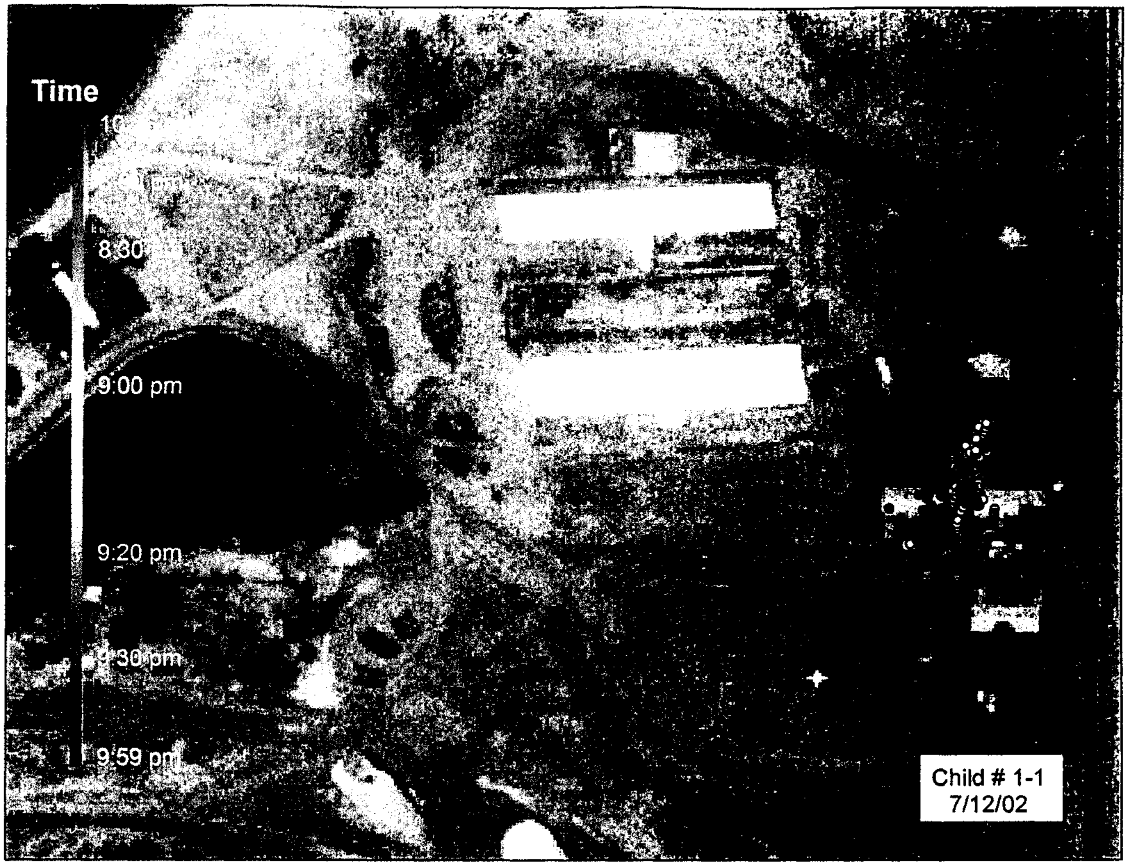
EPA believes this statement is problematic from an enforcement perspective because the burden of proof must be shifted from the simple fact of drift to the ``effect'' of drift, which is less compatible with the nature of evidence gathered in field investigations. This would require the determination of the definition of ``adverse effects'' under numerous circumstances on a case-by-case basis.

An additional problem with this label statement is it suggests to applicators that drift is acceptable unless someone recognizes and reports effects and appropriate authorities rule the effects are ``adverse.''

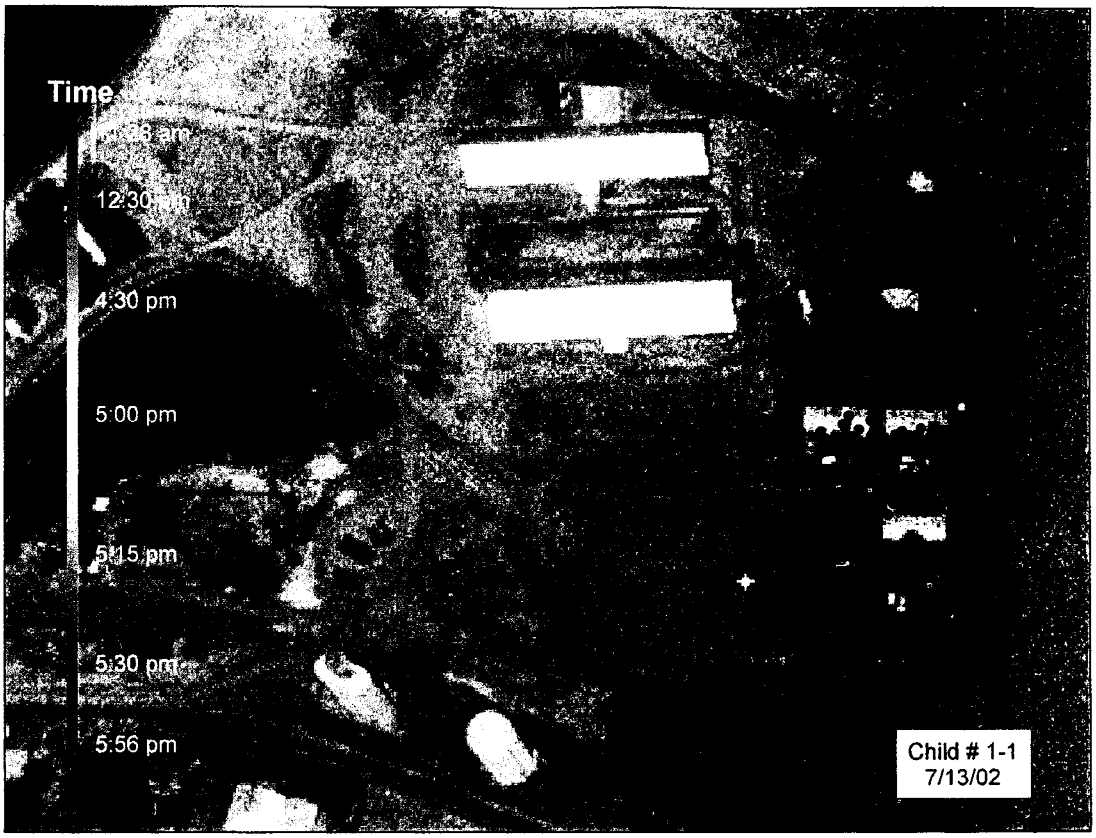
Label Statement Option-``Minimize Drift to Sensitive Areas. If Drift Occurs and Causes Environmental and Economic Effects, Enforcement Action May be Taken''

``Minimize drift'' suggests the Agency finds certain levels of off-target drift acceptable, contrary to EPA's policy as discussed above. Further, Agency enforcement authorities believe this statement compromises their responsibilities by jeopardizing their ability to take enforcement action when necessary. The second proposed statement also causes concern. Under this label statement EPA, states, and tribes would have to prove drift as well as both environmental and economic effects before taking further action.

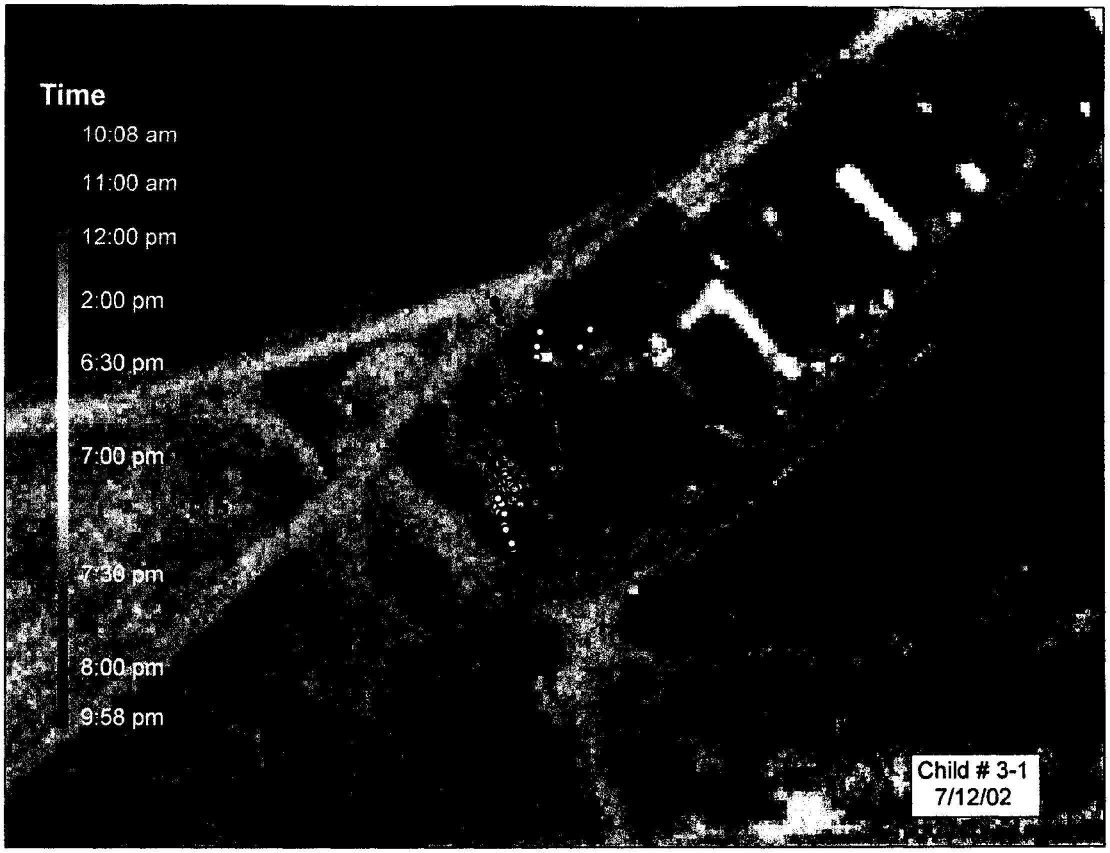
Since there is no label minimization standard, this statement essentially provides tacit permission to allow drift to occur at certain levels, presumably at levels up to those that do not cause ``environmental and economic effects.'' If certain levels of drift are permissible, a statement that off-target drift may result in enforcement action is nonsensical.



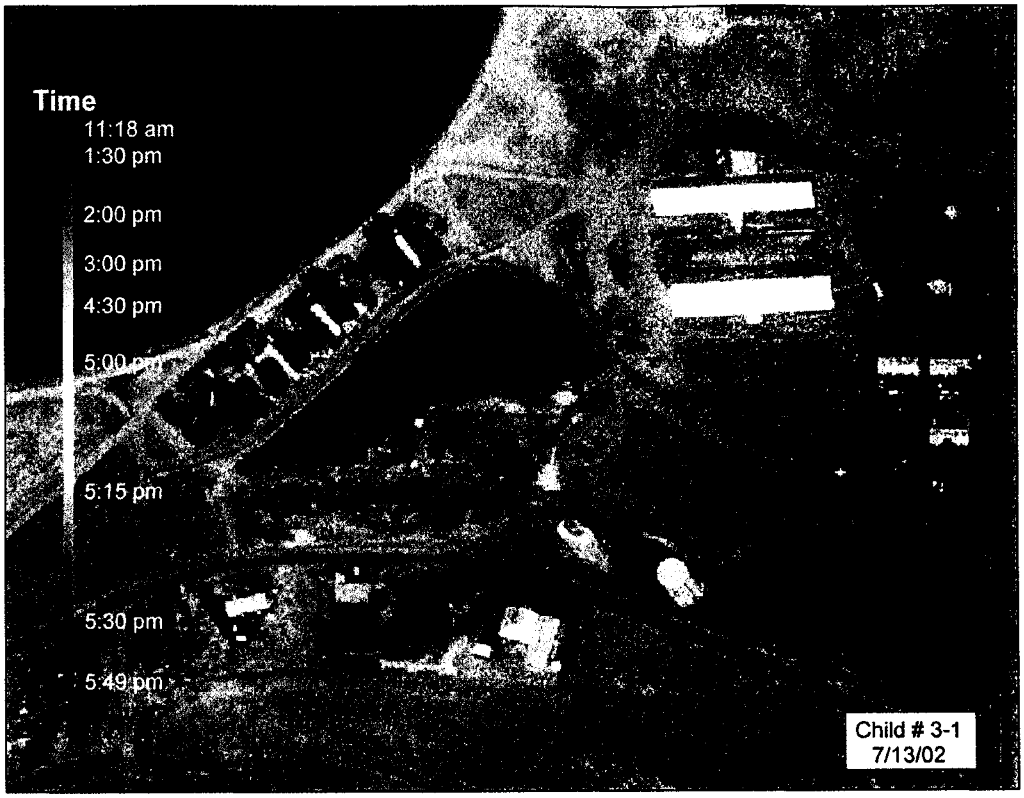
Appendix 4 F: Child 1 Time location on spray day



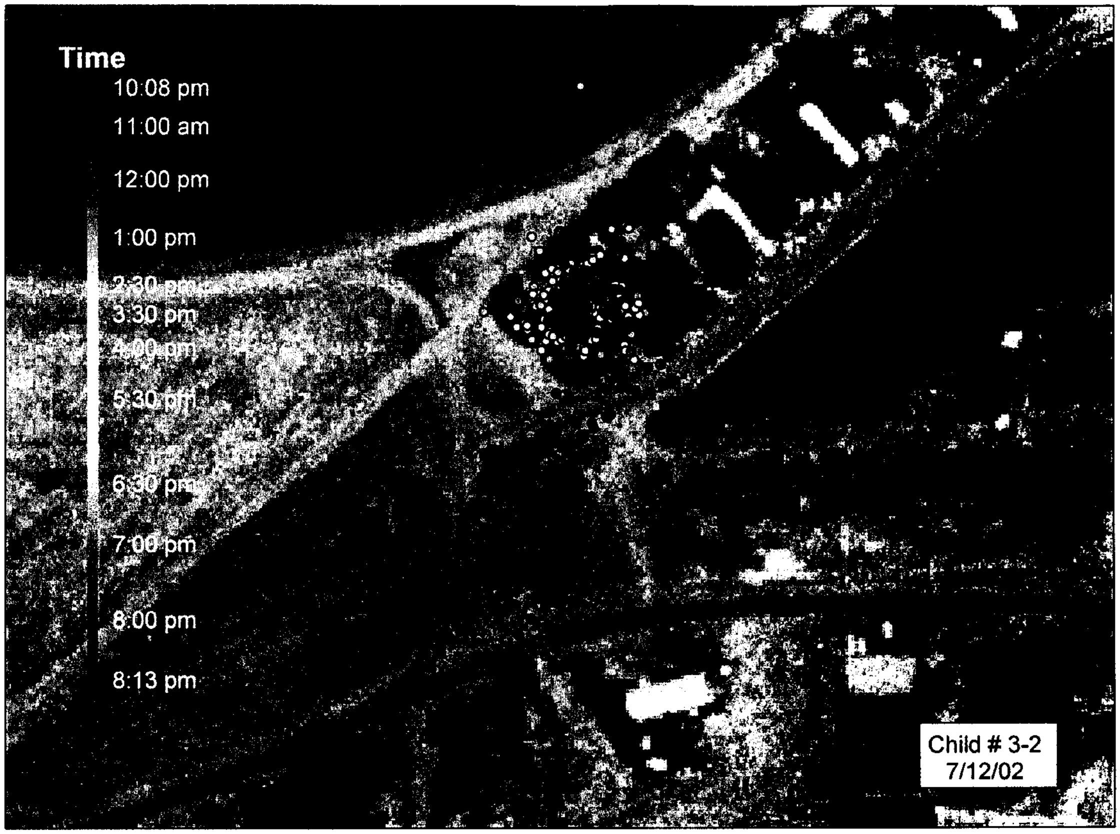
Appendix 4 G: Child 1 time location on day after spray



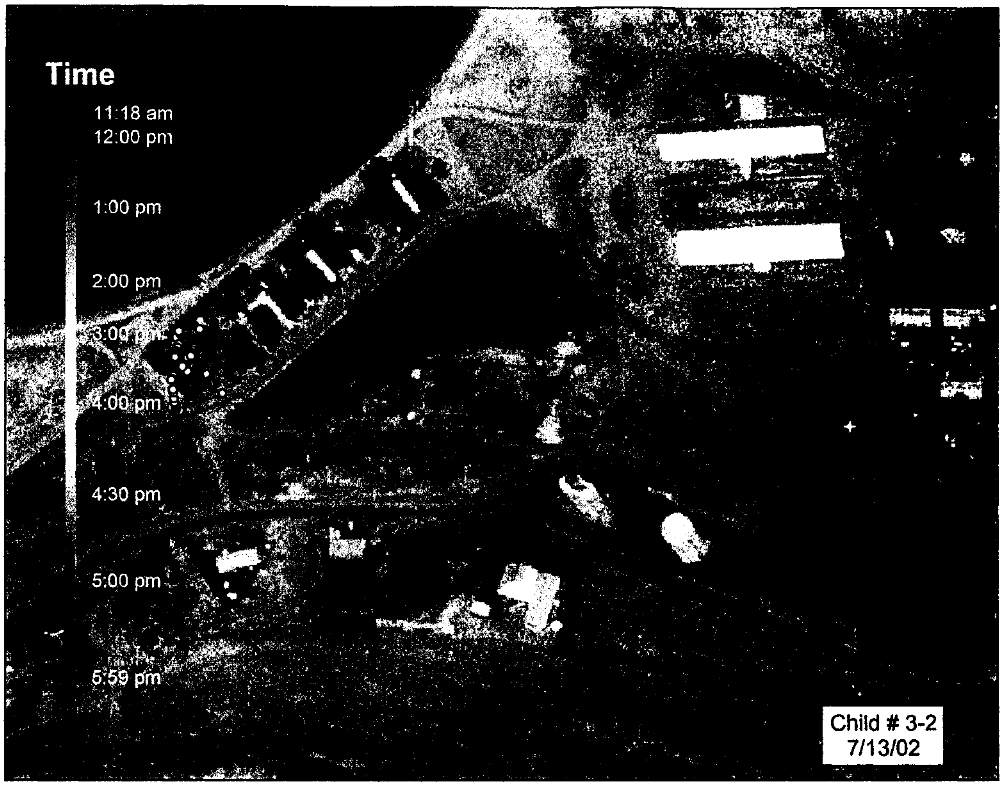
Appendix 4 H: Child 2 time location on spray day



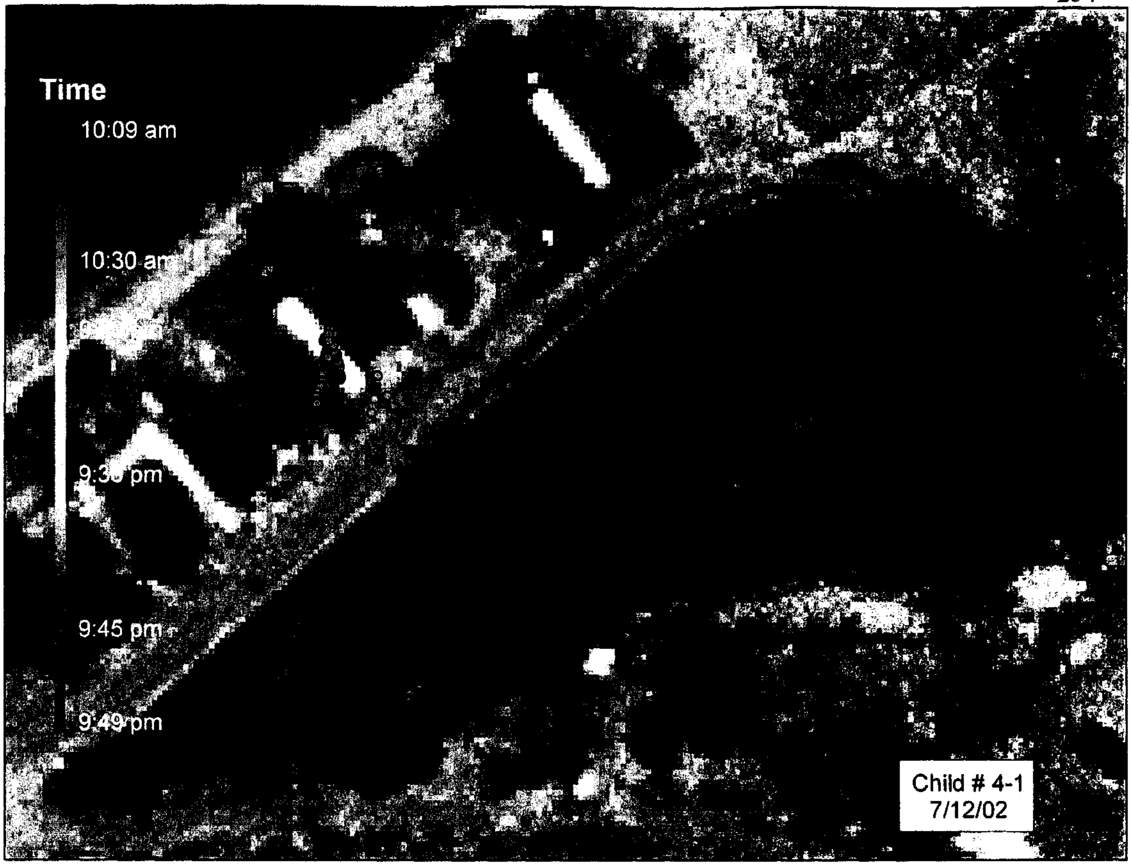
Appendix 4 I: Child 2 time location on day after spray



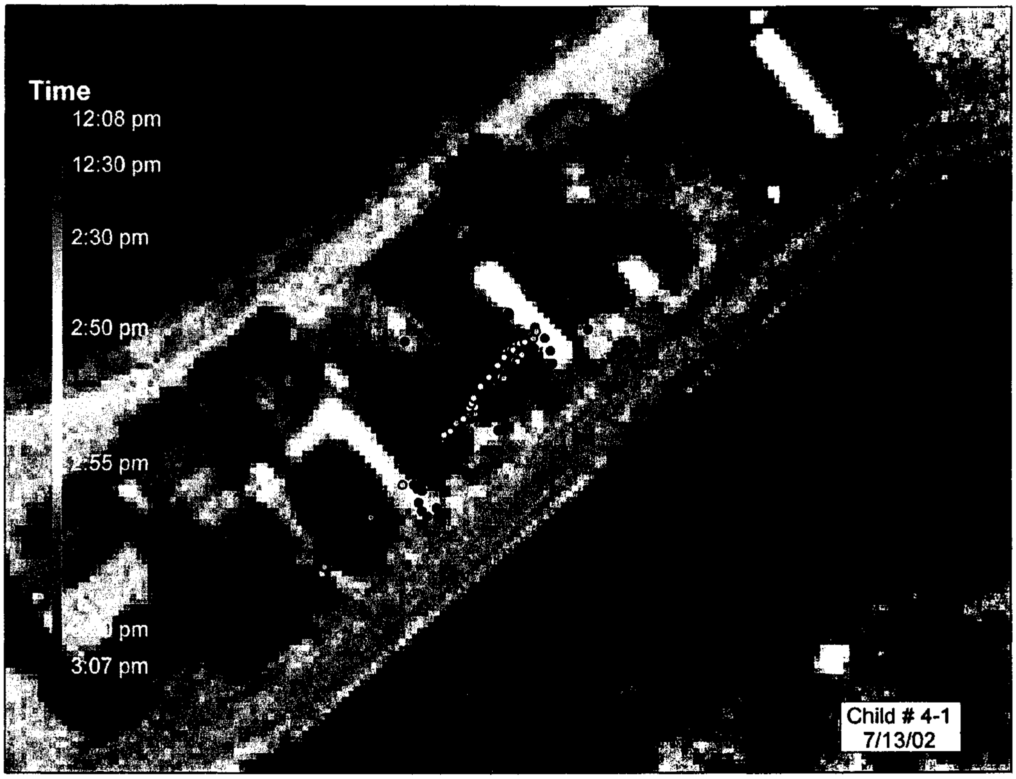
Appendix 4 J: Child 3 time location on spray day



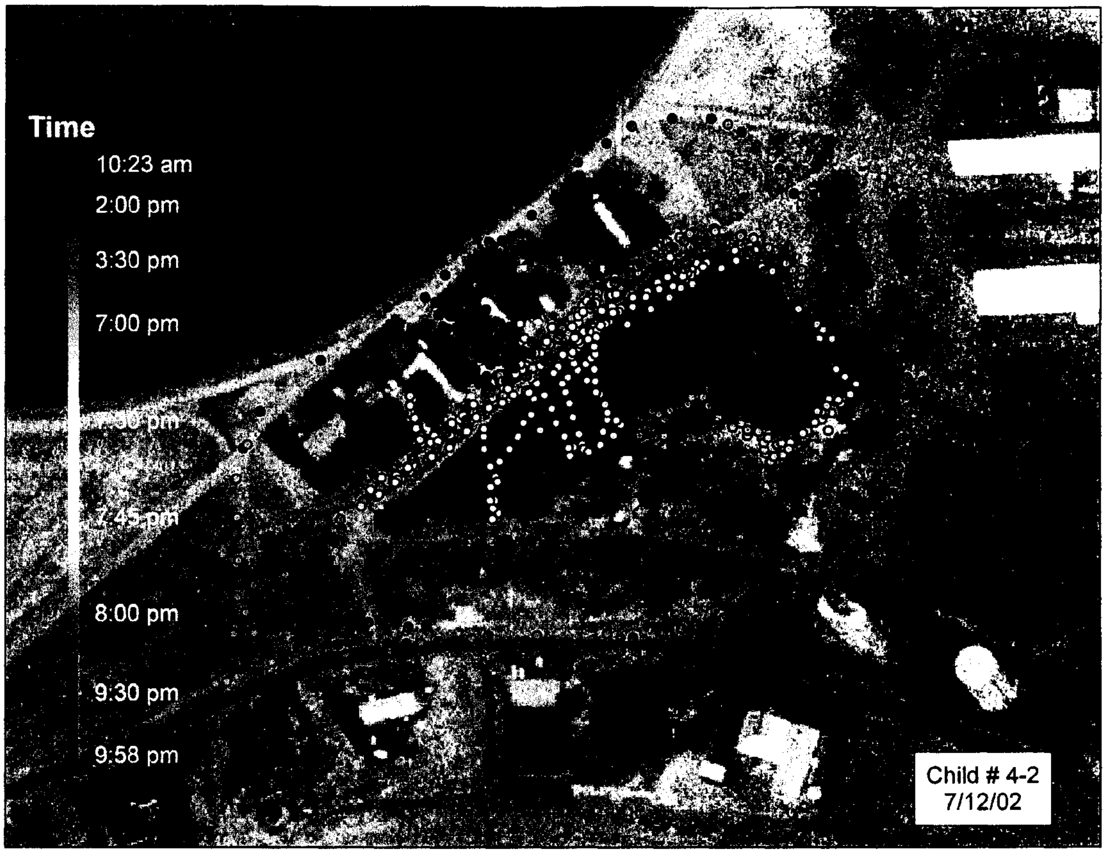
Appendix 4 K: Child 3 time location on day after spray



Appendix 4 L: Child 4 time location on spray day

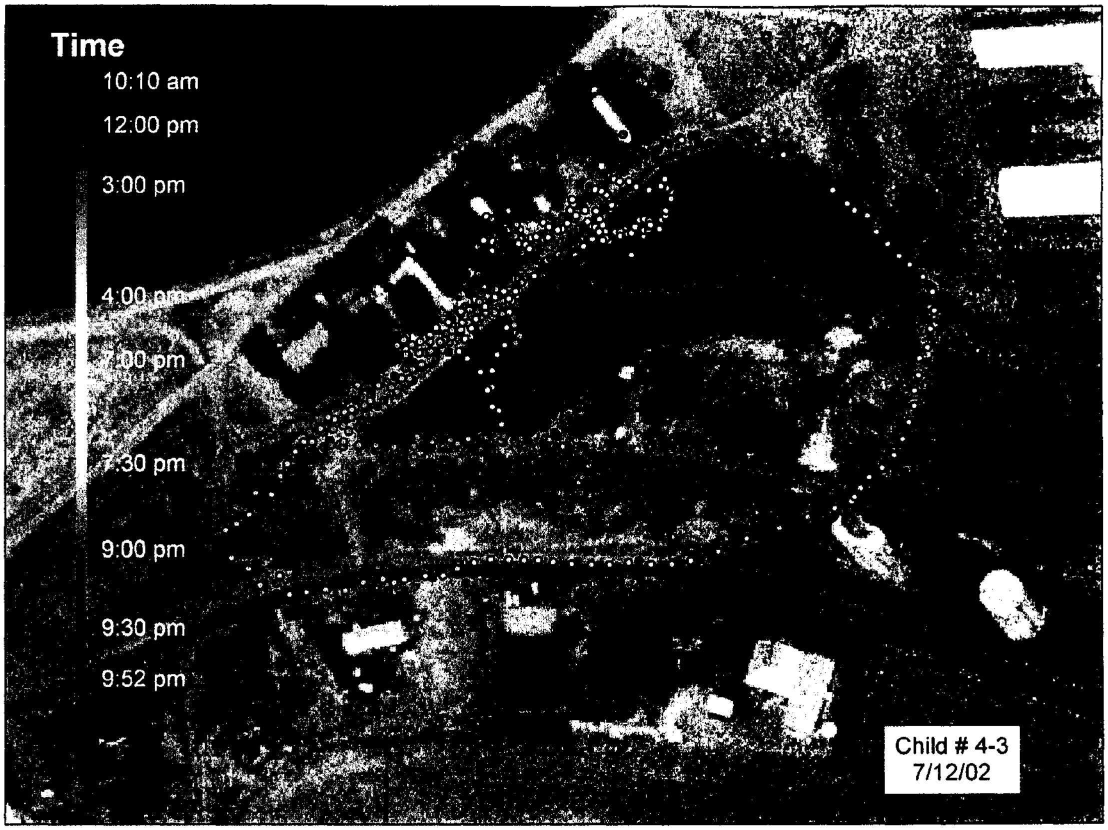


Appendix 4 M: Child 4 time location on day after spray

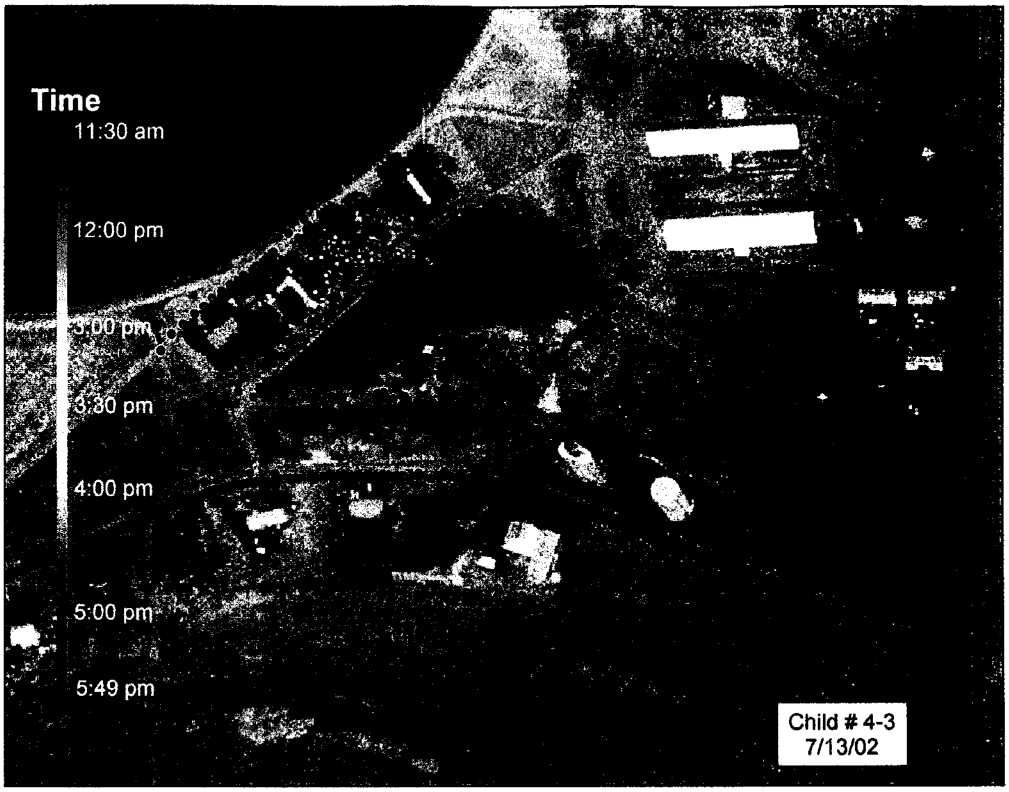


Appendix 4 N: Child 5 time location on spray day

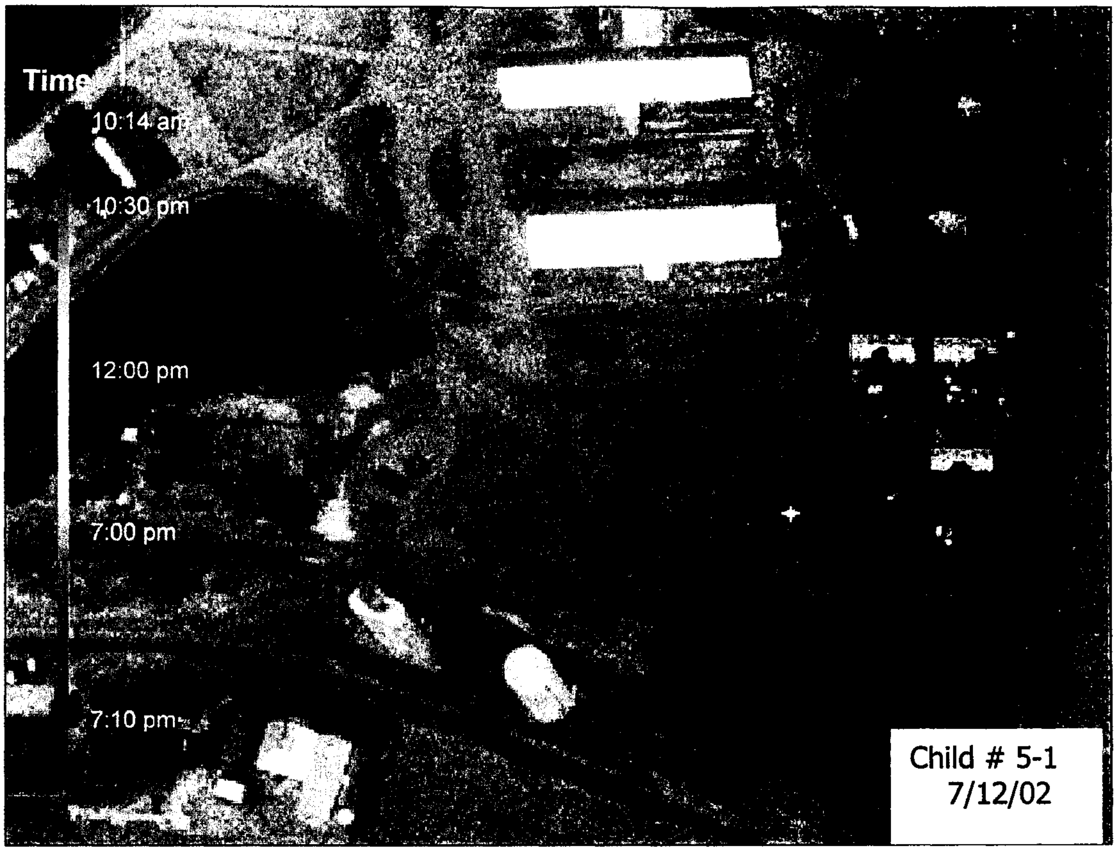
Appendix 4 O: Child 5 time location on day after spray



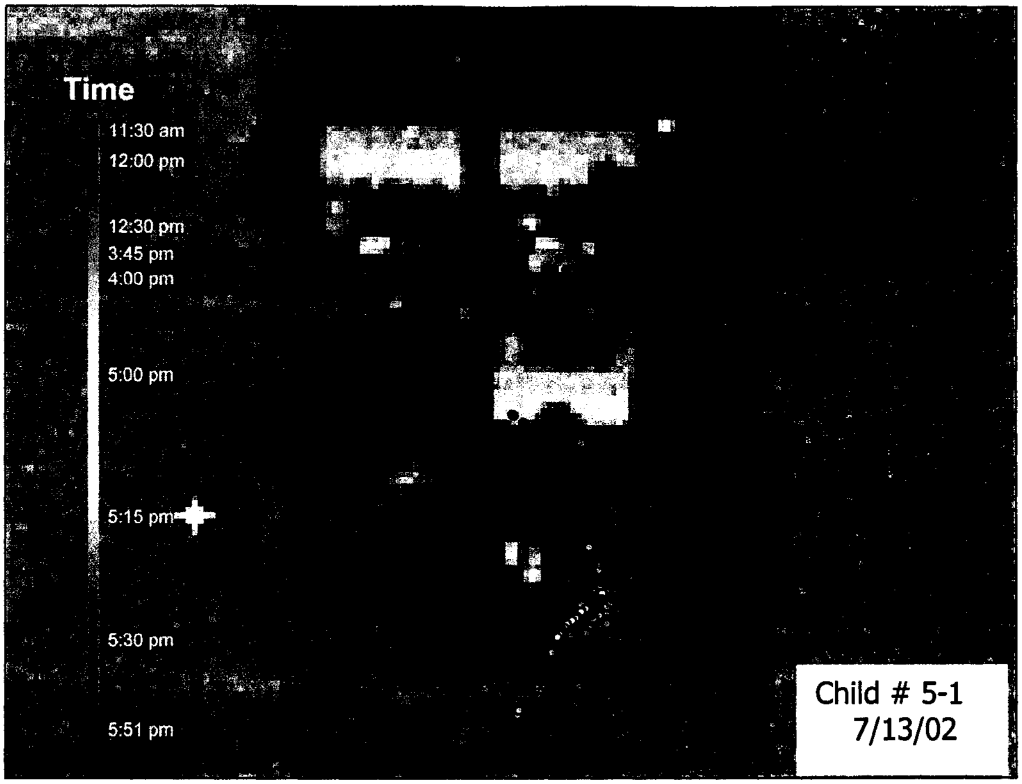
Appendix 4 P: Child 6 time location on spray day



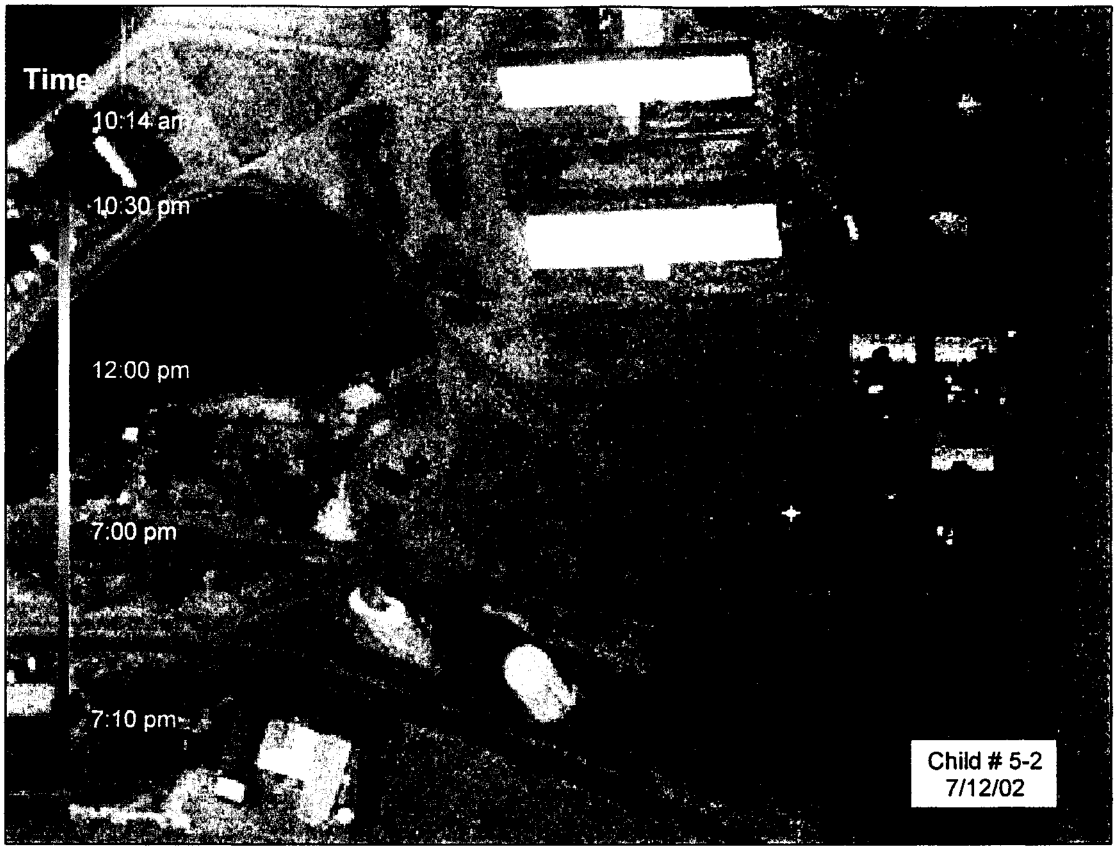
Appendix 4 Q: Child 6 time location on day after spray



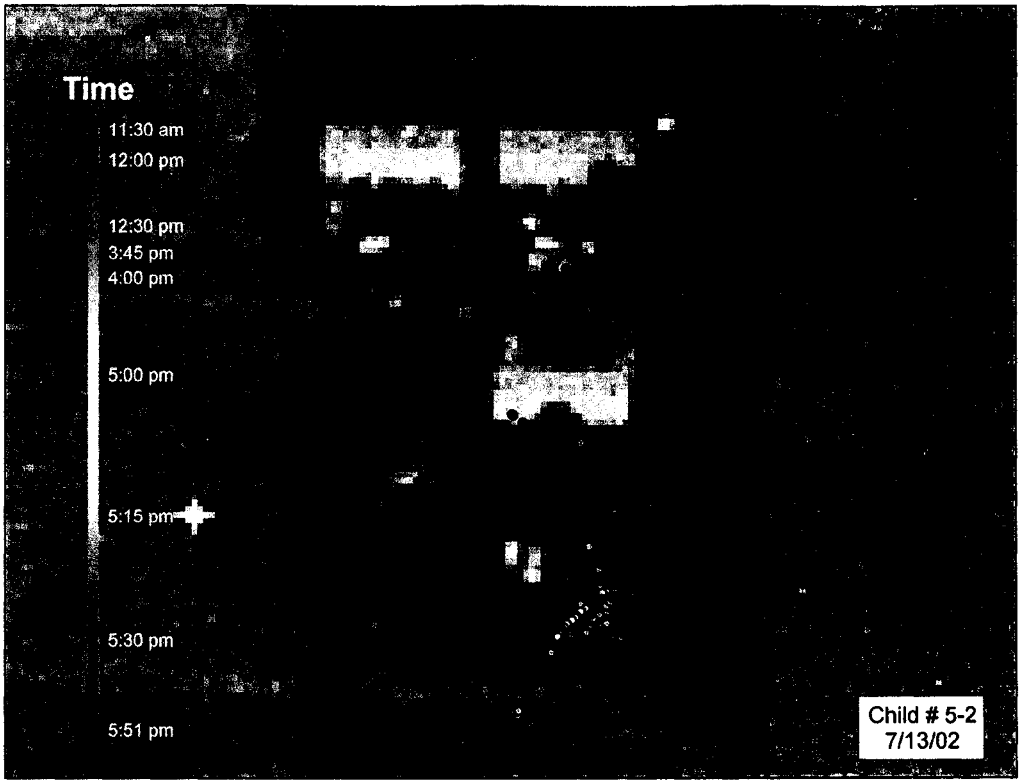
Appendix 4 R: Child 7 time location on spray day



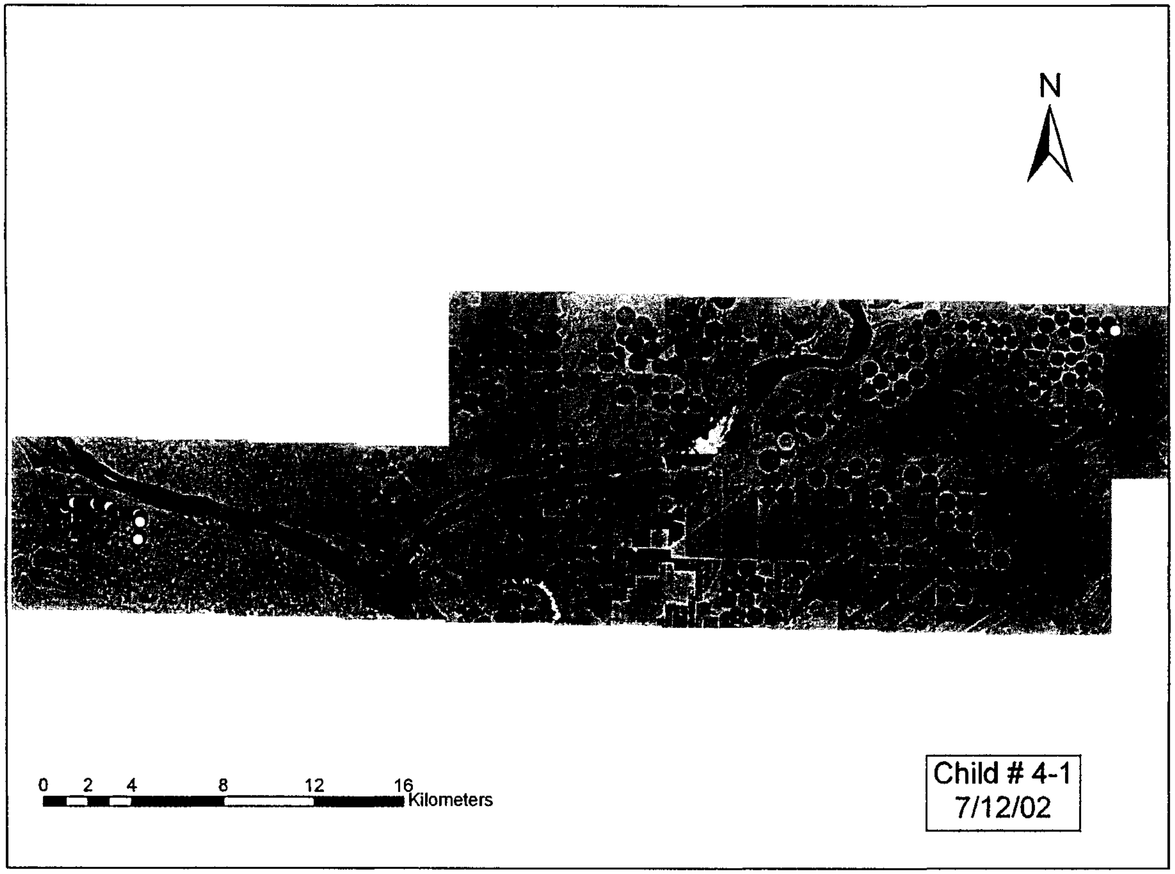
Appendix 4 S: Child 7 time location on day after spray



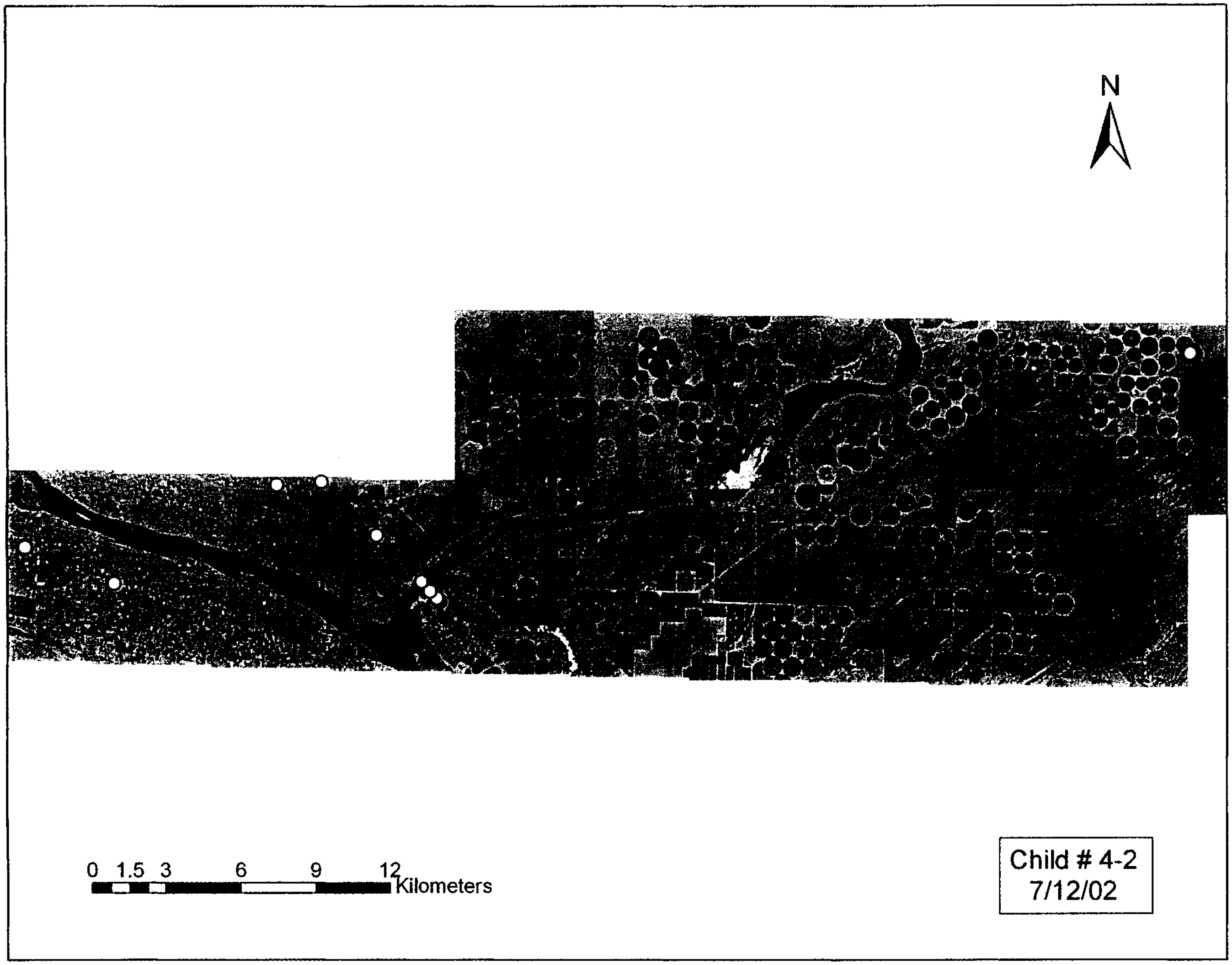
Appendix 4 T: Child 8 time location on spray day



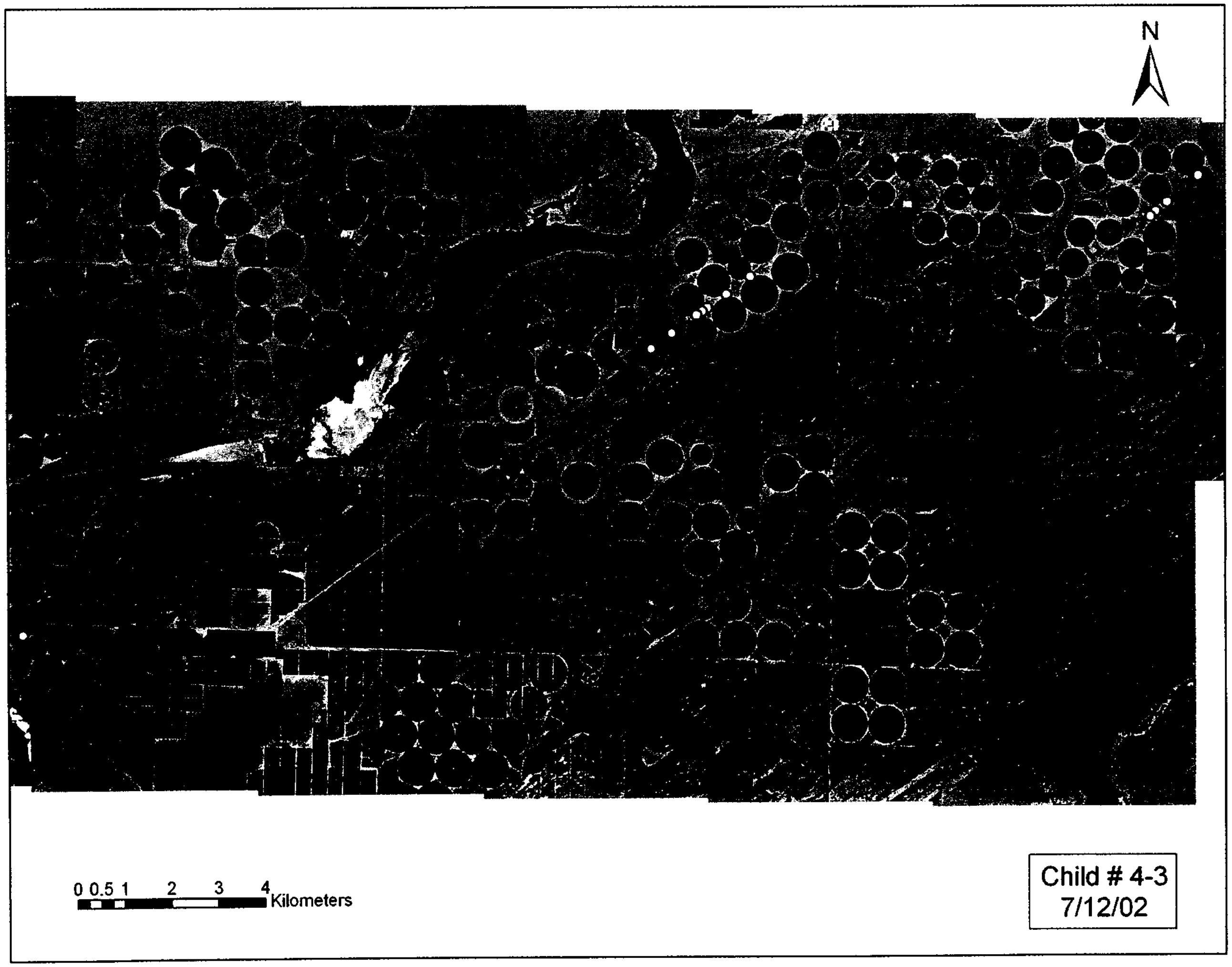
Appendix 4 U: Child time location on day after spray



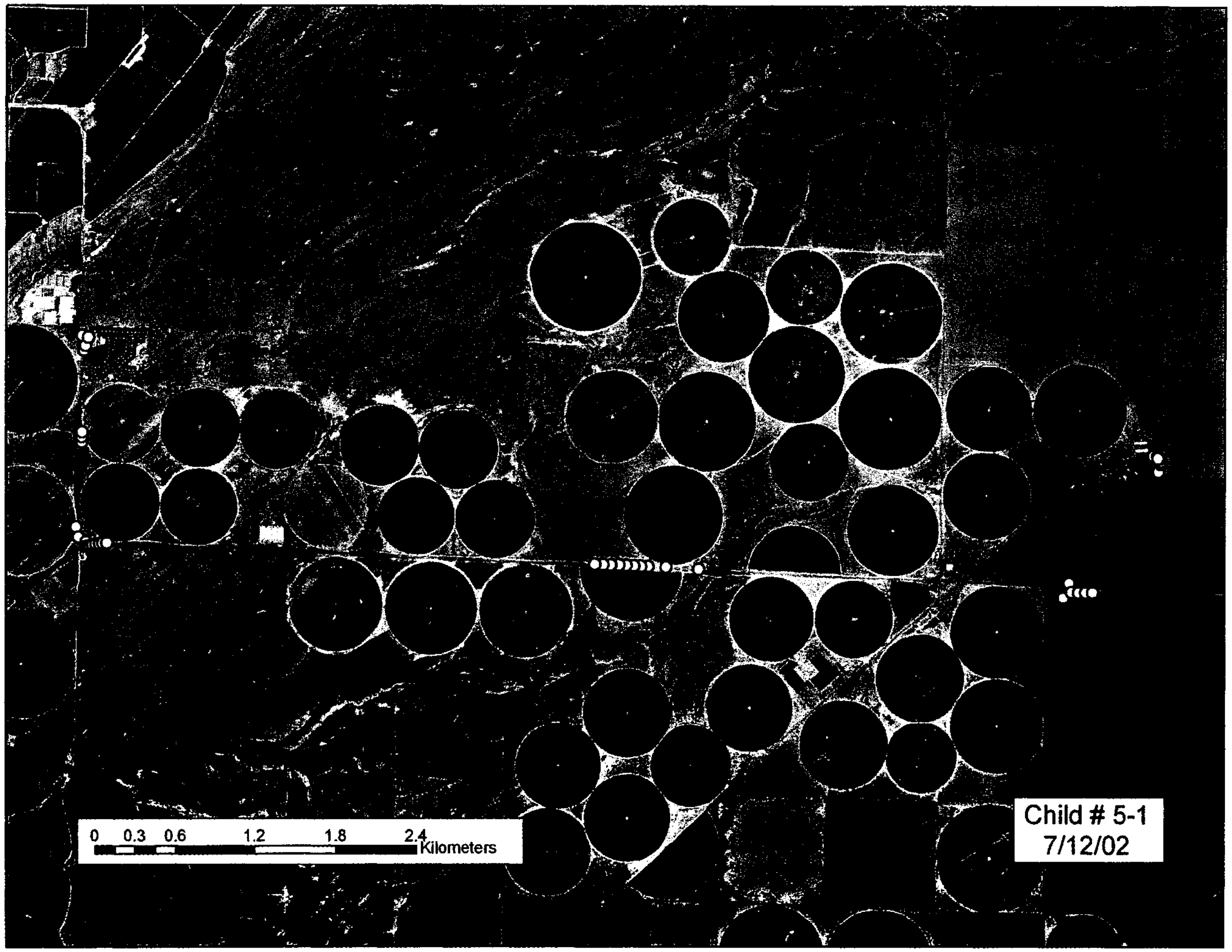
Appendix 4 V: Child 4 time location (regional view) on spray day



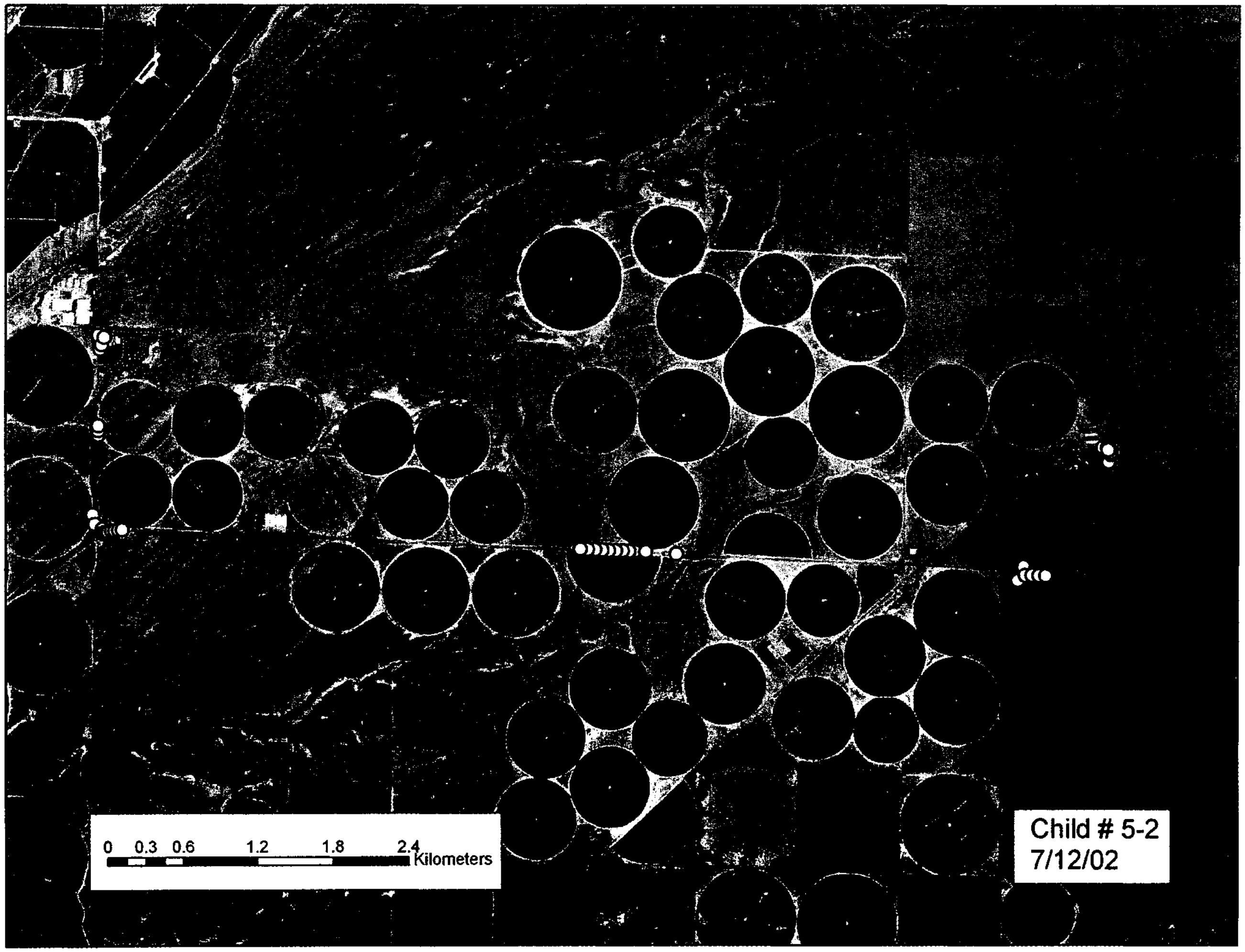
Appendix 4 W: Child 5 time location (regional view) on spray day



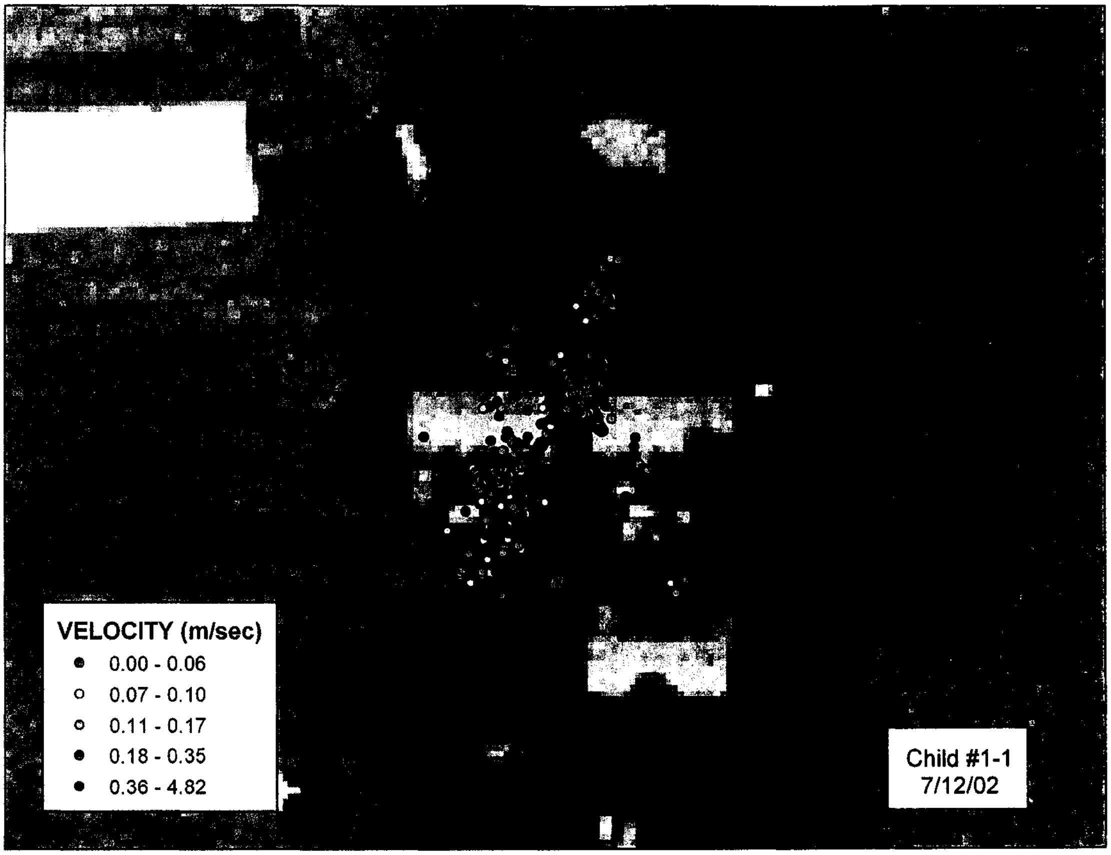
Appendix 4 X: Child 6 time location (regional view) on spray day



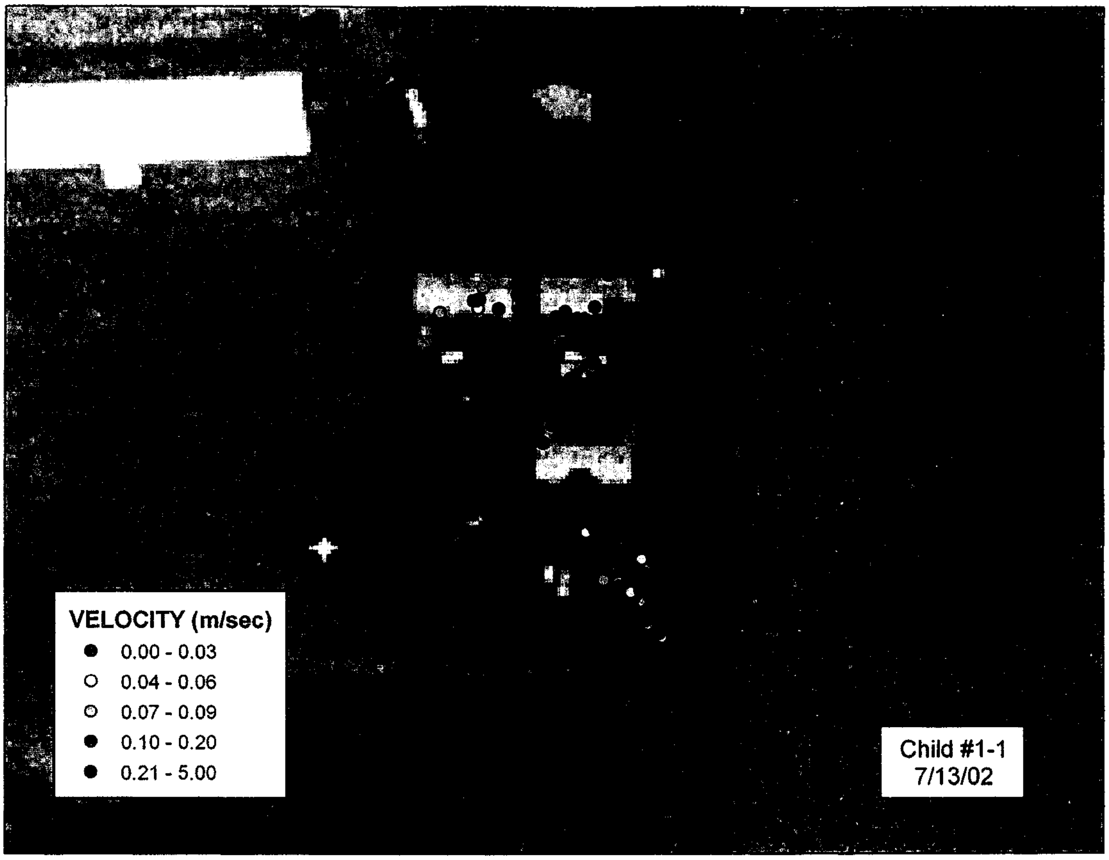
Appendix 4 Y: Child 7 time location (regional view) on spray day



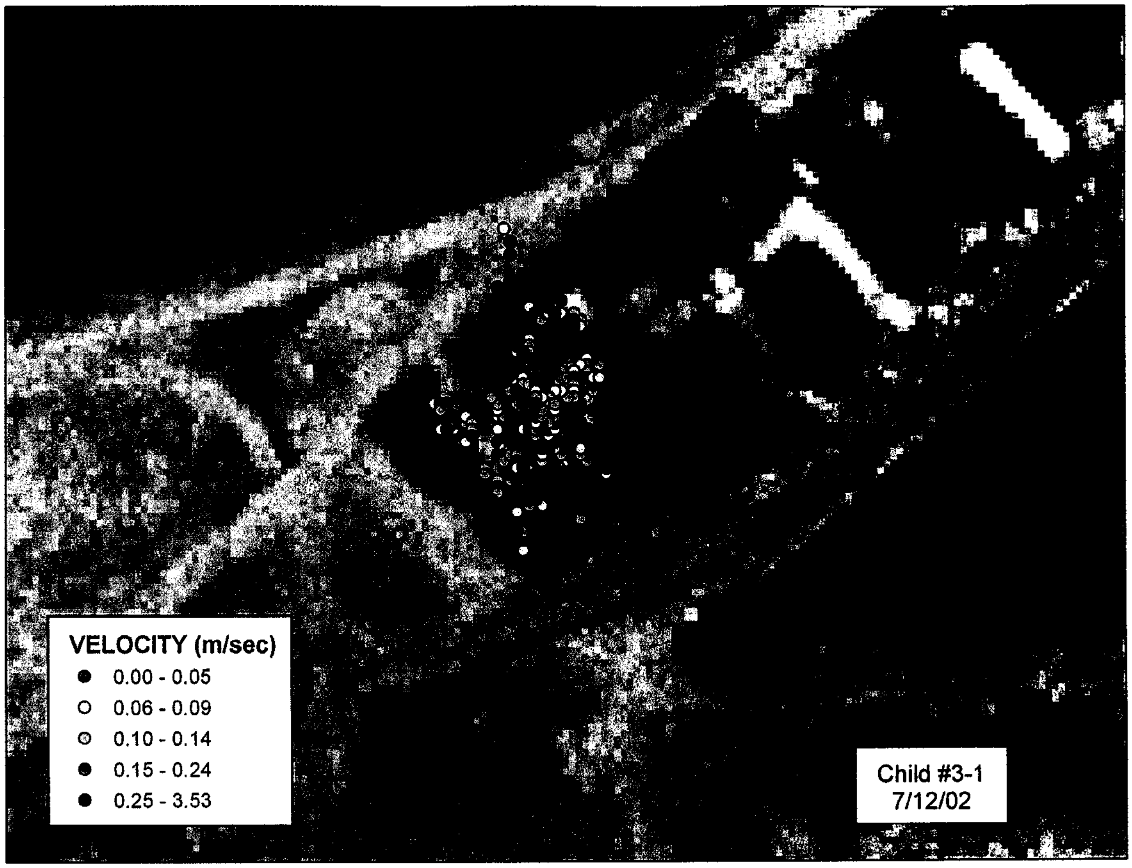
Appendix 4 Z: Child 8 time location (regional view) on spray day



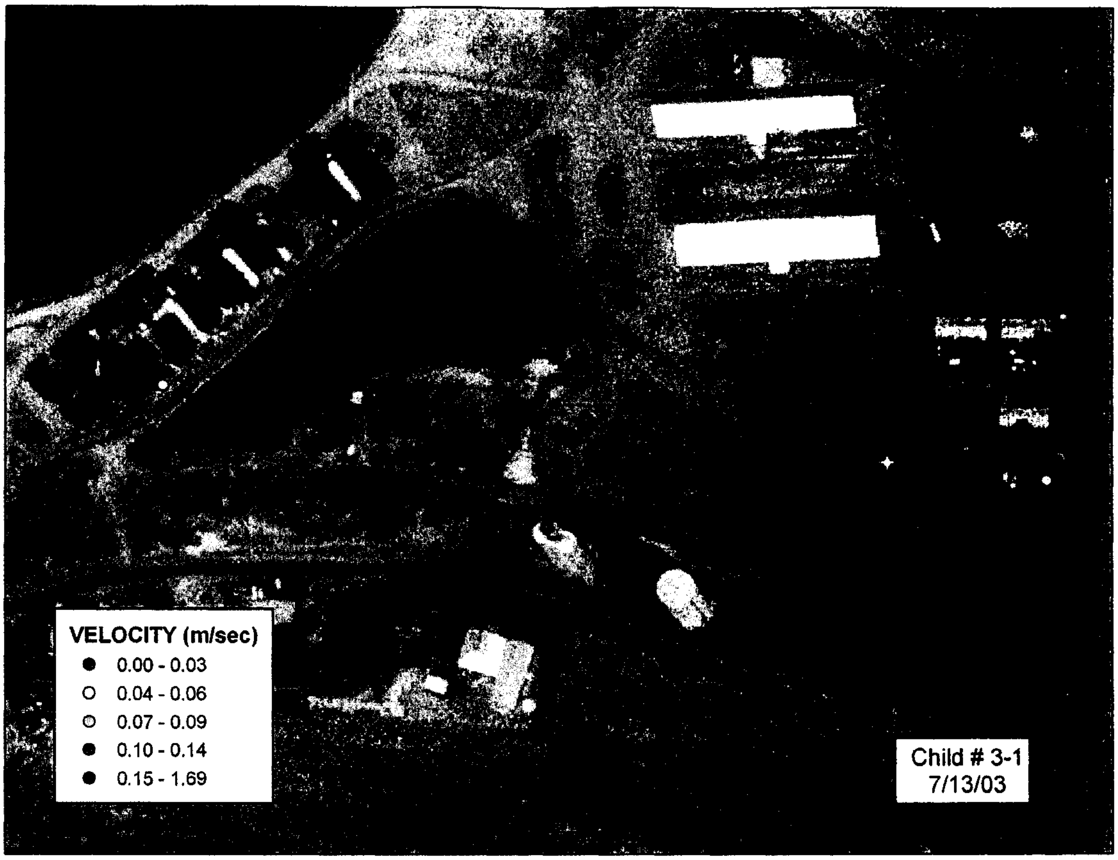
Appendix 4 AA: Child 1 velocity (on foot) on spray day



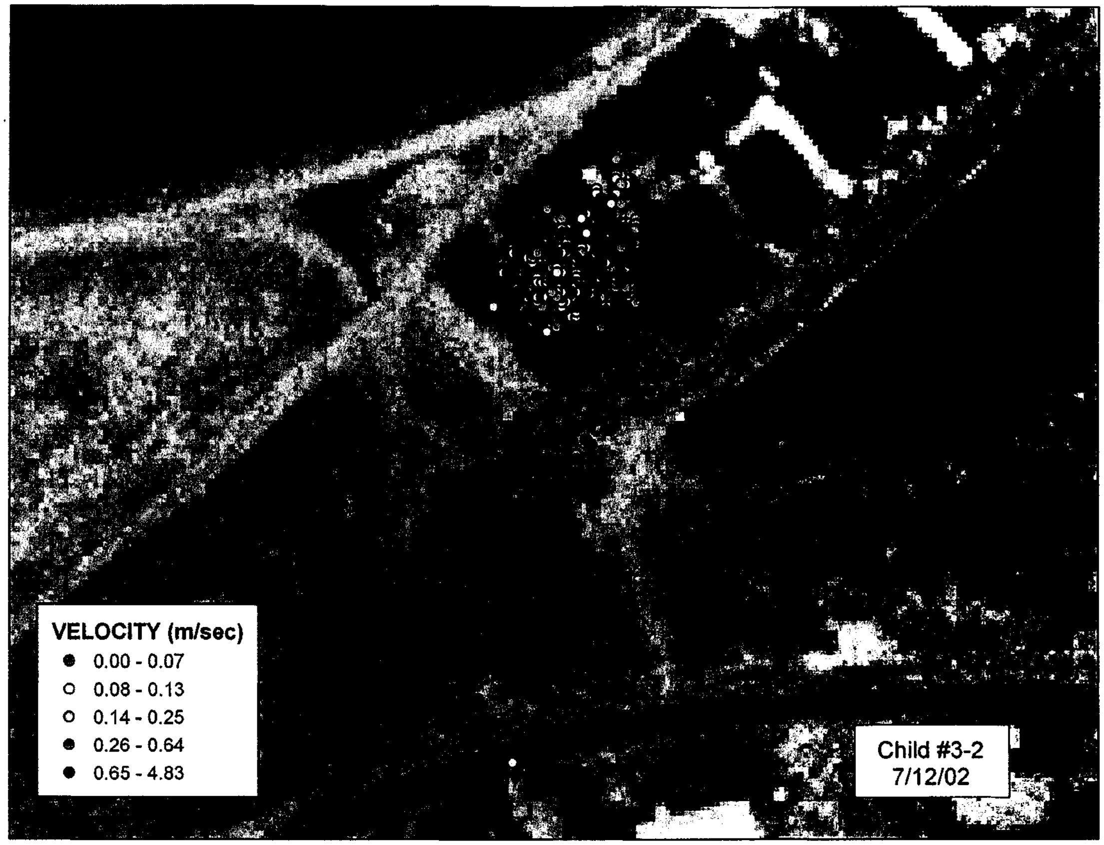
Appendix 4 BB: Child 1 velocity (on foot) on day after spray



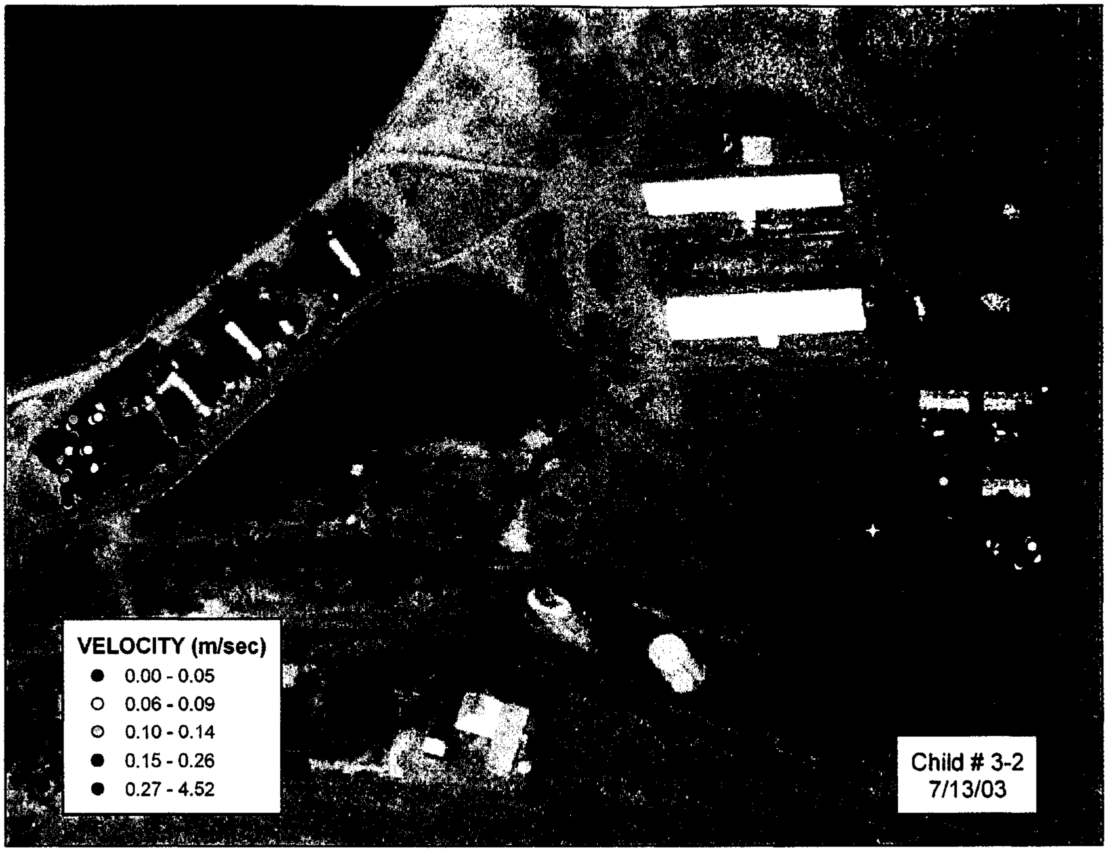
Appendix 4 CC: Child 2 velocity (on foot) on spray day



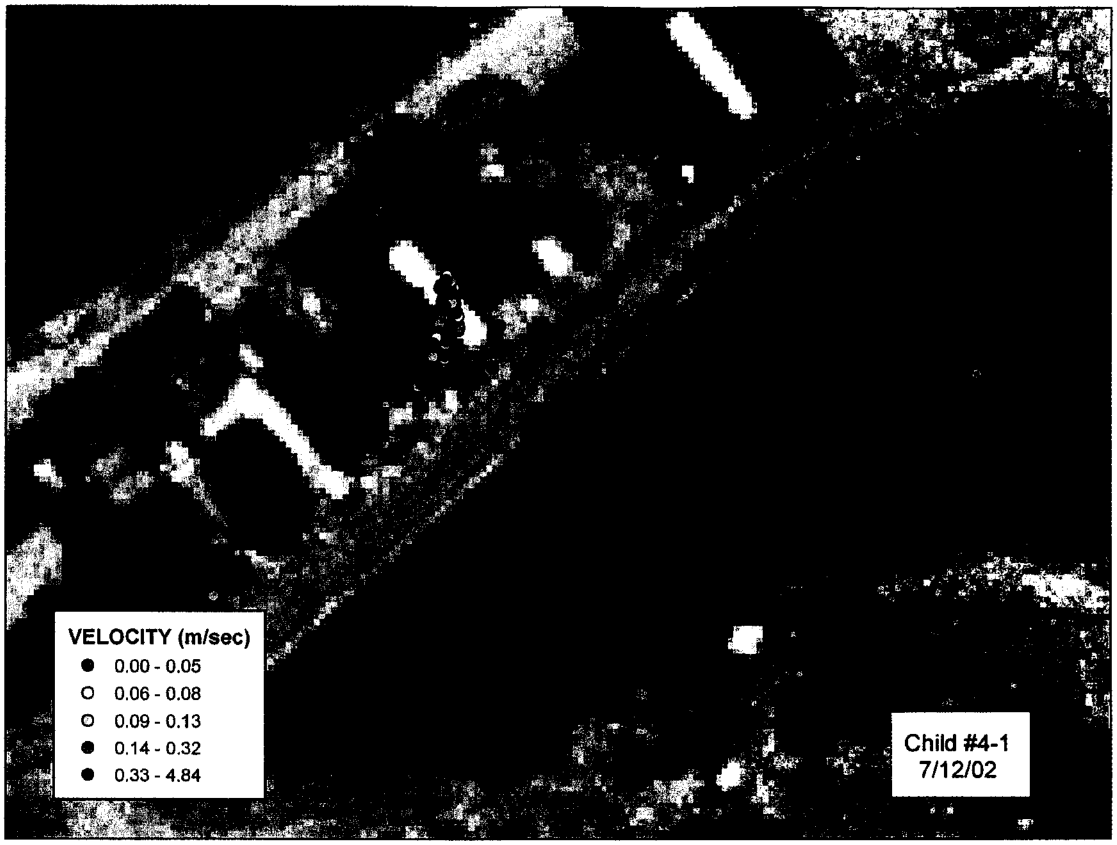
Appendix 4 DD: Child 2 velocity (on foot) on day after spray



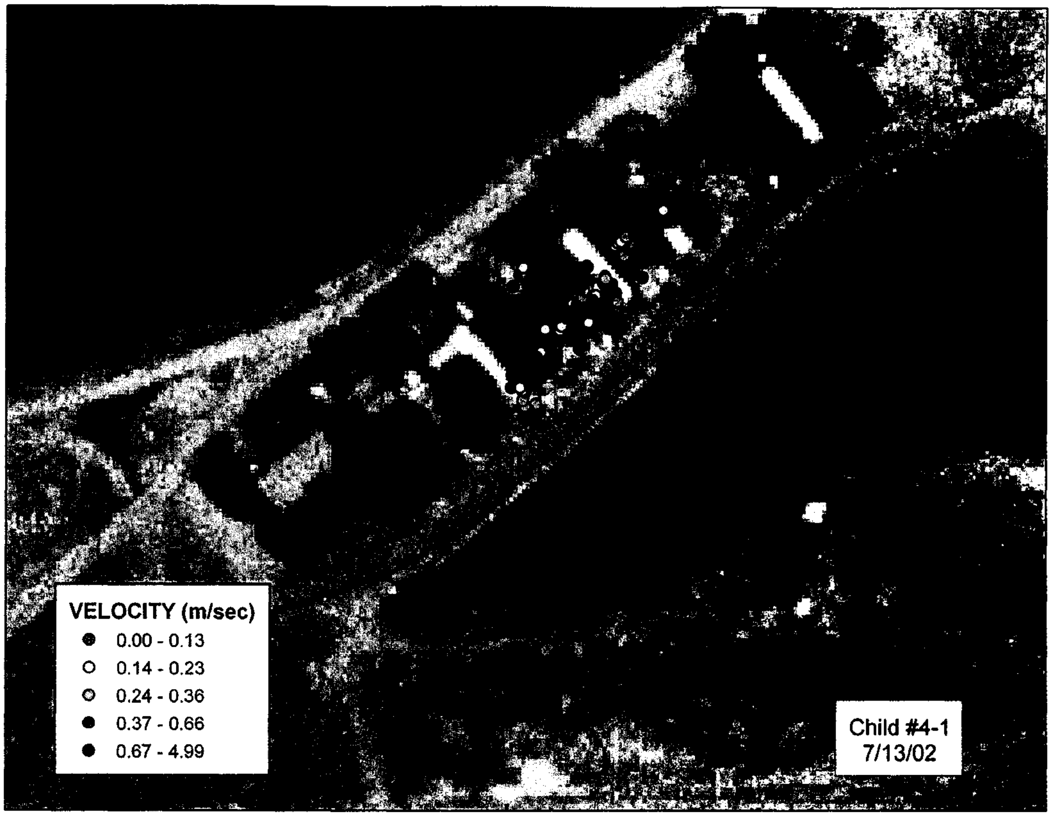
Appendix 4 EE: Child 3 velocity (on foot) on spray day



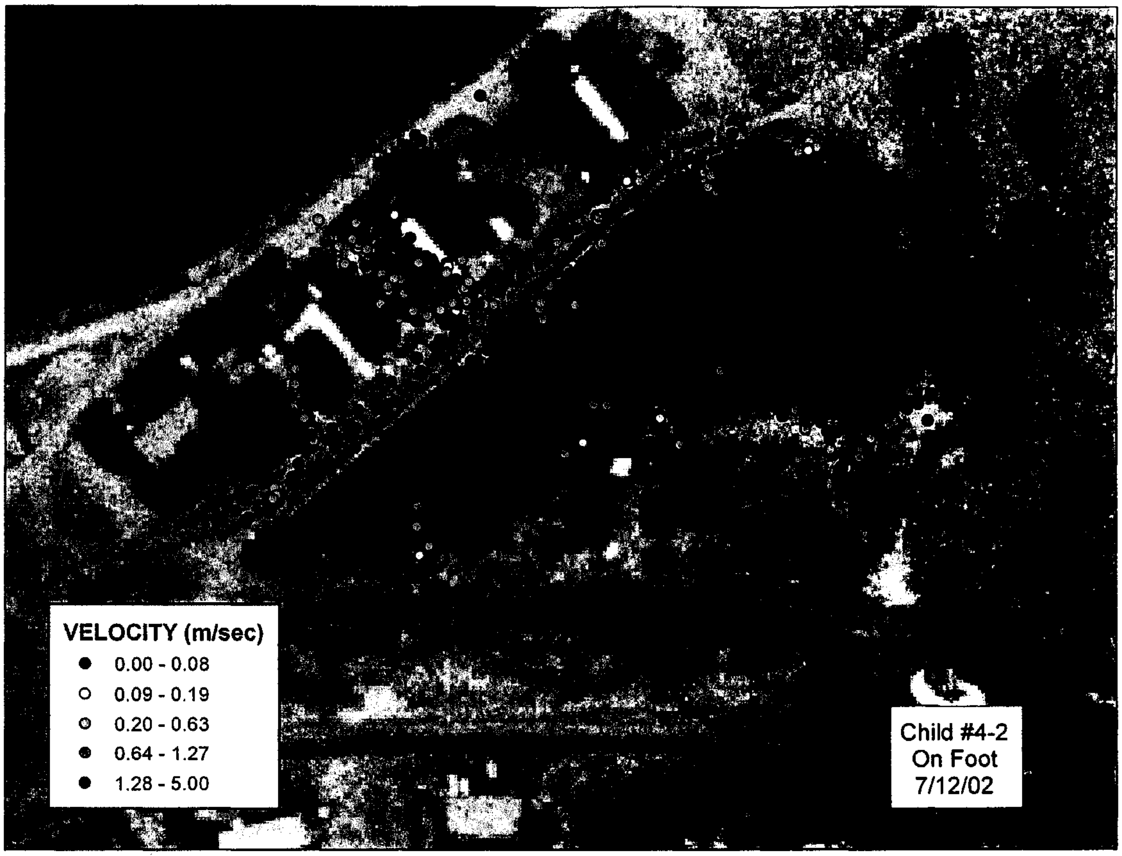
Appendix 4 FF: Child 3 velocity (on foot) on day after spray



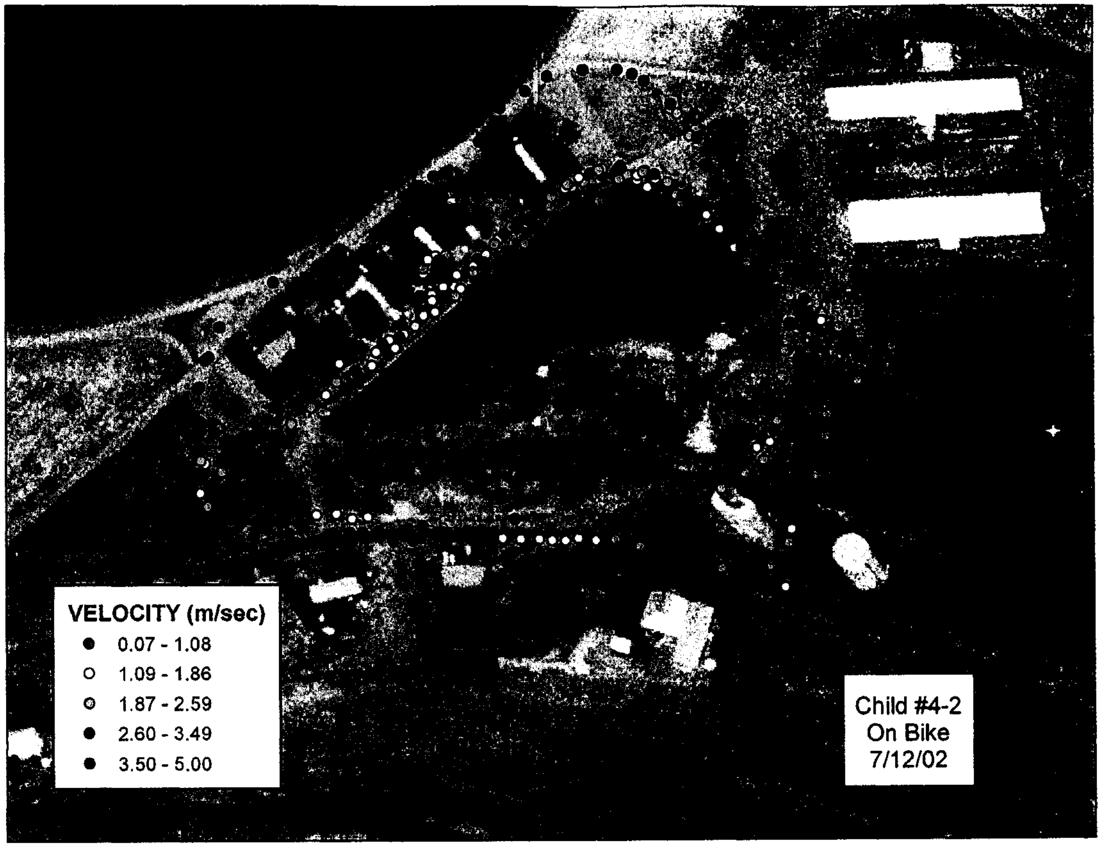
Appendix 4 GG: Child 4 velocity (on foot) on spray day



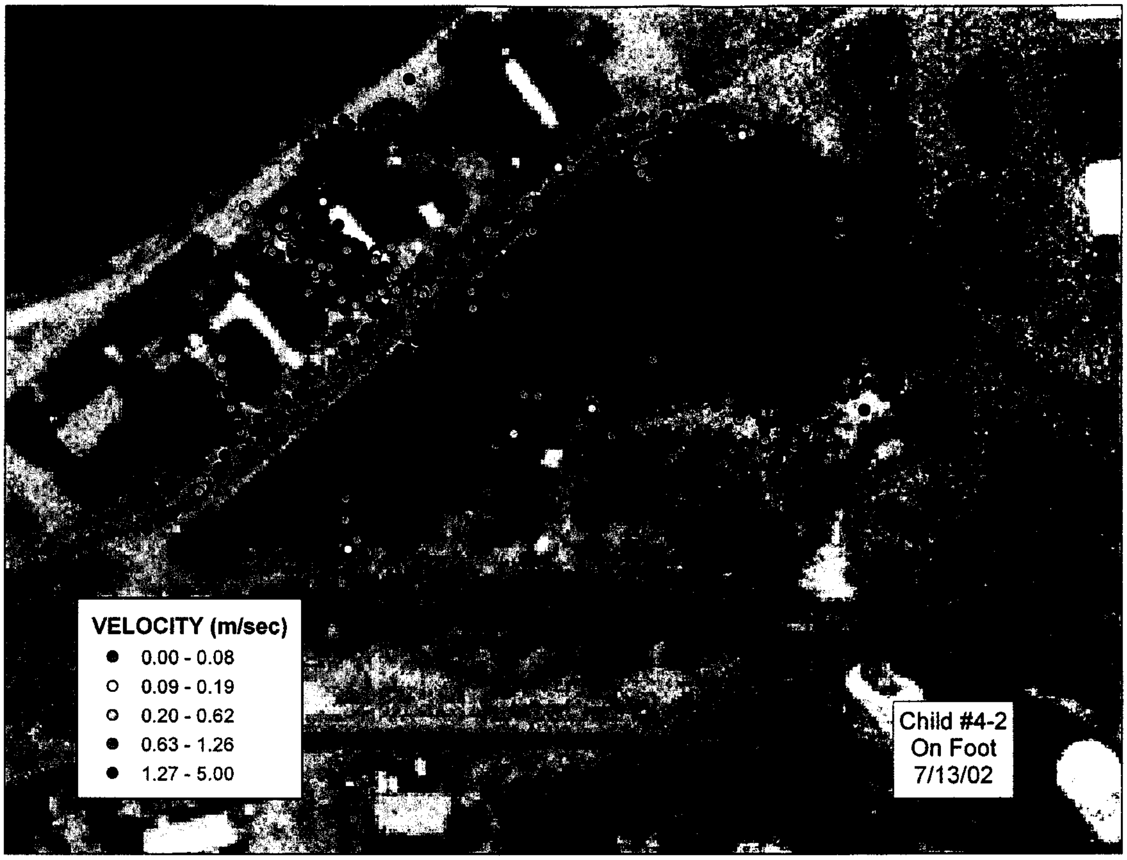
Appendix 4 HH: Child 4 velocity (on foot) on day after spray



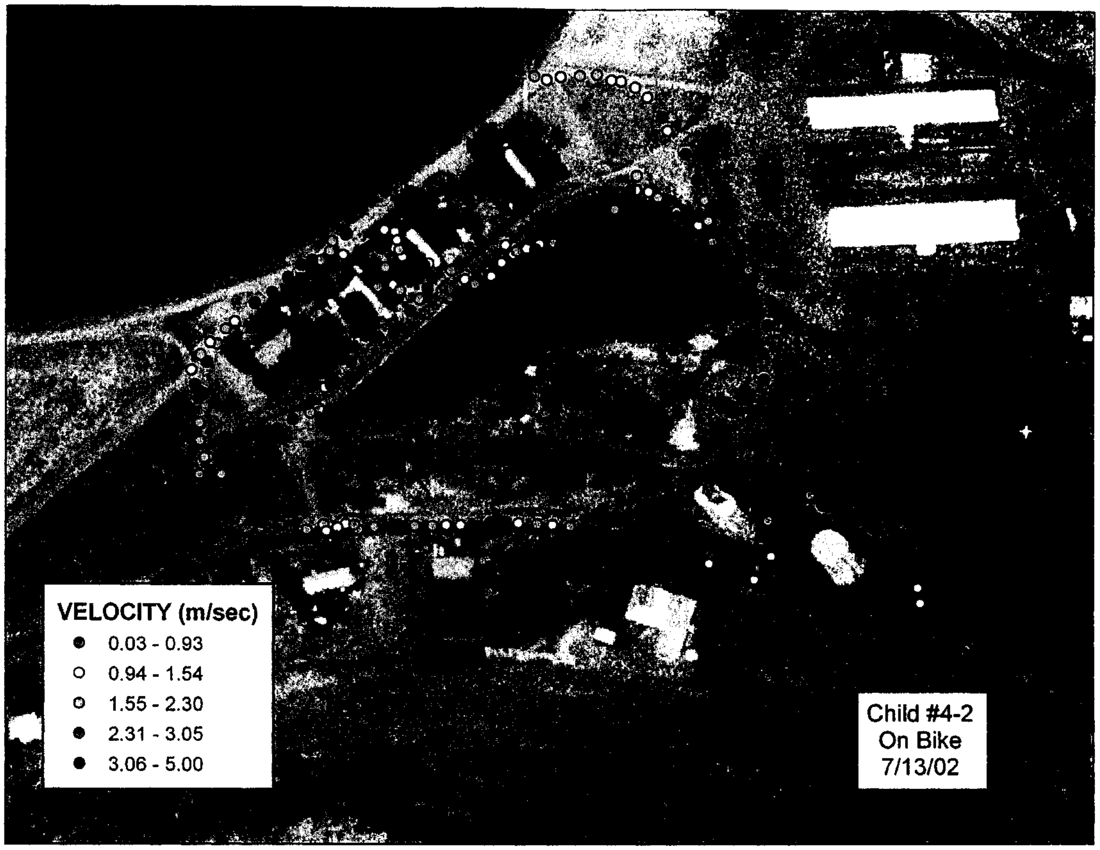
Appendix 4 II: Child 5 velocity (on foot) on spray day



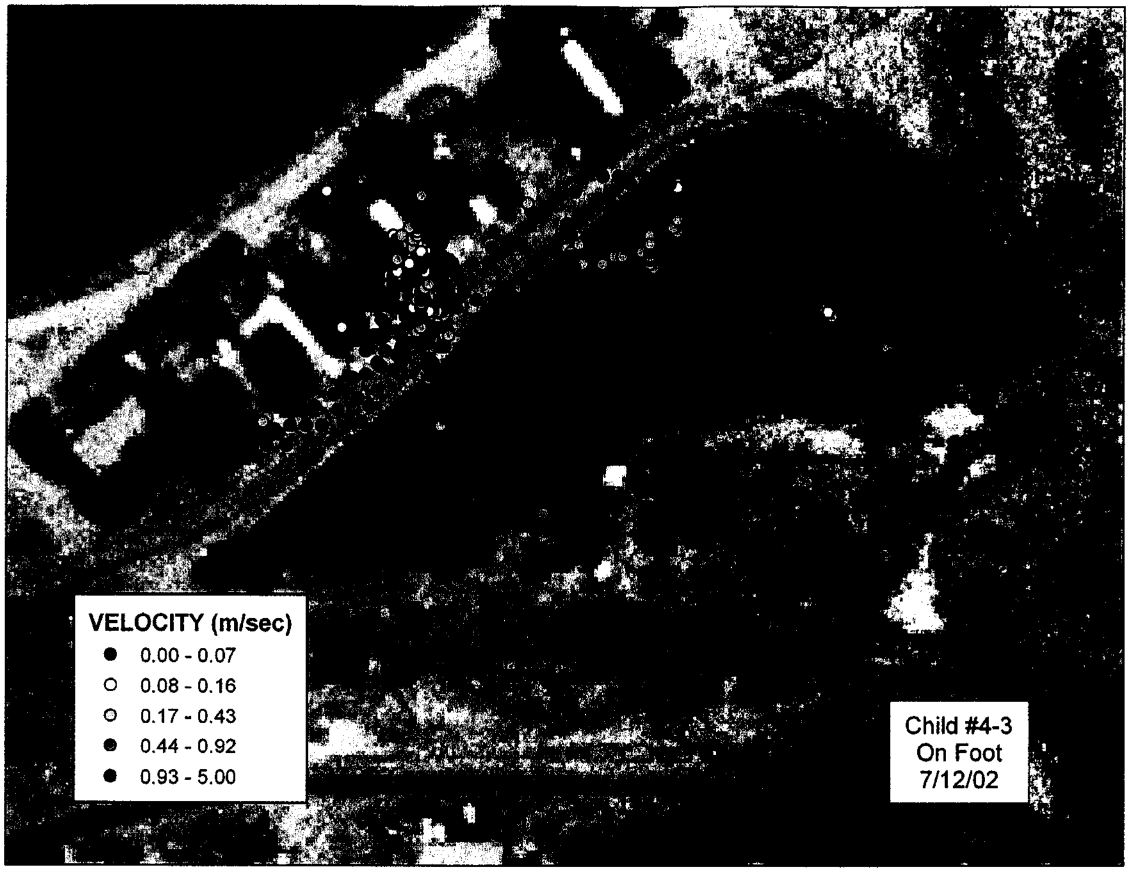
Appendix 4 JJ: Child 5 velocity (on bicycle) on spray day



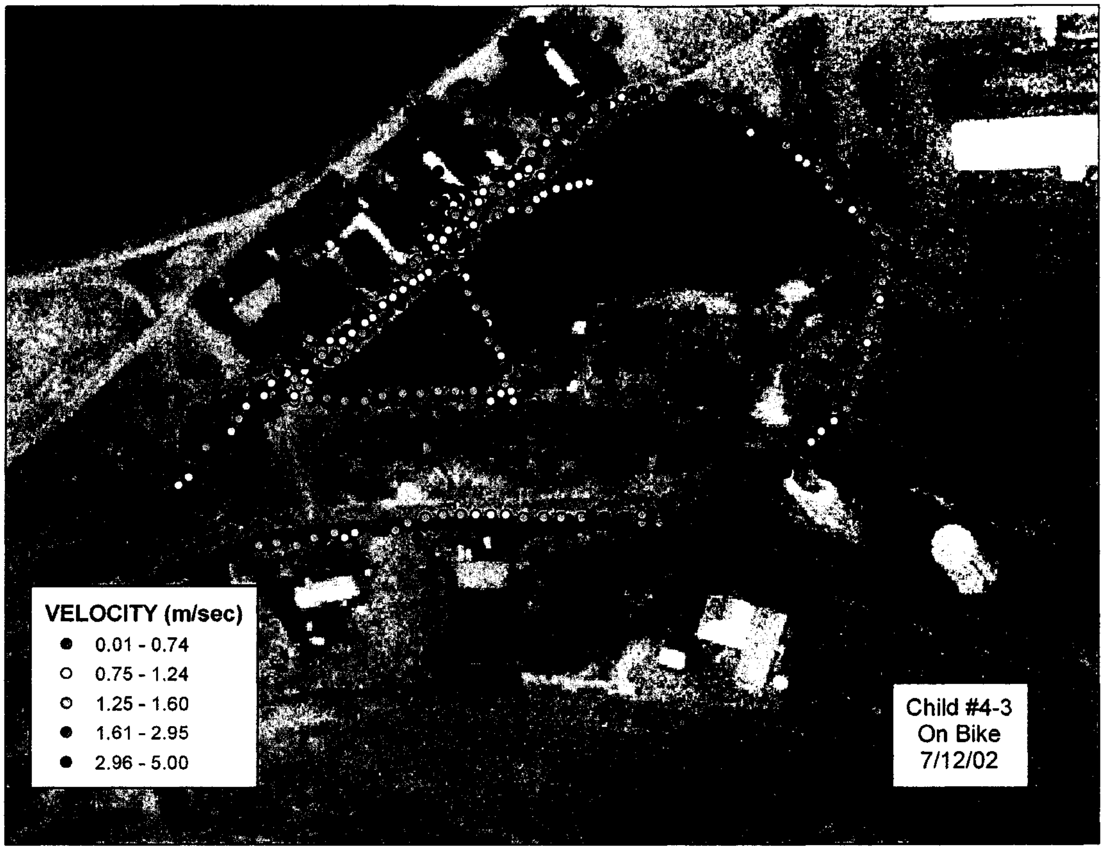
Appendix 4 KK: Child 5 velocity (on foot) on day after spray



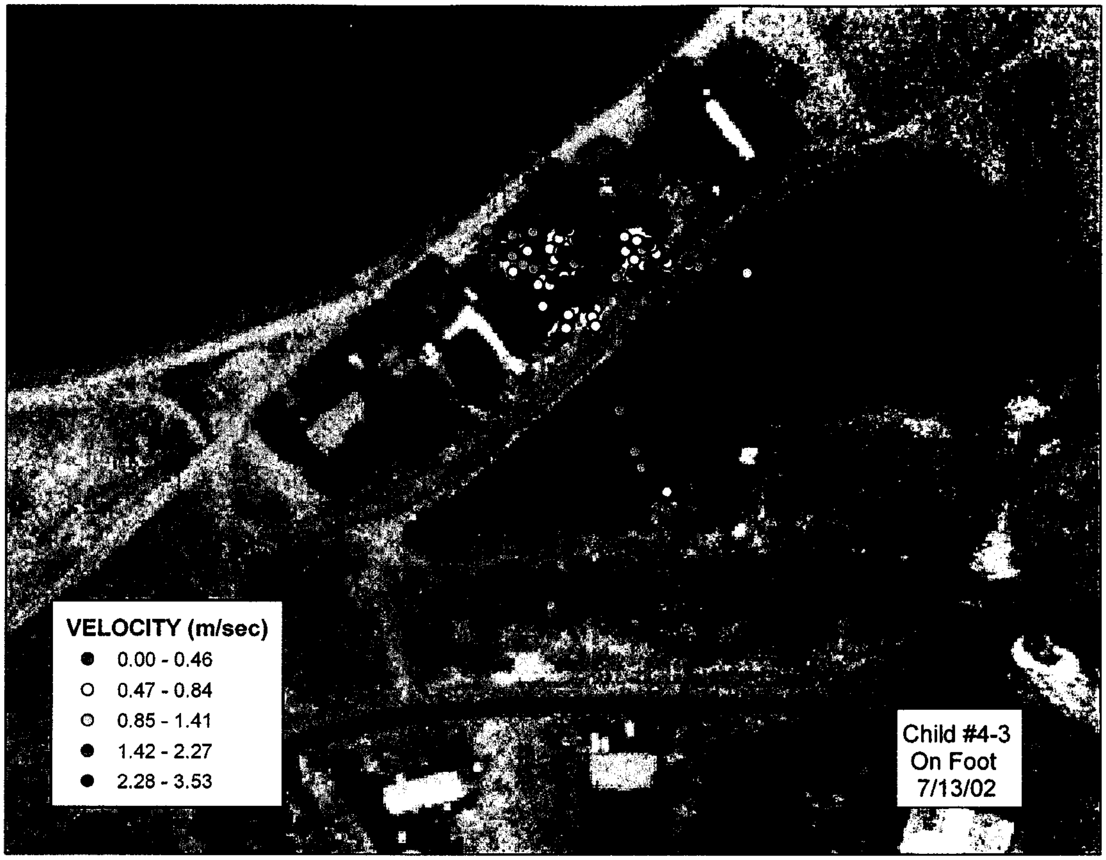
Appendix 4 LL: Child 5 velocity (on bicycle) on day after spray



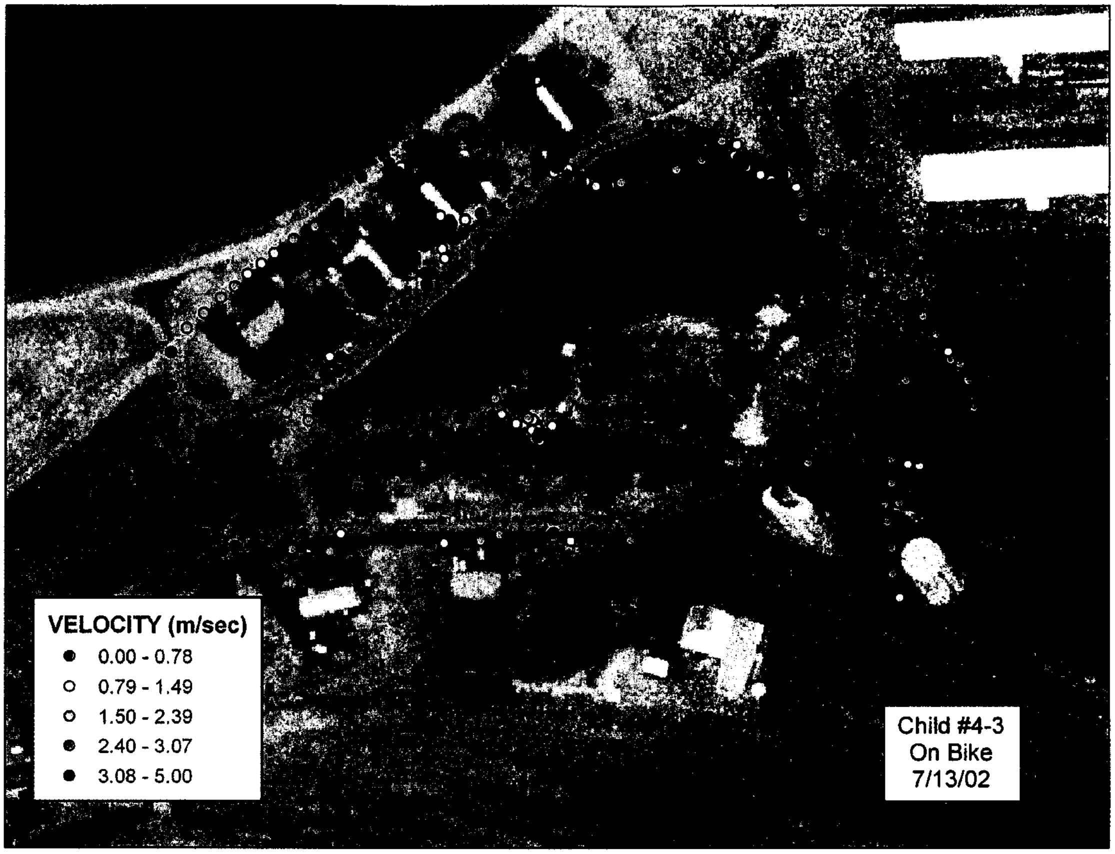
Appendix 4 MM: Child 6 velocity (on foot) on spray day



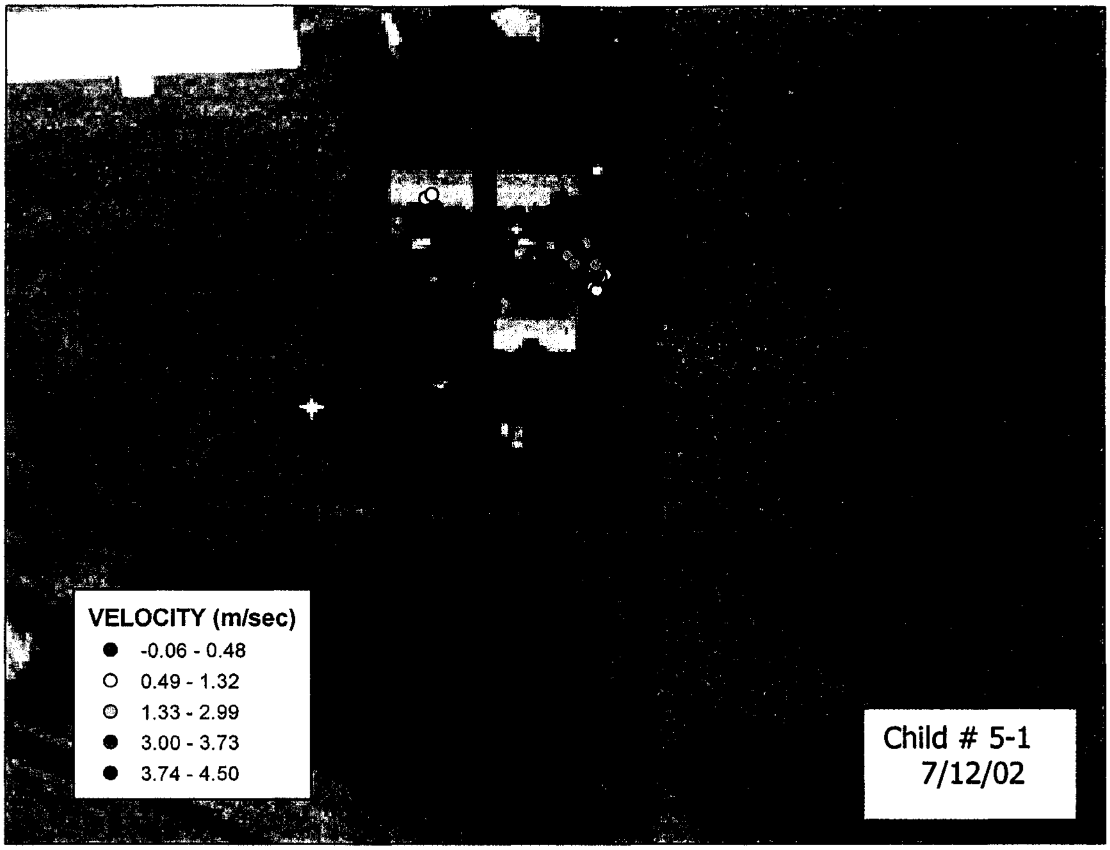
Appendix 4 NN: Child 6 velocity (on bicycle) on spray day



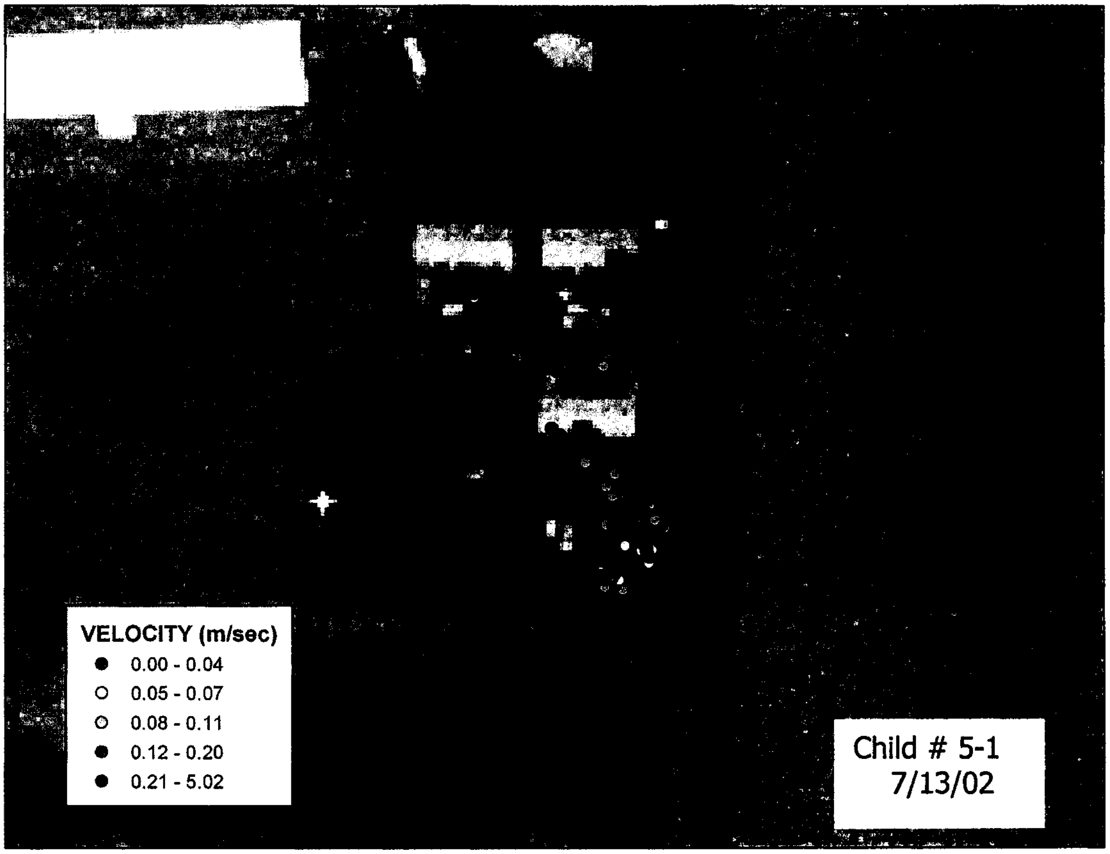
Appendix 4 OO: Child 6 velocity (on foot) on day after spray



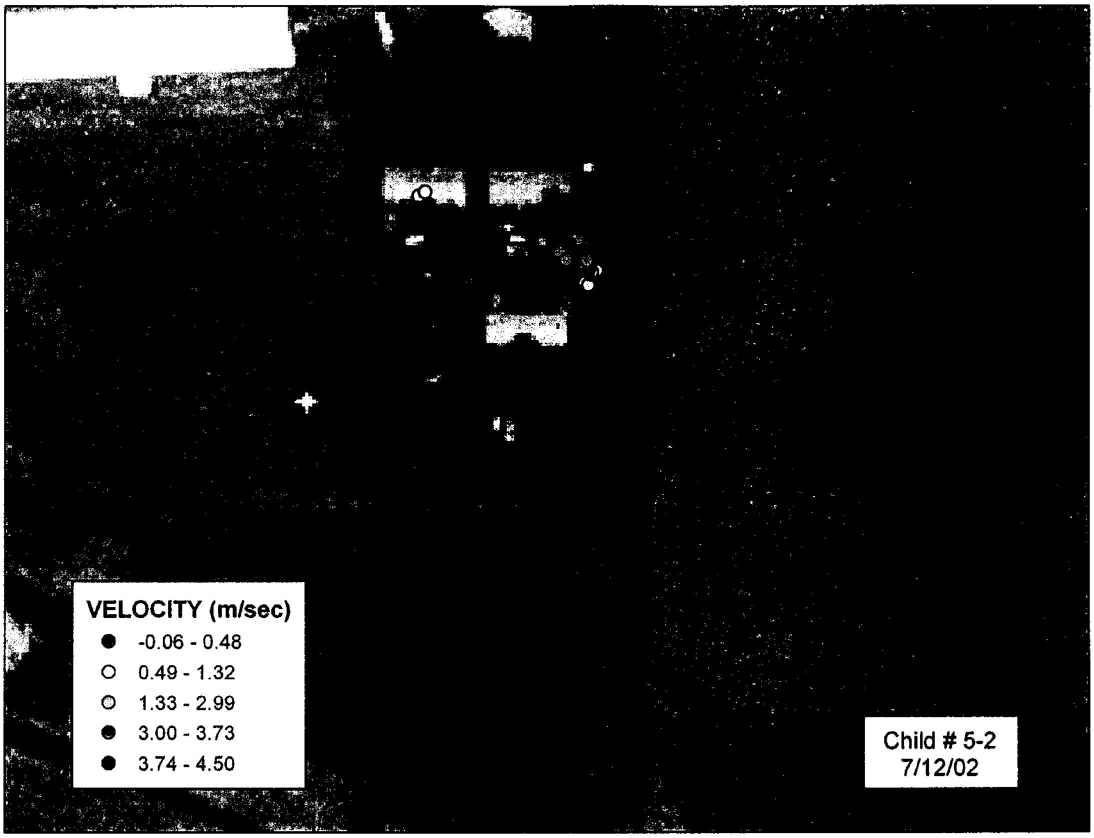
Appendix 4 PP: Child 6 velocity (on bicycle) on day after spray



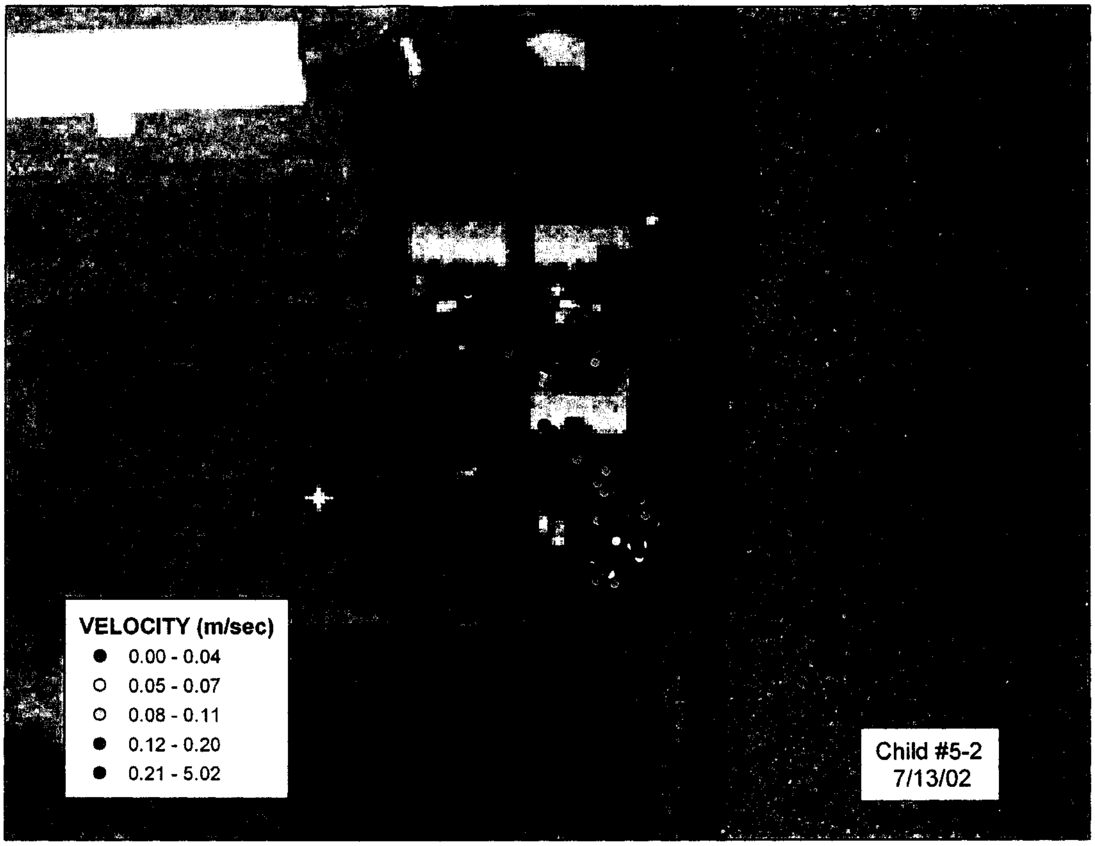
Appendix 4 QQ: Child 7 velocity (on foot) on spray day



Appendix 4 RR: Child 7 velocity (on foot) on day after spray



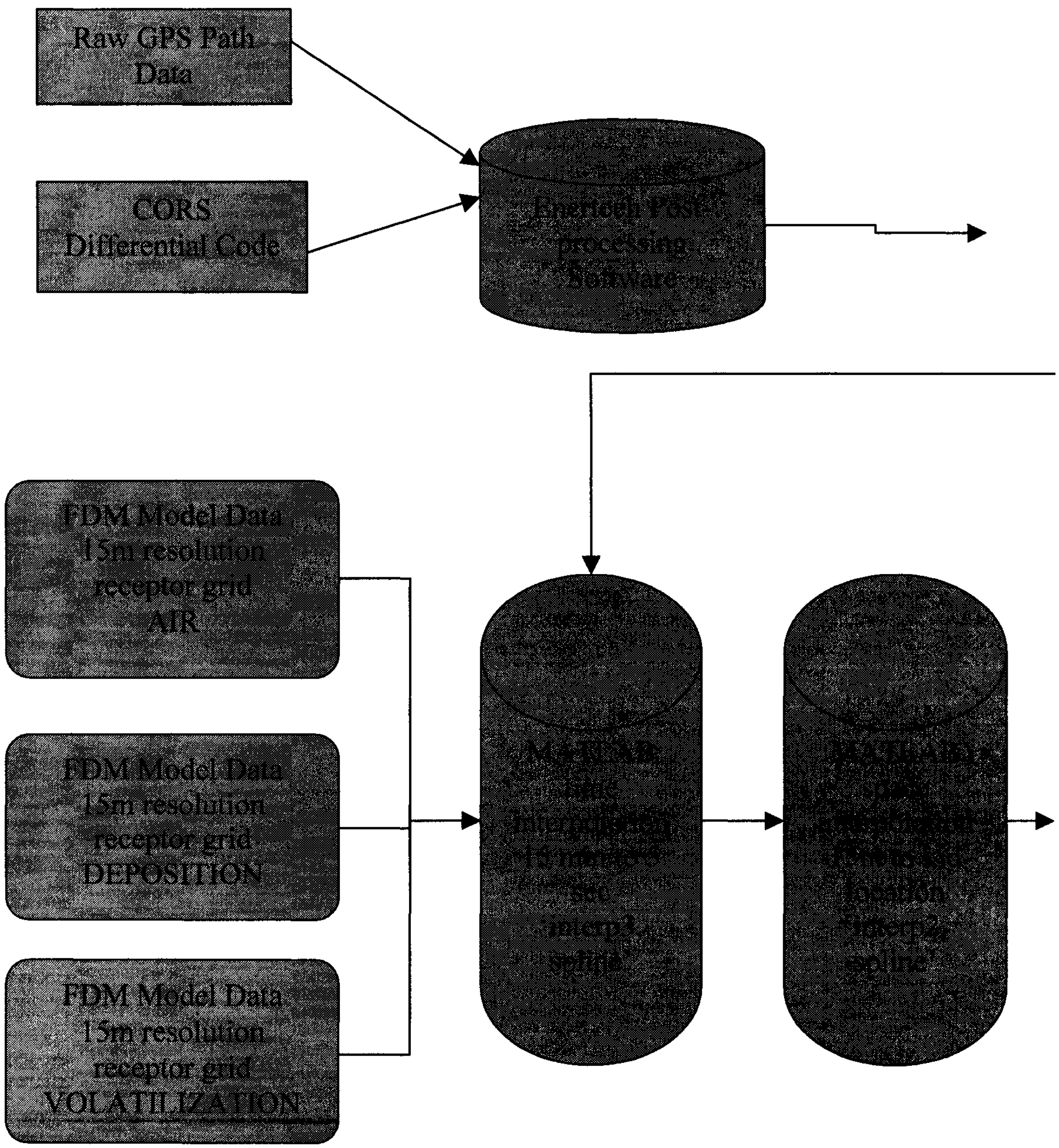
Appendix 4 SS: Child 8 velocity (on foot) on spray day



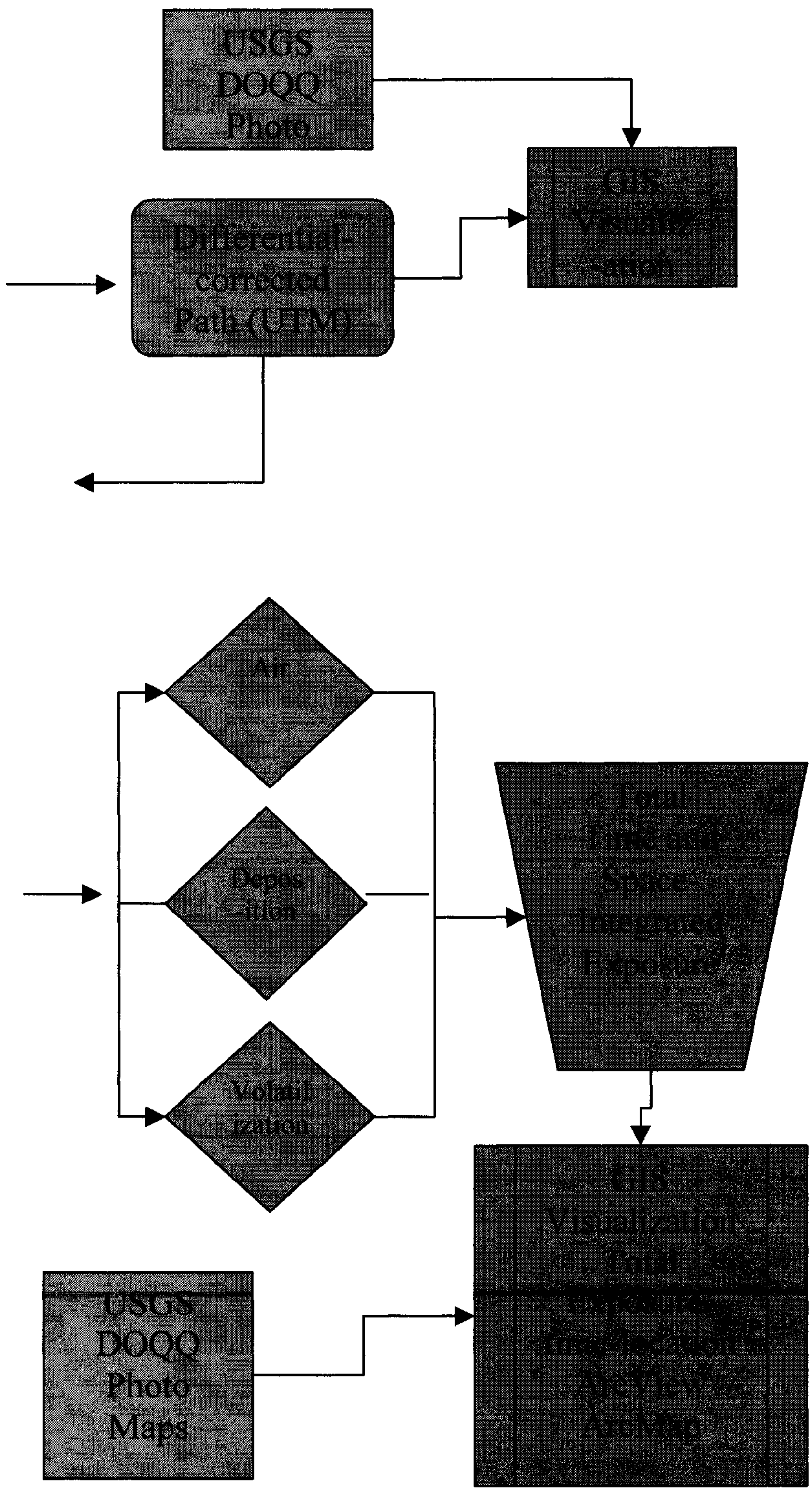
Appendix 4 TT: Child 8 velocity (on foot) on day after spray

Appendix 5A: Data processing flowchart.

Part one.



Part two.


USGS
DOQQ
Photo
GIS
Differential-
corrected
Path (UTM)
Air
Depos
-ition
Volatil
ization
Total
Time and
Space
Integrated
Exposure
GIS
Visualization
Total
ArcView
ArcMap
USGS
DOQQ
Photo
Maps

Appendix 5B: Time-Location Determination for 'GPS+Model' and 'Standard' Methods

GPS+Model

- The GPS-PAL was set to record once every 5 seconds.
- Paths were reviewed to determine which points fell indoors and outside of the community. Indoor points were excluded from exposure analysis.
- Paths were reviewed to determine mode of transit: on foot, on bicycle, or in vehicle.

Standard

- GPS-PAL path was categorized into 5 categories similar to the NHEXAS diary: Indoors in Community, Indoors out of Community, Outdoors in Community, Outdoors out of Community, and Transit. Indoor points were excluded from exposure analysis.
- One hour resolution was used. The location category with the majority of time counts during a given hour was coded as the correct time-location for that hour.

Appendix 5C. Formulae for breathing rate calculations

GPS+Model

$$\text{Weighted Breathing Rate} = \left(1 + \frac{V}{V_b}\right) * (R_{br})$$

V = *velocity (m/s)*
V_b = *baseline velocity (m/s)*
R_{br} = *age specific breathing rate (m3/hr)*

Velocity calculated from GPS time-location data.

Baseline Velocity from Knoblauch et al. 1996.
Baseline walking velocity = 1.22 m/s
Baseline bicycling velocity = 2.44 m/s

Age Specific Resting Breathing Rates from Adams et al. 1993, EPA 2002.

<2yo = 0.35 m3/hr
3yo-5.9 yo = 0.40 m3/hr
6yo-12yo = 0.47 m3/hr

Standard

No Weighting.

Age-gender Specific Moderate Activity Breathing Rates from Adams et al. 1993, EPA 2002.

M <3yo = 0.78 m3/hr
3yo-10 yo = 0.96 m3/hr
>10yo = 1.5 m3/hr

F <3yo = 0.60 m3/hr
3yo-10 yo = 0.90 m3/hr
>10yo = 1.26 m3/hr

Appendix 5D. Formulae for inhalation exposure (encountered air concentration) calculations

GPS+Model

Total is the mean of all time intervals (minimum 5 seconds):

1. If Within the Community Model Output Grid

$$C_E = \Sigma\ [(C_{ae} + C_{ve})*t]\ /\Sigma t$$

C_E = *Encountered Air Concentration (ng/m3)*
C_{ae} = *Concentration Output from Aerosol Model for that Time and Location (ng/m3)*
C_{ve}=*Concentration Output from Gas & Vapor Phase Volatility Model for that Time and Location (ng/m3)*
t = *interval time (sec)*
Σt = *sum of time over all intervals (sec)*

2. If Outside the Community Model Output Grid

Encountered Air Concentration = C_{uf}

C_{uf} = *Upwind pump fixed location concentration for that time period (ng/m3)*

Standard

For a given time period.

1. If Within the Community Model Output Grid

Fixed Air Concentration = C_{cf}

C_{cf} = *Mean community concentration at fixed locations for all pumps for that time period (ng/m3)*

2. If Outside the Community Model Output Grid

Fixed Air Concentration = C_{uf}

C_{uf} = *Upwind pump fixed location concentration for that time period (ng/m3)*

Appendix 5E. Formulae for inhaled mass calculations

GPS+Model

Total is a summation of all time intervals (minimum 5 seconds):

$$Mi = \Sigma \left[C_{ei} * R_{brw} * \frac{1\ hr}{3600\ sec} * t \right]$$

Mi = *Inhaled mass (ng)*
C_{ei} = *Encountered Interval Air Concentration (ng/m3 per interval duration)*
R_{brw} = *Weighted Breathing Rate (m3/hr)*
t = *Interval Time in seconds (sec*

Standard

For a given time period:

$Mi = C_f * BR * T$

Mi = *Inhaled mass (ng)*
C_f = *Fixed Air Concentration (ng/m3)*
BR = *Breathing Rate (m3/hr)*
T = *Time Outside in hours (hr)*

Appendix 5.F. Formulae for dermal exposure (encountered ground load) calculations

GPS+Model

Total is the mean of all time intervals (minimum 5 seconds):

$L_E = \Sigma\ [M_{cd} * t] / \Sigma t$

L_E = *Encountered ground load (ng/cm2)*
M_{cd} = *Deposition Cumulative mass per area output from model for location during that time interval (ng/cm2 per interval duration)*
t = *interval time (sec)*
Σt = *sum of time over all intervals (sec)*

Standard

For a specific time period:

Fixed Ground Load = D_{gf}

D_{gf} = *Mean cumulative deposition plate fixed location load for all deposition plates in the community for that time period (ng/cm2). This number is cumulative through the end of deposition, at which point it becomes constant.*

Appendix 5.G. Formulae for mass on skin calculations

Assumed transfer factor for all calculations: 400 cm2/hour

GPS+Model

Total is a summation of all time intervals (minimum 5 seconds):

$$M_S = \Sigma \left[R_{cd} * F_t * \frac{1\ hr}{3600\ sec} * t\right]$$

> M_S = *mass on skin (ng)*
> R_{cd} = *Deposition Cumulative rate output from model for location during that time interval (ng/cm2 per interval duration)*
> F_t = *Transfer Factor (cm2/hr)*
> t = *Interval Time in seconds (sec*

Standard

For a given time period:

$$M_S = D_{gf} * F_t * T$$

> M_S = *mass on skin (ng)*
> D_{gf} = *Mean deposition plate fixed location load for all deposition plates in the community for that time period (ng/cm2)*
> F_t = *Transfer Factor (cm2/hr)*
> T = *Time period in hours (hr)*

Appendix 5.H. Formula for transfer factor calculation.

$$F_t = \frac{E_d}{20\ \text{min}} * \frac{1}{D_p} * \frac{60\ \text{min}}{1\ \text{hr}}$$

> E_d = dermal exposure (from Bernard et al 2001, 1600 ug)

D_p = application rate (measured on deposition coupons) (from Bernard et al. 2001, 12 ug/cm2)

The application rate as measured on deposition coupons was selected for use in the denominator because both deposition coupons and silica deposition plates are assumed to capture 100% of the deposited pesticide. The transfer factor (F_t) was estimated from these calculations to be 400 cm2/hr.

VITA

Education

PhD, Environmental & Occupational Hygiene, University of Washington , 2004

PhD Student, Pharmacology/Toxicology, Washington State University, 1998-99

MPH, Public Health Promotion & Education, Environmental Health & Safety Emphasis (Magna cum laude), Oregon State University, 1998

BS, Biology (Honors), University of Puget Sound, 1994

Experience

1999–present University of Washington

Dissertation research, "GPS tracking to characterize children's exposure to pesticides"

1999-present University of Washington

Other research projects

Evaluation of creatinine levels in the urine of Seattle children (1999-2000)

Measurement of spray drift using LIDAR remote sensing (2001-2002)

Comparison of urinary organophosphate pesticide metabolite levels in two groups of Seattle children: those eating mainly organically-produced foods and those eating a conventional diet (2001)

Development and evaluation of an FTIR-ATR spectrophotometric probe technique to measure pyrethroid pesticide concentration on skin (2002)

2002-2003 University of Washington

Pre-doctoral Instructor

ENVH 111 Exploring Environment & Health Connections
http://courses.washington.edu/envh111/faculty.html

ENVH 511Environmental & Occupational Health

2001-2002 University of Washington

Graduate Teaching Assistant

ENVH 453 Industrial Hygiene

ENVH 511Environmental & Occupational Health

1998-1999 Washington State University

Graduate Researcher "Biomarkers of renal oxidative stress and injury"

1997-1998 Oregon State University

Graduate Instructor

SMILE (Science & Math Integrated Learning Experiences) Program Staffer

1997 Oregon State University / US EPA, Corvallis, OR

Pesticide Specialist

Publications

Elgethun K, Fenske RA, Yost MG and GJ Palcisko. Time-location analysis for exposure assessment studies of children using a novel global positioning system instrument. Environmental Health Perspectives 111(1): 115-122 (2003).

Curl CL, Fenske RA and K Elgethun. Organophosphorus pesticide exposure to urban and suburban pre-school children with organic and conventional diets. Environmental Health Perspectives 111(3): (2003).

Elgethun K, Neumann C and P Blake. Butyltins in shellfish, finfish, water and sediment from the Coos Bay estuary (Oregon, USA). Chemosphere 41: 953-64 (2000).

Presentations

Elgethun K, Weppner S, Lu C, Tsai MY, Ramaprasad J, Yost M, Fenske RA, Kissel J, Hebert V. GPS/GIS –aided assessment of children's exposure to pesticide drift in a farm community. ISEA Annual Meeting, Stresa, Italy, 24 September 2003.

Elgethun K. GPS to characterize children's time-location (Invited talk). EPA National Children's Study Workshop, Boston, MA, 13 May 2003.

Elgethun K. Progress report: Integration of GPS/GIS with environmental and biological monitoring to characterize children's exposure to methamidophos. 15th Annual UBC-UW Occupational & Environmental Health Conference, Blaine, WA, 10 January 2003.

Elgethun K, Fenske RA, Yost MY, Kissel JC, Lu C and S Weppner. Integration of GPS/GIS & heart rate monitoring in a sampling plan to characterize children's exposure to pesticide spray drift. ISEA/ISEE Annual Meeting, Vancouver, BC Canada, 13 August 2002.

Elgethun K, Fenske R, Yost M, Kissel J and G Palcisko. Evaluation of a new GPS instrument to characterize children's time-location in pesticide exposure assessment studies. Society for Risk Analysis Annual Meeting, Seattle, WA, 3 December 2001.

Elgethun K, Fenske R, Yost M, Kissel J and G Palcisko. Evaluation of a new GPS instrument to characterize children's time-location in pesticide exposure assessment studies. ISEA Annual Meeting, Charleston, SC, 6 November 2001.

Elgethun K. GPS for human time-location studies. 13th Annual UBC-UW Occupational & Environmental Health Conference, Blaine, WA, 12 January 2003

Elgethun K, Neumann C and P Blake. Butyltins in shellfish, finfish, water and sediment from the Coos Bay estuary (Oregon, USA). American Association for the Advancement of Science Annual Meeting , Anaheim, CA, January 1999.

Conferences attended

International Society of Exposure Analysis, 2000, 2001, 2002, 2003.

UW-UBC Occupational & Environmental Health Conference 2000, 2001, 2002, 2003.

Society for Risk Analysis, 2001.

American Industrial Hygiene Conference & Exposition, 2001.

Pacific NW Association of Toxicologists, 1998.

Memberships & Activities

American Conference of Governmental Industrial Hygienists

International Society of Exposure Analysis

Washington State Environmental Health Association

Reviewer for journal: Environmental Health Perspectives

Faculty search committee, University of Washington

Languages

Scale: 1 (basic) to 3 (fluent)

Reading, writing, speaking: Spanish (2, 1, 1) , French (2, 2, 1), English (3, 3, 3).

Awards & Funding

Outstanding Student Award, Department of Environmental & Occupational Health Sciences, 2003.

EPA-NIEHS Center for Child Environmental Health Risks Research, 2001-present

NIOSH Pacific Northwest Agricultural Safety & Health Center, 2001-present.
NIOSH Training Grant 1999-2001

Murdock Charitable Trust, BS Thesis research in chemical ecology, 1993-1994.

Citizenship

US Citizen.