Estimation of norovirus and *Ascaris* infection risks to urban farmers in developing countries using wastewater for crop irrigation

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ABSTRACT

A quantitative microbial risk analysis—Monte Carlo method was used to estimate norovirus and *Ascaris* infection risks to urban farmers in developing countries watering their crops with wastewater. For a tolerable additional disease burden of $\le 10^{-4}$ DALY loss per person per year (pppy), equivalent to 1 percent of the diarrhoeal disease burden in developing countries, a norovirus reduction of 1–2 log units and an *Ascaris* egg reduction to 10–100 eggs per litre are required. These are easily achieved by minimal wastewater treatment—for example, a sequential batch-fed three tank/pond system. Hygiene improvement through education and regular deworming are essential complementary inputs to protect the health of urban farmers.

Key words | agriculture, *Ascaris*, norovirus, quantitative microbial risk analysis, reuse, urban, wastewater

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URBAN AGRICULTURE

Urban agriculture is an important part of the urban economy and makes an important contribution to urban food security, especially in developing countries. Smit *et al.* (1996) estimated that one-third of all urban households, totalling ~ 800 million people, are involved in one way or another in urban agriculture which produces one-third of all food consumed in urban areas from one-third of all urban land. Some developing-country figures for the production of urban agriculture are, as percentages of urban consumption (unless otherwise stated) (RUAF Foundation 2009):

- Accra, Ghana: 90% of fresh vegetables;
- Dakar, Senegal: 60% of national vegetable consumption and 65% of national urban poultry production, and 60% of milk consumed in the city;
- Hanoi, Vietnam: 80% of fresh vegetables, 50% of pork, poultry and freshwater fish, and 40% of eggs; and
- Shanghai, China: 60% of fresh vegetables, 100% of milk, 90% of eggs, and 50% of pork and poultry meat.

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In many countries urban farmers use wastewater to water their crops commonly because freshwater is unavailable or too expensive (Redwood 2004). This usage of wastewater will only increase with increasing water scarcity and as urban populations grow–the urban population in developing countries is projected to be over 5 billion in 2050, up from ~2 billion in 2000 (UN DESA 2008). The current global financial and food-price crises are affecting the nutritional status of the urban poor, especially pregnant women and children, very adversely (UNSCN 2009). Urban agriculture can do much to provide the urban poor with affordable high-quality fresh fruit and vegetables.

DISEASE EXPOSURE OF URBAN FARMERS

Infection with human nematode worms, particularly the large human roundworm *Ascaris lumbricoides* and the two human hookworms *Ancylostoma duodenale* and *Necator americanus*, is very common in developing countries: de Silva *et al.* (2003) reported that 1,240 million people were infected with *Ascaris*, with a further 4,210 million at risk of *Ascaris* infection; the corresponding figures for hookworm disease were 740 million and 3,200 million. One group particularly at risk are farm labourers working in raw-wastewater-irrigated fields–for example, Krishnamoorthi *et al.* (1973) found that in India they had excess prevalences of ascariasis (47 vs. 13% in a control group) and hookworm disease (69 vs. 31%), and that they also had an excess intensity of infection as evidenced by higher egg counts per g faeces (69 vs. 33% for ascariasis; 62 vs. 35% for hookworm disease) (see also Shuval *et al.* 1986). More recent work in Mexico, reviewed by Blumenthal & Peasey (2002), showed that both adults and children under 15 were protected against *Ascaris* infection if the wastewater had been treated to achieve an *Ascaris* reduction of 2–3 log units (Figure 1).

Diarrhoeal disease is slightly more common in farm workers and their children than in control groups, and partial treatment (2–3-log unit reduction of faecal coliforms) has only a small protective effect (Blumenthal & Peasey 2002). In Mexico norovirus ('Norwalk-like virus Mexico') infections, measured by percentage seroresponse, were three-times more common in farm workers: 33 vs. 11% in a control group (Blumenthal, unpublished, reviewed in Blumenthal & Peasey 2002).

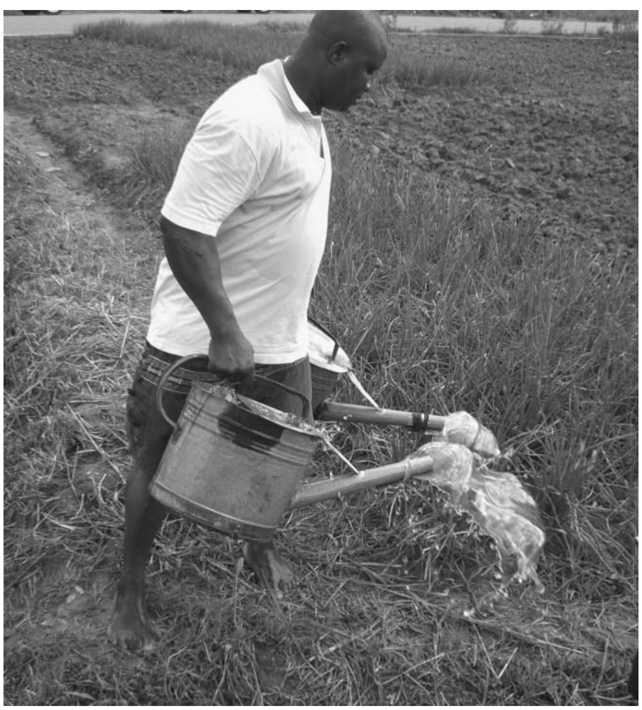

Figure 1 | An urban farmer in Accra, Ghana, applying wastewater to his crops—note that he is barefoot.

TOLERABLE ADDITIONAL BURDEN OF DISEASE

The WHO guidelines on the safe use of wastewater in agriculture use a default value of $\leq 10^{-6}$ DALY (disability-adjusted life year) loss per person per year (pppy) for the tolerable additional burden of disease due to wastewater pathogens (WHO 2006). This value is also used in the current edition of the WHO guidelines on drinking-water quality (WHO 2004). However, in *Levels of Protection*, part of the rolling revision of its drinking-water guidelines, WHO (2007) states that $\leq 10^{-5}$ or $\leq 10^{-4}$ DALY loss pppy may "be more realistic, yet still consistent with the goal of providing high-quality, safer water and encouraging incremental improvement of water quality." Following the principles of the Stockholm Framework (Fewtrell & Bartram 2001), this should also be applied to wastewater use in agriculture.

How realistic is a level of protection of $\leq 10^{-4}$ DALY loss pppy? This is now considered for diarrhoeal diseases and ascariasis.

Diarrhoeal diseases

In 2001 in low- and middle-income countries diarrhoeal diseases caused a burden of disease of 59 million DALYs (Lopez *et al.* 2006). Thus, for a total population in these countries of 5,615 millions, the DALY loss due to diarrheal diseases was:

$$\frac{59 \text{ million DALYs lost per year}}{5,615 \text{ million people}} = \sim 10^{-2} \text{ pppy}$$

This DALY loss is two orders of magnitude greater than a tolerable additional burden of disease of 10^{-4} pppy–i.e. this additional burden of disease of 10^{-4} DALY loss pppy is only 1% of the 'background' burden of diarrhoeal diseases in developing countries of $\sim 10^{-2}$ DALY loss pppy. If this additional DALY loss were accepted, then the total burden of diarrheal diseases would be the sum of this background burden of diarrheal disease and this additional burden of diarrheal disease, as follows:

$$10^{-2}\,\text{DALY loss pppy} + 10^{-4}\,\text{DALY loss pppy}$$

i.e. a DALY loss of 0.0101 pppy, which is epidemiologically indistinguishable from a DALY loss of 0.01 pppy.

Ascariasis

The annual burden of ascariasis is ~10 million DALYs (de Silva *et al.* 2003). Thus, for an exposed population of 5,450 millions, the potential DALY loss is [10 million ÷ 5,450 million]–i.e. 1.8×10^{-3} pppy. Accepting a tolerable additional burden of ascariasis from wastewater use in agriculture of 10^{-4} DALY loss pppy means that the burden of ascariasis would increase from 0.0018 to 0.0019 DALY loss pppy, which is not epidemiologically significant.

QUANTITATIVE MICROBIAL RISK ANALYSES

The quantitative microbial risk analysis–Monte Carlo (QMRA-MC) methodology used to estimate norovirus (NV) and *Ascaris* infection risks as a result of working in wastewater-irrigated fields was based on the work of Haas *et al.* (1999), Mara *et al.* (2007) and Karavarsamis & Hamilton (2010). The Karavarsamis and Hamilton method for calculating the annual risk of infection firstly determines an annual risk of infection by doing a Monte Carlo simulation with the number of iterations set equal to the number of days of exposure per year, and it then repeats this any specified number of times (usually for a total of 1,000 or 10,000 times) and determines the resulting median annual infection risk.

The first step was to determine the tolerable NV and *Ascaris* disease and infection risks corresponding to a tolerable DALY loss of 10^{-4} pppy. For NV, using a DALY loss of 9×10^{-4} per case of NV disease (Kemmeren *et al.* 2006) and an NV disease/infection ratio of 0.8 (Moe 2009), these are:

$$\text{Tolerable NV disease risk} = \frac{\text{Tolerable DALY loss pppy}}{\text{DALY loss per case of NV disease}} = \frac{10^{-4}}{9\times10^{-4}} = 0.11\,\text{pppy}$$

$$\text{Tolerable NV infection risk} = \frac{\text{Tolerable NV disease risk pppy}}{\text{NV disease/infection ratio}} = \frac{0.11}{0.8} = 0.14\,\text{pppy}$$

For *Ascaris*, using a DALY loss per case of ascariasis of 8.25×10^{-3} (Chan 1997) and assuming, as a worst-case scenario, a disease/infection ratio of 1 (i.e. all those infected with *Ascaris* develop ascariasis), the tolerable infection risk is given by:

$$\frac{\text{Tolerable DALY loss pppy}}{\text{DALY loss per case of ascariasis}} = \frac{10^{-4}}{8.25\times10^{-3}} = 1.2\times10^{-2}\,\text{pppy}$$

Annual infection risks were obtained from the equation:

$$P_{I(A)}(d) = 1 - [1 - P_I(d)]^n$$

where $P_{I(A)}(d)$ is the annual risk of infection in an individual resulting from n exposures per year to the same pathogen dose d and $P_I(d)$ is the risk of infection in an individual resulting from a single exposure to this pathogen dose d.

For *Ascaris* the β-Poisson equation was used to estimate $P_I(d)$:

$$P_I(d) = 1 - \left(1 + \frac{d}{N_{50}}(2^{1/\alpha} - 1)\right)^{\alpha}$$

where N_{50} is the median infective dose and α is an 'infectivity constant'–$N_{50} = 859$ and $\alpha = 0.104$ for *Ascaris* (Navarro *et al.* 2009). For NV the dose–response dataset of Teunis *et al.* (2008) was used in place of the β-Poisson equation.

For the exposure scenario of involuntary soil ingestion (WHO 2006; Mara *et al.* 2007) a series of 10,000 risk simulations was run using a QMRA-MC computer program based on the Karavarsamis & Hamilton (2010) method for calculating annual risk (the program is available at www.personal.leeds.ac.uk/~ cen6ddm/QMRA.html) and an involuntary soil ingestion of 1–10 mg per urban farmer per day. (In the 2006 WHO Guidelines health risks for restricted irrigation were estimated by assuming the fieldworkers involuntarily ingested wastewater-contaminated soil. Two situations were assessed: ingestions of 10–100 mg of soil per day for 300 days per year and 1–10 mg of soil per day for 100 days per year to represent labor-intensive agriculture in developing countries and highly mechanized agriculture more typical of industrialized countries, respectively. Neither of these exposure scenarios may be typical of urban agriculture in developing countries, although the former may be closer. However, with hygiene education and the provision of gloves and on-site hand-washing facilities, the quantity of soil ingested can be substantially reduced to, for example, ~ 1–10 mg per day.) The resulting estimates of median infection risks obtained, and the assumptions on which they are based, are given in Tables 1 and 2 for NV and *Ascaris*, respectively.

For norovirus, Table 1 shows that an NV reduction of 1 log unit results in an NV infection risk of 0.32 pppy (i.e. one episode of NV diarrhoea every three years), which is higher than the tolerable risk of 0.14 pppy determined above (one episode of NV diarrhoea every seven) years, but acceptable if combined with hygiene education and the provision of (a) hand-washing facilities on or adjacent to the site being irrigated, and (b) oral rehydration salts/solutions when required (WHO 2005*a*; rehydrate.org). For *Ascaris*, Table 2 shows that a reduction to 10–100 eggs/L results in an ascariasis risk of 1.5×10^{-2} pppy, which is close to the tolerable risk of 1.2×10^{-2} pppy determined above. A reduction to 10 eggs/L, which could be used as a guideline value (as recommended by Ayres *et al.* 1992; Ensink & van der Hoek 2009 recommended ≤15 eggs/L), results in a risk of $\sim 3 \times 10^{-3}$ pppy. Even so, the farmers should be dewormed regularly (e.g., twice per year) (see WHO 2005*b*; Hotez *et al.* 2007).

Table 1 | Median norovirus infection risks from the involuntary ingestion of 1–10 mg of wastewater-saturated soil per day for 300 days per year estimated by 10,000 Karavarsamis-Hamilton Monte Carlo simulations*

Noroviruses per 100 g soil	Median norovirus infection risk pppy
100–1,000	0.98
10–100	0.32
1–10	3.8×10^{-2}

*Assumptions: soil quality per 100 g taken, as a worst-case scenario, as the wastewater quality per 100 ml; no norovirus die-off.

Table 2 | Median *Ascaris* infection risks from the involuntary ingestion of 1–10 mg of wastewater-saturated soil per day for 300 days per year estimated by 10,000 Karavarsamis-Hamilton Monte Carlo simulations†

Ascaris eggs per kg soil	Median *Ascaris* infection risk pppy
100–1,000	0.14
10–100	1.5×10^{-2}
10	2.7×10^{-3}
1–10	1.4×10^{-3}

†Assumptions: soil quality (eggs/kg) taken, as a worst-case scenario, as the wastewater quality (eggs/L); $N_{50} = 859 \pm 25\%$ and $\alpha = 0.104 \pm 25\%$; no *Ascaris* die-off.

The wastewater treatment required to achieve these pathogen reductions has to be simple, inexpensive, yet robust. Probably the most suitable, and almost foolproof, system is the three-tank or three-pond system operated as a sequential batch-fed process: on any one day one tank or pond is filled with wastewater, the contents of another are settling, and the contents of the third are used for irrigation.

If hygiene education, gloves and hand-washing facilities are not provided, it would be prudent to have a 2-log unit reduction of norovirus and *Ascaris* by wastewater treatment, as soil ingestion would likely be higher (~ 10–100 mg per day).

CONCLUSIONS

1. For a maximum tolerable additional burden of disease of 10^{-4} DALY loss per urban farmer per year risk analyses show that norovirus and *Ascaris* reductions of 1 log unit are required.
2. These log reductions can be obtained by simple but robust methods of wastewater treatment. Urban farmers should receive hygiene education and be provided with gloves and on-site hand-washing facilities, together with the availability on demand of oral rehydration salts/solutions and regular deworming.

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