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# A Method for Semi-quantitative Assessment of Exposure to Pesticides of Applicators and Re-entry Workers: An Application in Three Farming Systems in Ethiopia

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## ABSTRACT

**Objective:** To develop an inexpensive and easily adaptable semi-quantitative exposure assessment method to characterize exposure to pesticide in applicators and re-entry farmers and farm workers in Ethiopia.

**Methods:** Two specific semi-quantitative exposure algorithms for pesticides applicators and re-entry workers were developed and applied to 601 farm workers employed in 3 distinctly different farming systems [small-scale irrigated, large-scale greenhouses (LSGH), and large-scale open (LSO)] in Ethiopia. The algorithm for applicators was based on exposure-modifying factors including application methods, farm layout (open or closed), pesticide mixing conditions, cleaning of spraying equipment, intensity of pesticide application per day, utilization of personal protective equipment (PPE), personal hygienic behavior, annual frequency of application, and duration of employment at the farm. The algorithm for re-entry work was based on an expert-based re-entry exposure intensity score, utilization of PPE, personal hygienic behavior, annual frequency of re-entry work, and duration of employment at the farm.

**Results:** The algorithms allowed estimation of daily, annual and cumulative lifetime exposure for applicators, and re-entry workers by farming system, by gender, and by age group. For all metrics, highest exposures occurred in LSGH for both applicators and female re-entry workers. For male re-entry workers, highest cumulative exposure occurred in LSO farms. Female re-entry workers appeared to be higher exposed on a daily or annual basis than male re-entry workers, but their cumulative exposures were similar due to the fact that on average males had longer tenure. Factors related to intensity of exposure (like application method and farm layout) were indicated as the main driving factors for estimated potential exposure. Use of personal protection, hygienic behavior, and duration of employment in surveyed farm workers contributed less to the contrast in exposure estimates.

**Conclusions:** This study indicated that farmers' and farm workers' exposure to pesticides can be inexpensively characterized, ranked, and classified. Our method could be extended to assess exposure to specific active ingredients provided that detailed information on pesticides used is available. The resulting exposure estimates will consequently be used in occupational epidemiology studies in Ethiopia and other similar countries with few resources.

**KEYWORDS:** algorithms; exposure assessment; farming systems; occupational; pesticide

## INTRODUCTION

In Ethiopia, 85% of the labor force is employed in the agricultural sector contributing 46% of the country's gross domestic product (Ethiopian Economy Profile, 2015). Due to the introduction and evolving new farming systems such as greenhouses and small-scale irrigation schemes, there has been an almost 3-fold increase in pesticides import (from 1440 to 4240 ton in, respectively, 2001 and 2010) in Ethiopia (Ministry of Agriculture, 2011). Though pesticides are vital in order to minimize production loss due to pests and plant diseases, they could be hazardous to health for non-target species including human beings (Bolognesi and Merlo, 2011).

Most pesticides can readily be absorbed through the skin, ingested, or inhaled and can produce diverse health effects ranging from acute poisoning to chronic health effects such as respiratory, neurological, and reproductive/developmental health effects (Steenland *et al.*, 2000; Thudiyil *et al.*, 2008; Fieten *et al.*, 2009; Naidoo *et al.*, 2011).

In studies of health effects from occupational exposure to pesticides, collection and analyses of personal samples for every individual in a study are often not feasible due to high cost (Arbuckle *et al.*, 2002). This is even more pertinent in low- and middle-income countries where funds for field research are limited. In the absence of personal monitoring results, investigators may either use work histories, expert assessments, self-reported exposures, or by applying crop, job, or task exposure matrices (London and Myers, 1998; Dick *et al.*, 2010).

A semi-quantitative pesticide exposure algorithm developed for the Agricultural Health Study (AHS) (Dosemeci *et al.*, 2002) has been extensively used and evaluated by different field monitoring studies. Those evaluations showed that estimated values using the algorithm had appreciable correlation with post-application urinary concentration of pesticide biomarkers (Coble *et al.*, 2005; Acquavella *et al.*, 2006). Estimated values were also significantly predictive of dermal exposure (Hines *et al.*, 2008) and correlated with post-application urine concentration, estimated hand and body loading, and also air concentrations (Thomas *et al.*, 2010). This algorithm however was not developed for contemporary situations in low- and middle-income countries where farming systems and pesticide-related practices could be rather different.

The aim of this article was to develop an inexpensive and easily adaptable semi-quantitative exposure assessment method for pesticide applicators and re-entry farm workers. We describe the developed algorithms and present the pesticide exposure distributions for 601 farmers and farm workers and compare the differences between farming systems, between male and female farmers and farm workers, and between age groups . In addition, we identify what the main drivers of the resulting semi-quantitative exposure metrics are.

## MATERIALS AND METHODS

A cross-sectional study was conducted in the central eastern part of Ethiopia among a group of 601 farmers and farm workers comprising 256 pesticide applicators and 345 re-entry workers. Re-entry workers are workers who are exposed to pesticides indirectly via entering treated fields after hours or days depending on the farming system and/or crop type (e.g. harvesters and pest assessors) or those who handle the farm produce every day (e.g. packing and transport workers). Details of the population and selection procedures can be found elsewhere (Negatu *et al.*, 2016). In brief, we aimed to include all applicators and a randomly chosen subset of re-entry workers from farms randomly selected from the three main commercial farming systems [large-scale greenhouses (LSGH), small-scale irrigated farms (SSIF), and large-scale open farms (LSOF)]. Two LSGH were selected randomly from two clusters of greenhouses in the study area. For LSOF, four farm units were randomly selected from nine units from two big farms which are under the umbrella of Upper Awash Agro-Industry Enterprise (UAAIE). In SSIF, a random selection was taken of 5 primary farmers' cooperatives out of 69 primary cooperatives, which were all under Meki–Batu vegetables and fruit growers' cooperatives union. Study subjects were selected if they had been working on the selected farms for the past 12 months preceding the study period, and participation was on voluntary and anonymous basis after verbal informed consent was obtained from the participants.

A pretested structured questionnaire with closed and open-ended questions was administered to obtain the following information:

1. Socio-demographic characteristics (e.g. gender and age);
2. Pesticide exposure-related factors (e.g. job title, application methods, the presence of pesticide mixing, the presence of indoor application, cleaning of equipment, total amount of pesticides used in kilogram and liter (kg + l) of pesticide used per day, number of working days per year, and duration of employment);
3. Personal protection and hygienic behavior-related factors (i.e. use of personal protective equipment (PPE), replacement of PPE, washing, and bathing after pesticide-related work).

## Development of semi-quantitative exposure assessment algorithms

### *Applicator algorithm*

The applicators algorithm was adapted from the semi-quantitative approach for estimating exposure to pesticides developed for the AHS (Dosemeci *et al.*, 2002). The algorithm consisted of three factors: pesticide exposure intensity, personal protection and hygienic behavior, and frequency of applications combined with number of years workings as an applicator. Values for each of the exposure-modifying factors were assigned based on data collected through the survey questionnaire, published in the literature or based on expert judgments.

#### Cumulative applicator exposure

The exposure algorithm to estimate cumulative exposure to pesticides for applicators consisted of three parts: pesticide exposure intensity, pesticide exposure (personal) protection, and pesticide exposure duration.

The intensity part of the algorithm consists of three exposure-modifying variables: application method, presence of pesticide mixing, and cleaning of spray equipment. The intensity score for each of the three exposure-modifying factors was further adjusted by indoor/outdoor application and closed/open mixing system. The sum of the factor weights (adjusted scores of the three intensity-related variables) were consequently multiplied with average pesticide use (kg + l) per applicator per day (papa). Personal exposure protection factors, i.e. use of PPE and hygienic behavior, were included in the algorithm in a multiplicative way with weighting factors <1 (no PPE use) depending on the assumed effectiveness of the PPE and hygienic behavior configurations. To arrive at a cumulative estimate, this score was further multiplied with pesticide exposure duration factors, i.e. frequency of applications per year and number of years employed as an applicator.

$$
\begin{aligned}
&\text{Cumulative applicator exposure to a mixture of pesticides} \\
&= | \{ [ (\text{application method} \times \text{indoor / outdoor application}) \\
&\quad + (\text{mixing of pesticides x enclosed / open tank}) \\
&\quad + (\text{cleaning of spray equipment}) ] \} \\
&\quad \times \{ \text{amount pesticide used per application day (kg + l) / applicator} \} | \\
&\quad \times | \{ \text{use of PPE} \times \text{replacement of PPE} \} \times \{ \text{hygienic measures} \} | \\
&\quad \times | \{ \text{application days per year} \} \times \{ \text{duration of employment} \} |
\end{aligned}
$$

Each of the variables in the algorithm weighting factors (see Supplementary Annex 1 is available at *Annals of Occupational Hygiene* online) was based on results of previously published data, but (if necessary) appropriate modifications were made using expert judgment and/or information collected in the questionnaire.

Weighting factors for application methods and mixing status from the AHS were used (Coble *et al.*, 2011), but modifications were made provided the different farming systems in Ethiopia. For example, since most farm workers used more than one application method, additional weighting values were incorporated [i.e. (1) for using that specific application method always (1.00), most of the time (0.75), half of the time (0.5), and sometimes (0.25), respectively] for specific usage of a particular application method.

In case of assignment of weighting scores for farm layout (i.e. indoor/outdoor pesticide spraying), the occupational pesticide handler unit exposure surrogates reference table (US Environmental Protection Agency, 2013) was used. Exact scores provided by Dosemeci *et al.* (2002) were used as weights for mixing equipment (using closed versus open mixing tank) and cleaning of spraying equipment. The score of cleaning of spraying equipment was multiplied by the corresponding frequency of equipment cleaning [i.e. (1) for always cleaning an application equipment, most of the time (0.75), half of the time (0.5), and sometimes (0.25), respectively] to arrive at an exposure estimate for cleaning of spraying equipment.

Weighted values for other exposure-modifying variables (i.e. use of PPE, replacement of PPE, and hygienic behavior) were also adapted from Dosemeci *et al.* (2002). Modifications were made based on the contemporary exposure situations in the studied farming systems in Ethiopia. For example, the maximum reported replacement PPE (two times a year) in our study was assigned the lowest weighting score (1.1) similar to Dosemeci *et al.* (2002). Also, for replacement of old PPE, a weighting score of 1.15 was incorporated for those farmers who reported replacement of PPE once a year because only weighting factors for substitution of PPEs twice a year (1.1) and until worn out without substitution (1.2) were available from Dosemeci *et al.* (2002).

Even though studies have indicated a wide range of protection for rubber gloves 27% (Nigg *et al.*, 1986), 40% (Dosemeci *et al.*, 2002), 50% (de Cock *et al.*, 1998), and 60% (Coble *et al.*, 2011). We assigned a default value of 35% to rubber gloves as a protection factor, due to variation in type of gloves used (i.e. material and thickness), chemical class of pesticide applied, and difference in knowledge of proper PPE usage which can possibly affect potential protection factors. Additionally, a protection factor of 10% was assigned for each of the PPE items used (i.e. overall, boots, respirators, and goggles) with a maximum protection reduction of 40%. Using a hat/handkerchief/boots alone was not considered to be effective PPE (Ohayo-Mitoko *et al.*, 1999), so it was assigned a protection factor of 0%. The score of using a particular PPE or a combination of PPE was calculated by dividing the corresponding percentile value of the protection factor by 100 then subtracting the result from 1 (e.g. 45% protection corresponds to a score of 0.55 to be used in the algorithm).

Expert judgment based on payroll documents and interviews with farm workers was used to assign, respectively, 150 and 250 times per year as an average frequency (days) of application in the two LSGH farms where one was a cuttings and the other a rose farm. Similarly, an average application of 295 times a year was used as a default value in all LSOF farms, since all farm workers were employed by UAAIE.

Total pesticide use per day per applicator (kg + l) was estimated to be, respectively, 1.24 and 2.93 (kg + l) in the two LSGH farms based on total annual pesticide use collected from farm records, estimated annual number of application days, and number of applicators. Similarly, for the two LSOF farms, this amounted to 2.39 (kg + l). In the case of SSIF, the actual reported amount of pesticide use was used. This value ranged from 0.32 to 3.58 (kg + l).

Duration of employment was defined as number of years worked as an applicator or re-entry worker and was based on what was reported by individual farmers and farm workers in the questionnaire.

#### Average annual applicator exposure

Applicators' annual exposure was estimated by dividing the estimated cumulative exposure by the number of working years as an applicator.

#### Average daily applicator exposure

Applicators exposure per day was estimated by dividing the estimated annual exposure by the number of application days per year.

### *Re-entry worker algorithm*

#### Cumulative re-entry exposure

The algorithm to estimate cumulative exposure to pesticides for re-entry farm workers was similarly structured and consisted of the following factors: pesticide exposure intensity (i.e. re-entry exposure intensity score), pesticide exposure protection (i.e. use of personal protection and hygienic behavior), and pesticide exposure duration (i.e. years of employment as a re-entry worker).

The re-entry exposure intensity score was assigned in two steps. In a first step, weights were given for each of the re-entry tasks (activities). Re-entry workers (i.e. pest assessors and harvesters) who usually enter/work in pesticide-treated fields were assigned a high potential exposure (Jurewicz *et al.*, 2009). Those who usually do not enter the sprayed fields directly, but might only be in contact with pesticide residues on the foliage of treated crops (i.e. sorting and packing, rooting and propagation, irrigation, and transport workers) or other activities involving pesticides (i.e. packers, storekeepers), were assigned a medium potential exposure. Other farm workers (i.e. construction and maintenance workers) were assigned a low potential exposure. Weighting factors of 1, 3, and 10 were given to respectively low, medium, high pesticide exposure based on van Wendel de Joode *et al.* (2003).

In a second step, the three farming systems were assessed for an overall potential re-entry exposure level and given relative weights of low, medium, and high based on expert judgment and the peer-reviewed literature (Garreyn *et al.*, 2008; Jurewicz *et al.*, 2009; Baldi *et al.*, 2014). The relative ranking was based on expert judgment of re-entry exposure-modifying situations across the three farming systems (i.e. pesticide application rate per hectare, the usual re-entry time after pesticide application, crop type, and closeness of a farm) and was given similar weighting values of 1, 3, and 10 as that of weighting values of step one (i.e. cluster of re-entry tasks) for SSIF, LSOF, and LSGH, respectively, based on van Wendel de Joode *et al.* (2003).

The final re-entry exposure intensity score was assigned by multiplying the exposure score based on task performed by the exposure score due to working in a specific farming system. This resulted in a re-entry exposure intensity score by task and farm type as shown in Supplementary Annex 2 at *Annals of Occupational Hygiene* online.

The final re-entry cumulative exposure estimate was calculated by taking into account use of PPE and hygienic behavior in combination with frequency and duration of re-entry work:

$$\begin{aligned}&\text{Cumulative re-entry exposure to pesticides}\\&=|\{\text{re-entry exposure intensity score}\}|\\&\quad\times|\{\text{use of PPE}\times\text{replacement of PPE}\}\\&\quad\times\{\text{hygienic measures}\}|\\&\quad\times|\{\text{frequency of re-entry work per year}\}\\&\quad\times\{\text{duration of employment}\}|\end{aligned}$$

Weighting values for personal protective and hygienic behavior factors (see Supplementary Annex 3 is available at *Annals of Occupational Hygiene* online) were assigned based on similar arguments as those for applicators.

Similarly, average re-entry working frequency per year was estimated to be 165, 250, and 295 in SSIF, LSGH, and LSOF, respectively, based on expert judgments via information obtained from payroll documents and/or interviews with farm workers. Duration of employment (i.e. number of years worked as re-entry worker) was based on what was reported by individual farm workers in the questionnaire.

### Average annual re-entry exposure

Re-entry exposure per year/annual exposure was estimated by dividing estimated cumulative re-entry exposure (CRE) by number of working years for each of the re-entry workers.

### Average daily re-entry exposure

Re-entry exposure per day was estimated by dividing estimated annual exposure by the number of re-entry working days per year.

## DATA ANALYSIS

The collected data were computerized using Epi Data version 3 and analyzed using Stata SE/11.0. The exposure estimates appeared to be log normally distributed so in addition to the arithmetic mean, the geometric mean and geometric standard deviation and percentiles were used to describe cumulative exposure (CAE and CRE), average annual exposure [average annual applicator exposure (AAE) and average annual re-entry exposure (ARE)], and average daily exposure (DAE and DRE) across the farming systems and age groups. Analyses of variance were done to assess statistical significant differences in the six estimated exposure variables between farming systems, gender, and age groups. Pearson correlation coefficients were used to assess correlations among the estimated exposure variables and duration of employment as an applicator or re-entry worker.

## RESULTS

### Characteristics surveyed population

In Table 1, an overview is presented of the surveyed farmers and farm workers. In LSOF and LSGH, the majority of studied farmers and farm workers were re-entry workers (72 and 81%, respectively), while in SSIF, most of the farmers were applicators (66%). Gender differences in tasks performed were observed with all applicators being male, while females formed the majority of re-entry workers (80%).

The surveyed population was relatively young with a mean age of 27.4 ± 6.7 years, which was similar across farming systems. The average duration of employment was 4.4 years, which was on average almost a year longer in LSOF (5.2) compared to the duration of employment of farmers and farm workers in LSGH and SSIF.

### Cumulative applicator exposure

Table 2 shows cumulative applicator exposure (CAE) being statistically significant ($P < 0.05$) different across farming systems with higher values in LSGH (23 252) than in LSOF (7745) and SSIF (2462). A 30-fold difference was observed between estimated $P_{(10)}$ and $P_{(90)}$ values (Table 3).

### Average annual applicator exposure

Statistically significant ($P < 0.05$) higher annual applicator exposure was indicated in LSGH (7315) than in LSOF (3505) and SSIF (484) (Table 2). A 33-fold difference was observed between estimated values of $P_{(10)}$ and $P_{(90)}$ (Table 3).

### Average daily applicator exposure

Daily applicator exposure was statistically significantly ($P < 0.05$) different among farming systems with highest daily applicator exposure in LSGH (30) followed by SSIF (16) and lowest in LSOF (12). A 7-fold difference between $P_{(10)}$ and $P_{(90)}$ values was also indicated (Table 3).

The three applicator exposure variables (cumulative, annual, and daily) were strongly correlated ($r$ = 0.71–0.86). Interestingly, number of years of being an applicator showed a weak correlation with cumulative exposure ($r$ = 0.01) indicating that exposure contrast is mostly driven by the intensity component of the algorithm (Table 5).

### Cumulative re-entry exposure

CRE was similar for male (21 581) and female (22 936) re-entry workers. Female re-entry workers

**Table 1. Socio-demographic and exposure characteristics of the surveyed population.**

| Variables | Total ($n$ = 601) | LSOF ($n$ = 134) | SSIF ($n$ = 258) | LSGH ($n$ = 209) |
|---|---|---|---|---|
| | Number (%) | Number (%) | Number (%) | Number (%) |
| **Exposure type** | | | | |
| Applicator | 256 (42.60) | 26 (19.40) | 171 (66.28) | 59 (28.23) |
| Re-entry | 345 (57.40) | 108 (80.60) | 87 (33.72) | 150 (71.77) |
| **Sex** | | | | |
| Male | 326 (54.24) | 62 (46.27) | 171 (66.28) | 93 (44.49) |
| Female | 275 (45.76) | 72 (53.73) | 87 (33.72) | 116 (55.50) |
| | Mean (SD) | Mean (SD) | Mean (SD) | Mean (SD) |
| **Age (years)** | 27.44 (6.67) | 27.10 (6.80) | 27.27 (6.50) | 27.86 (6.80) |
| **Duration of employment (years)** | 4.44 (3.48) | 5.19 (5.89) | 4.62 (2.63) | 3.74 (1.82) |

SD, standard deviation.

**Table 2. Estimated AM of exposure intensity variables in different exposure groups by farm and age groups**

| | Pesticide applicators | | | Female re-entry workers | | | Male re-entry workers | | |
|---|---|---|---|---|---|---|---|---|---|
| | *N* (%) | AM | *P* value | *N* (%) | AM | *P* value | *N* (%) | AM | *P* value |
| **Cumulative exposure** | | | | | | | | | |
| **Total** | 256 (100) | 7790 | — | 275 (100) | 22 936 | — | 70 (100) | 21 581 | $P = 0.72$ |
| **Farm** | | | | | | | | | |
| LSO | 26 (10) | 7745 | $P < 0.05$* | 72 (26) | 22 857 | $P < 0.05$* | 36 (51) | 25 907 | $P = 0.31$ |
| SSI | 171 (67) | 2462 | | 87 (32) | 5463 | | — | — | |
| LSGH | 59 (23) | 23 252 | | 116 (42) | 36 089 | | 34 (49) | 17 000 | |
| **Age** | | | | | | | | | |
| 16–23 | 62 (24) | 6179 | $P = 0.57$ | 95 (35) | 13 681 | $P < 0.05$* | 13 (18) | 8421 | $P = 0.14$ |
| 24–26 | 93 (36) | 8528 | | 81 (30) | 21 987 | | 20 (29) | 14 972 | |
| 27–30 | 53 (21) | 7089 | | 42 (15) | 29 157 | | 16 (23) | 22 472 | |
| 31–57 | 48 (19) | 9213 | | 57 (20) | 35 125 | | 21 (30) | 35 343 | |
| **Annual exposure** | | | | | | | | | |
| **Total** | 256 (100) | 2365 | — | 275 (100) | 5879 | — | 70 (100) | 3177 | $P < 0.05$* |
| **Farm** | | | | | | | | | |
| LSO | 26 (10) | 3505 | $P < 0.05$* | 72 (26) | 4980 | $P < 0.05$* | 36 (51) | 2381 | $P < 0.05$* |
| SSI | 171 (67) | 484 | | 87 (32) | 1312 | | — | — | |
| LSGH | 59 (23) | 7315 | | 116 (42) | 9862 | | 34 (49) | 4019 | |
| **Age** | | | | | | | | | |
| 16–23 | 62 (24) | 2572 | $P = 0.55$ | 95 (35) | 5960 | $P = 0.95$ | 13 (18) | 2527 | $P = 0.22$ |
| 24–26 | 93 (36) | 2666 | | 81 (30) | 6063 | | 20 (29) | 4060 | |
| 27–30 | 53 (21) | 2013 | | 42 (15) | 5801 | | 16 (23) | 3325 | |
| 31–57 | 48 (19) | 1902 | | 57 (20) | 5540 | | 21 (30) | 2626 | |

**Table 2.** *Continued*

| | Pesticide applicators | | | Female re-entry workers | | | Male re-entry workers | | |
|---|---|---|---|---|---|---|---|---|---|
| | *N* (%) | AM | *P* value | *N* (%) | AM | *P* value | *N* (%) | AM | *P* value |
| **Daily exposure** | | | | | | | | | |
| **Total** | 256 (100) | 19 | — | 275 (100) | 24 | — | 70 (100) | 12 | $P < 0.05$* |
| **Farm** | | | | | | | | | |
| LSO | 26 (10) | 12 | $P < 0.05$* | 72 (26) | 17 | $P < 0.05$* | 36 (51) | 8 | $P < 0.05$* |
| SSI | 171 (67) | 16 | | 87 (32) | 8 | | — | — | |
| LSGH | 59 (23) | 30 | | 116 (42) | 39 | | 34 (49) | 16 | |
| **Age** | | | | | | | | | |
| 16–23 | 62 (24) | 19 | $P = 0.85$ | 95 (35) | 24 | $P = 0.95$ | 13 (18) | 9 | $P = 0.12$ |
| 24–26 | 93 (36) | 20 | | 81 (30) | 24 | | 20 (29) | 16 | |
| 27–30 | 53 (21) | 18 | | 42 (15) | 23 | | 16 (23) | 13 | |
| 31–57 | 48 (19) | 19 | | 57 (20) | 22 | | 21 (30) | 9 | |

AM, arithmetic mean.
*Statistically significant.

**Table 3. Cumulative exposure, annual exposure, and daily exposure per application day estimates for applicators by farming system and by age group**

| | Number (%) | GM | GSD | $P_{(10)}$ | $P_{(50)}$ | $P_{(90)}$ |
|---|---|---|---|---|---|---|
| **Cumulative exposure** | | | | | | |
| **Total** | 256 (100) | 3271 | 3.60 | 737 | 2620 | 21 918 |
| **Farms** | | | | | | |
| LSO | 26 (10) | 5800 | 2.24 | 1905 | 6335 | 16 005 |
| SSI | 171 (67) | 1704 | 2.31 | 603 | 1568 | 48 24 |
| LSGH | 59 (23) | 16 802 | 2.39 | 4509 | 20 295 | 46 124 |
| **Age** | | | | | | |
| 16–23 | 62 (24) | 2277 | 3.63 | 536 | 1806 | 14 206 |
| 24–26 | 93 (36) | 3199 | 3.52 | 724 | 2412 | 26 637 |
| 27–30 | 53 (21) | 3797 | 3.65 | 862 | 3429 | 21 644 |
| 31–57 | 48 (19) | 4621 | 3.60 | 1340 | 3859 | 35 515 |
| **Annual exposure** | | | | | | |
| **Total** | 256 (100) | 912 | 3.81 | 214 | 657 | 7103 |
| **Farms** | | | | | | |
| LSO | 26 (10) | 3099 | 1.68 | 1191 | 3430 | 6628 |
| SSI | 171 (67) | 402 | 1.83 | 184 | 375 | 904 |
| LSGH | 59 (23) | 5737 | 2.18 | 1288 | 7103 | 14 612 |
| **Age** | | | | | | |
| 16–23 | 62 (24 | 1043 | 3.85 | 241 | 703 | 7103 |
| 24–26 | 93 (36) | 1002 | 3.82 | 201 | 724 | 7103 |
| 27–30 | 53 (21) | 758 | 3.65 | 176 | 509 | 7103 |
| 31–57 | 48 (19) | 786 | 3.81 | 217 | 643 | 7103 |
| **Daily exposure** | | | | | | |
| **Total** | 256 (100) | 15 | 1.96 | 6 | 14 | 36 |
| **Farms** | | | | | | |
| LSO | 26 (10) | 10 | 1.68 | 4 | 12 | 22 |
| SSI | 171 (67) | 13 | 1.85 | 6 | 13 | 30 |
| LSGH | 59 (23) | 26 | 1.81 | 8 | 28 | 58 |

**Table 3. *Continued***

| | Number (%) | GM | GSD | $P_{(10)}$ | $P_{(50)}$ | $P_{(90)}$ |
|---|---|---|---|---|---|---|
| **Age** | | | | | | |
| 16–23 | 62 (24) | 15 | 1.95 | 6 | 14 | 33 |
| 24–26 | 93 (36) | 16 | 1.96 | 7 | 14 | 36 |
| 27–30 | 53 (21) | 14 | 1.97 | 6 | 13 | 31 |
| 31–57 | 48 (19) | 16 | 1.96 | 6 | 18 | 40 |

$P_{(10)}$, $P_{(50)}$, and $P_{(90)}$ are the 10th, 50th, and 90th percentile of the distribution, respectively. GM, geometric mean; GSD, geometric standard deviation.

in LSGH had statistically significant ($P < 0.05$) higher cumulative exposure (36 089) than re-entry workers in LSOF (22 857) and SSIF (5464). But male re-entry workers in LSOF had higher cumulative exposure (25 907) than LSGH (17 000) among the three faming systems (Table 2).

The difference between $P_{(10)}$ and $P_{(90)}$ values of CRE varied considerably within exposure groups (108- and 23-fold for, respectively, male and female re-entry workers) (Table 4). The estimated cumulative exposure values significantly ($P < 0.05$) increased with age for female re-entry workers (Table 2). The age patterns for male re-entry workers were similar to that of female re-entry workers, but the differences between age groups were not statistically significant ($P = 0.14$).

### Average annual re-entry exposure

Annual exposure values were higher among female (5879) than male (3177) re-entry workers ($P < 0.05$). In both male and female re-entry workers, the highest values were estimated in LSGH (i.e. 4019 and 9862, respectively). Annual exposure showed 5- and 9-fold differences between $P_{(10)}$ and $P_{(90)}$ values in male and female re-entry workers, respectively (Table 4).

### Average daily re-entry exposure

Female re-entry-workers had a statistically significant ($P < 0.05$) 2-fold higher average daily re-entry exposure than male re-entry workers (24 versus 12). Re-entry workers (both male and female) in LSGH had higher daily re-entry exposure values than re-entry workers in other farming systems. The ratio of estimated daily $P_{(90)}$ and $P_{(10)}$ values showed 6- and 7-fold differences for male and female re-entry workers (Table 4). Differences between age groups were not apparent.

Correlation analyses of the three re-entry metrics (cumulative, annual, and daily) showed moderate to strong correlations among male and female re-entry workers ($r$ = 0.41–0.99 and $r$ = 0.69–0.99, respectively). Duration of employment as a re-entry worker showed a moderate correlation ($r = 0.51$) with cumulative exposure among female workers, while it showed a stronger correlation (0.75) in male re-entry workers (Table 5).

## DISCUSSION

In this study, we developed two semi-quantitative exposure algorithms to estimate cumulative exposure to pesticides for applicators and re-entry workers in different farming systems in Ethiopia. Applying these algorithms in an extensive survey enabled detailed characterization of (cumulative, annual, and daily) pesticide exposure in contemporary farming systems in Ethiopia showing considerable differences between farming systems and to a lesser extent between gender and age categories for both applicators and re-entry workers.

The most likely explanation for the relatively high exposure for applicators in LSGH is due to factors modifying the intensity of pesticide exposure (e.g. type of application method and indoor versus outdoor application). Conversely, use of PPE and hygienic behavior were better in LSGH than other farming systems (Negatu *et al.*, 2016), and the average duration of employment (years) was somewhat lower (3.3) in LSGH than on average in the two other farming systems (4.5) (data not shown).

Similarly, the higher estimated values of AAE and DAE in LSGH are due to the higher estimated intensity-related pesticide exposure variables (e.g. application methods and indoor spraying) than other

**Table 4. Cumulative exposure, annual exposure, and daily exposure estimates for re-entry workers (female and male) by farming system and by age group**

| | N (%) | GM | GSD | $P_{(10)}$ | $P_{(50)}$ | $P_{(90)}$ | N (%) | GM | GSD | $P_{(10)}$ | $P_{(50)}$ | $P_{(90)}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Cumulative exposure in female re-entry workers | | | | | | Cumulative exposure in male re-entry workers | | | | | |
| **Total** | 275 (100) | 12 576 | 3.17 | 2475 | 13 200 | 56 640 | 70 (100) | 12 269 | 2.68 | 3560 | 12 724 | 385 335 |
| **Farms** | | | | | | | | | | | | |
| LSO | 72 (26) | 13 703 | 2.81 | 4030 | 12 126 | 42 480 | 36 (51) | 12 427 | 2.89 | 3717 | 13 452 | 39 825 |
| SSI | 87 (32) | 4147 | 2.18 | 1320 | 4620 | 11 880 | — | — | — | — | — | — |
| LSGH | 116 (42) | 27 332 | 2.38 | 10 890 | 27 534 | 75 625 | 34 (49) | 12 103 | 2.36 | 3403 | 12 385 | 36 000 |
| **Age** | | | | | | | | | | | | |
| 16–23 | 95 (35) | 13 681 | 3.21 | 1650 | 7080 | 34 031 | 13 (18) | 7113 | 2.71 | 2655 | 8496 | 14 160 |
| 24–26 | 81 (30) | 12 825 | 3.19 | 2887 | 14 160 | 49 500 | 20 (29) | 8914 | 2.70 | 2344 | 10 620 | 36 625 |
| 27–30 | 42 (15) | 19 211 | 2.28 | 9075 | 17 696 | 43 000 | 16 (23) | 19 235 | 2.68 | 9075 | 17 696 | 43 000 |
| 31–57 | 57 (20) | 21 858 | 3.22 | 5625 | 18 150 | 39 570 | 21 (30) | 16 545 | 2.70 | 5625 | 18 150 | 39 570 |
| | Annual exposure in female re-entry workers | | | | | | Annual exposure in male re-entry workers | | | | | |
| **Total** | 275 (100) | 3856 | 2.53 | 1320 | 4425 | 12 100 | 70 (100) | 2573 | 2.21 | 1327 | 2269 | 6000 |
| **Farms** | | | | | | | | | | | | |
| LSO | 72 (26) | 4232 | 2.08 | 1343 | 4425 | 7080 | 36 (51) | 2014 | 2.03 | 1099 | 2124 | 4580 |
| SSI | 87 (32) | 1283 | 1.25 | 825 | 1320 | 1650 | — | — | — | — | — | — |
| LSGH | 116 (42) | 8308 | 2.05 | 3630 | 9900 | 17 600 | 34 (49) | 3335 | 2.05 | 1980 | 3424 | 7500 |

**Table 4.** ***Continued***

| | *N* (%) | GM | GSD | $P_{(10)}$ | $P_{(50)}$ | $P_{(90)}$ | *N* (%) | GM | GSD | $P_{(10)}$ | $P_{(50)}$ | $P_{(90)}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Age** | | | | | | | | | | | | |
| 16–23 | 95 (35) | 3841 | 1.91 | 1327 | 2124 | 3630 | 13 (18) | 2259 | 2.23 | 1327 | 2124 | 3630 |
| 24–26 | 81 (30) | 3908 | 2.53 | 1327 | 2268 | 10 900 | 20 (29) | 3008 | 2.22 | 1327 | 2268 | 10 900 |
| 27–30 | 42 (15) | 4009 | 2.54 | 1512 | 3468 | 6000 | 16 (23) | 2993 | 2.21 | 1512 | 3469 | 6000 |
| 31–57 | 57 (20) | 3700 | 2.58 | 732 | 2124 | 4580 | 21 (30) | 2144 | 2.23 | 732 | 2124 | 4580 |
| | **Daily exposure in female re-entry workers** | | | | | | **Daily exposure in male re-entry workers** | | | | | |
| **Total** | 275 (100) | 17 | 2.27 | 7 | 15 | 48 | 70 (100) | 9 | 2.30 | 4 | 9 | 24 |
| **Farm** | | | | | | | | | | | | |
| LSO | 72 (26) | 14 | 2.08 | 5 | 15 | 24 | 36 (51) | 7 | 2.04 | 4 | 7 | 15 |
| SSI | 87 (32) | 8 | 1.25 | 5 | 8 | 10 | — | — | — | — | — | — |
| LSGH | 116 (42) | 33 | 2.05 | 14 | 39 | 70 | 34 (49) | 13 | 2.05 | 8 | 14 | 16 |
| **Age** | | | | | | | | | | | | |
| 16–23 | 95 (35) | 17 | 2.27 | 6 | 15 | 49 | 13 (18) | 8 | 2.32 | 4 | 7 | 14 |
| 24–26 | 81 (30) | 17 | 2.27 | 5 | 15 | 49 | 20 (29) | 11 | 2.30 | 4 | 9 | 43 |
| 27–30 | 42 (15) | 17 | 2.28 | 7 | 15 | 48 | 16 (23) | 11 | 2.30 | 6 | 12 | 24 |
| 31–57 | 57 (20) | 16 | 2.31 | 8 | 14 | 48 | 21 (30) | 8 | 2.33 | 2 | 7 | 17 |

$P_{(10)}$, $P_{(50)}$, and $P_{(90)}$ are respectively the 10th, 50th, and 90th percentile of the distributions, respectively. GM, geometric mean; GSD, geometric standard deviation.

**Table 5. Pearson correlation coefficient (*r*) between selected pesticide exposure-modifying factors in different exposure groups**

| | Daily exposure | Annual exposure | Cumulative exposure | Working years |
|---|---|---|---|---|
| **Correlation between exposure variables in applicators** | | | | |
| Daily exposure | 1.00 | | | |
| Annual exposure | 0.75 | 1.00 | | |
| Cumulative exposure | 0.71 | 0.86 | 1.00 | |
| Working years | −0.03 | −0.25 | 0.01 | 1.00 |
| **Correlation between exposure variables in male re-entry workers** | | | | |
| Daily exposure | 1.00 | | | |
| Annual exposure | 0.99 | 1.00 | | |
| Cumulative exposure | 0.41 | 0.46 | 1.00 | |
| Working years | −0.02 | 0.03 | 0.75 | 1.00 |
| **Correlation between exposure variables in female re-entry workers** | | | | |
| Daily exposure | 1.00 | | | |
| Annual exposure | 0.99 | 1.00 | | |
| Cumulative exposure | 0.69 | 0.70 | 1.00 | |
| Working years | −0.08 | −0.07 | 0.51 | 1.00 |

variables that affect pesticide exposure, e.g. personal protection measures.

Despite shorter duration of employment and better PPE utilization and hygienic behavior (Negatu *et al.*, 2016), female re-entry workers in LSGH had higher average cumulative exposure, annual exposure, and daily exposure estimates than female re-entry workers in the other farming systems. This is due to the higher average re-entry exposure intensity score in female re-entry workers in LSGH than female re-entry workers in the other farming systems [i.e. LSGH (71.03), SSIF (10.00), LSOF (24.75)] (data not shown).

The most appropriate justification for the higher values of cumulative exposure in male re-entry workers in LSOF than LSGH was longer employment duration (i.e. 9.05 in LSOF compared to 4.07 in LSGH) and slightly higher frequency of re-entry workdays per year (i.e. 295 in LSOF and 250 in LSGH). Higher daily and annual exposure estimates for male re-entry workers in LSGH than in LSOF was due to the higher re-entry intensity scores in LSGH rather than due to other exposure-modifying factors, e.g. personal protective measures.

The higher CRE of female versus male re-entry workers is due to female re-entry work (e.g. harvesting and packing) having higher estimated exposure than the usual male re-entry tasks (e.g. transportation and maintenance). Duration of employment (which is slightly shorter in female than male re-entry workers (4.1 versus 6.6 years)], PPE utilization and hygienic behavior will not have been driving the differences in cumulative exposures. Likewise, higher values of annual and daily exposure in female re-entry workers are mainly due to higher values of exposure intensity scores for female versus male re-entry tasks.

The reason for no correlation between cumulative exposure and duration of employment for applicators was due to those applicators with relatively higher cumulative exposure (i.e. most of LSGH, $n$ = 59) had been working as an applicator for relatively few years (3.29), while the applicators with relatively low CAE (i.e. most of SSIF, $n = 171$) had been working more years as an applicator (4.89). Moderate correlations ($r = 0.43$–0.67) between CAE and years of working as an applicator were seen when the analyses were done within each of the three farming systems (data not shown).

Our semi-quantitative pesticide exposure assessment algorithm for applicators was adapted from the AHS's pesticide exposure algorithm. It was modified, and new variables were included in order to make it fit with Ethiopian agriculture practices and pesticide exposure settings. For example, the algorithms we develop can be applied to a range of farming systems (i.e. LSGH, SSIF, and LSOF) rather than just LSOF which are common in the USA where the AHS algorithm was developed. Also in order to enable detailed assessment of exposure modifiers for applicators, we allowed the use of more than one application method by taking into account frequency of use of a particular application method. Additional variables accounting for variation in occupational pesticide exposure due to open/closeness of a farm and farming system-specific amounts of pesticide application per day by an applicator were incorporated.

The method allows for different exposure intensity estimates (i.e. daily, annual, and cumulative) which can be used in epidemiological studies focusing on chronic health effects (i.e. CAE, CRE and/or AAE, ARE) and on studies focusing on acute health effects (i.e. DAE, DRE).

Our method can be used with relative ease since it does not require input from a highly trained pesticide exposure assessment expert, it is inexpensive and can be easily adapted and used to estimate occupational pesticide exposure in low- and medium-income countries. Exposure to specific pesticides can also be estimated when information on application of specific pesticides (active ingredients) is available from spraying calendars and purchase records. This was however not possible in our study due to poor record keeping in surveyed farms.

The exposure assessment method that we developed needs further validation via objective measurements of applicators' and re-entry workers' exposure measurements. Based on such measurements, additional determinants may be identified and default weighting factors could be adjusted as to optimize the exposure algorithms. However, based on previous work on validating the AHS algorithm and detailed observations in Ethiopian farming systems, we believe that the exposure algorithms can be applied in settings of sub-Saharan Africa including Ethiopia where resources (financial, survey equipment, and required expertise) to undertake large-scale objective measurements of pesticide exposure (biological or environmental monitoring) are very limited.

## SUPPLEMENTARY DATA

Supplementary data can be found at http://annhyg.oxfordjournals.org/.

## DECLARATION

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