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**The Impact of Architecture and Natural Ventilation on the
Risk of Tuberculosis Transmission in Brazilian Prisons**

A Thesis Submitted to the
Yale University School of Public Health
in Partial Fulfillment of the Requirements for the
Degree of Master of Public Health

by
Juliana Urrego
2014

ABSTRACT

Background

Tuberculosis (TB) incidence in Brazilian penitentiaries is extremely high as prisons provide ideal conditions for airborne contagion by congregating infectious and susceptible individuals for extended periods of time. We aimed to determine the effects of architectural, environmental, and ventilation factors that impact TB transmission probabilities across prison cells in three penitentiaries of Mato Grosso do Sul, Brazil.

Methods

We collected descriptive data on cell architectural characteristics and estimated ventilation rates using steady-state exhaled carbon dioxide levels. A hierarchical linear, multivariable model was used to examine cell level architectural and environmental factors affecting absolute ventilation. We then estimated the probability of TB infection for inmates sharing a cell with an infectious case, using a modified Wells-Riley equation for airborne infection. We projected the impact of improving ventilation to international standards for infection control settings and reducing the time to TB diagnosis by 25%.

Results

The three prisons contained 141 prison cells with a range of occupancy from 2 – 30 inmates per cell ($p < 0.001$). In multivariable analysis, absolute ventilation was positively associated with floor area, ceiling height, opening area, opening area to floor area ratio, opening to volume ratio, and area of courtyard space, and negatively associated with number of cells per courtyard. The projected median risk of TB infection for a person sharing a cell with an infectious case for four months ranged from 53.3% – 69.6% between the three prisons ($p < 0.001$). Improving ventilation to a minimum of 12 air changes per hour or decreasing time-to-diagnosis decreased transmission by 8.3% and 9.1%, respectively. In contrast, improving per person ventilation rates to World

Health Organization recommended levels for health-care settings decreased TB transmission probability by 36.1% and 60.3%.

Conclusions

Environmental conditions of Brazilian prisons are highly conducive to the spread of TB.

Improving ventilation in prisons may decrease TB transmission risk and, combined with other strategies, may enhance TB control efforts.

Keywords: architecture; natural ventilation; tuberculosis; transmission; Brazil;

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude and respect to my thesis advisor, Dr. Albert Ko, for his indispensable guidance and providing me with an excellent atmosphere for doing research through the master thesis. His unsurpassed knowledge of infectious disease epidemiology in Brazil has continually inspired me throughout this process.

I would like to thank my preceptor, Dr. Julio Croda, who let me experience tuberculosis research in the field while affording me the unique opportunity to visit the incredibly beautiful state of Mato Grosso do Sul. He persuasively conveyed a spirit of adventure in regard to public health research that has influenced me in a number of ways.

Special thanks goes to Dr. Jason Andrews for his patience in guiding this project for the past several months and helping me to strengthen my knowledge of tuberculosis research and analyses. Without his involvement and constant help, this project would not have been possible. In addition, I would like to thank Dr. Catherine Yeckel, whose good advice, encouragement, and support have been invaluable on both an academic and a personal level.

I also want to thank the 2013 Jan A.J. Stolwijk committee at the Yale School of Public Health for their generous financial support.

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LIST OF ABBREVIATIONS

ACH	Air changes per hour
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
EPC	Estabelecimento Penal de Corumbá
MS	Mato Grosso do Sul, Brazil
PPM	Parts per million
PTL	Penitenciária de Três Lagoas
TB	Tuberculosis
UPRB	Unidade Penal Ricardo Brandão
WHO	World Health Organization

INTRODUCTION

Global tuberculosis (TB) control in prisons is facing major challenges. Over 10 million people are detained in penal institutions, worldwide, on any given day.[1] TB prevalence among inmates has been described as an alarming public health problem in many countries,[2-4] where reported rates among these marginalized populations are consistently 10 to 50 times higher than those observed in the general population – with the highest rates occurring in Russia, Afghanistan, Kazakhstan, Azerbaijan and Brazil.[5-8] As global prison populations continue to rapidly grow, TB epidemics are becoming concentrated in prison settings that amplify the transmission of infectious diseases.[9, 10] The dynamic nature of penitentiary systems, with inmates coming and going into, out of and between prisons, poses a critical threat to broader population-level TB control.

Currently, Brazil has the fourth highest number of inmates in the world with over 540,000 inmates in 1,478 prisons.[9] One of the largest prison population growths within Brazil is occurring in the Midwest state of Mato Grosso do Sul (MS) with a reported prison population of 11,298 in 2012.[11] In Mato Grosso do Sul, the incidence of active TB is over 30 times higher in the prison population, 1,278 – 2,941 cases per 100,000 individuals, than in the general population, 36 per 100,000 individuals (unpublished data). Consequently, the public health importance of mitigating TB in disease-ridden reservoirs is increasingly important as infectious disease control is failing in several communities where prisons are thought to be a major factor in sustaining TB epidemics.[10]

TB research in prison systems has historically focused on objectives of describing incidence, prevalence and risk factors for infection or disease using conventional epidemiological methods.[8, 12] Severe overcrowding, prolonged confinement, drug and alcohol

use, poor nutrition, and limited healthcare resources have long been identified in promoting the transmission of *Mycobacterium tuberculosis* within prison populations. [3, 4, 8] These environmental and host risk factors facilitate transmission of TB and progression of infections to active disease.[2, 13] Several studies have shown that ventilation is effective in the removal of infective droplet nuclei, reducing the risk of infection for individuals.[14] Although ventilation has been investigated in a number of healthcare settings[15-17] its role in the transmission of TB and other airborne diseases has not been examined in prisons.

There is a lack of specific environmental data related to the interaction between architecture and natural ventilation within prisons, and the levels of natural ventilation sufficient to lower TB transmission. To address this knowledge gap, our objective was to estimate ventilation rates in three penitentiary facilities in the Brazilian state of Mato Grosso do Sul. The intent was to examine the impact of architectural conditions on natural ventilation as well the effect of ventilation patterns, compared to international standards for healthcare and congregate settings, on estimates of tuberculosis transmission among incarcerated populations.

METHODS

Setting

Ventilation and other environmental characteristics were measured in 141 naturally ventilated prison cells in three medium-security prisons of Mato Grosso do Sul, Brazil. The three prisons are located near international or domestic borders where drug-trafficking crimes are prevalent. Estabelecimento Penal de Corumbá (EPC), located near the Brazil-Bolivia border, has an approximate occupant capacity of 208 inmates in 35 cells. Penitenciária de Três Lagoas (PTL) has an approximate occupancy of 255 inmates in 97 cells and is located near the state border with São Paulo. Unidade Penal Ricardo Brandão (UPRB), located near the border with Paraguay, has an approximately occupancy of 155 inmates in 26 cells. Across all three prisons, inmates are predominantly incarcerated in communal cells of 2 to 30 persons and confined for extended periods of time each day. With 1,217 combined inmates, overcrowding in all three prisons is persistently high. The reported state average occupancy rate was 175.4% in 2012.[11]

Architectural & Environmental Measurements

We recorded the following architectural and environmental characteristics for each cell: occupancy; length of confinement; floor area; ceiling height; amount of beds; bed layout; building materials; wall thickness; area of open windows and doors; window and door type; presence of cross-ventilation design; temperature; relative humidity; presence of openings facing prevailing winds; indoor ventilation obstructions; and portable fans. Research assistants entered each cell and collected measurements while inmates were in the adjacent courtyard spaces. The following characteristics were collected for each prison: number of cells per courtyard space; area of courtyard; outdoor temperature; and wind speed.

Ventilation Measurements

Room ventilation can be assessed by monitoring the diffusion of gases; carbon dioxide (CO₂) is frequently used because of its safety and ease of measurement.[18, 19] Typically, ventilation is estimated through the tracer gas concentration decay technique, wherein a room is cleared of occupants and a cartridge containing a high concentration of CO₂ is released. However, when a room cannot be cleared of its occupants, exhaled CO₂ can be used as a natural tracer gas to assess ventilation.[19] For security reasons, the latter approach was used. CO₂ concentration after at least 14 hours of closed cell occupancy were obtained using a portable continuous carbon dioxide sampling device (Extech Instruments, Waltham, Massachusetts).

The time required to reach steady-state CO₂ in a room depends on the outdoor air change rate, calculated as the room ventilation rate (Q) divided by room volume (V), where higher air change rates correspond to less time required to approach steady-state conditions.[19] It is reasonable to assume that CO₂ concentrations for prison cells have reached steady-state conditions after at least 14 hours across a wide range of ventilation rates. Beeswarm plots of CO₂ and CO₂ per cell occupants are presented for each prison. We compared CO₂ concentrations between prisons using a Kruskal-Wallis one-way analysis of variance (ANOVA).

Analytic Approach

The absolute ventilation (liters per second) rate (Q) for each cell was calculated based upon the equilibrium between ventilation and carbon dioxide production through respiration,[19] according to the following equation:

$$Q = \frac{10^6 \times G}{(C_{in,eq} - C_{out})}$$

The carbon dioxide generation rate in the space (G) for number of cell occupants is a function of the average carbon dioxide generation rate per person at rest, 0.0052 L/s, and the

number of occupants.[19] Here, equilibrium CO₂ concentration in the cell ($C_{in,eq}$) and outdoor CO₂ concentration (C_{out}) are expressed in parts per million (ppm).

Statistical Analysis

A one-way random effects ANOVA was used to determine the extent to which cells within the same prison were similar to each other in terms of absolute ventilation. We used univariable regression to assess the association between environmental characteristics of cells and absolute ventilation estimates. Continuous independent variables included: floor area; ceiling height; area of open windows and doors; opening to floor area ratio; opening to volume ratio; portable fans; interior walls; interior obstructions; area of courtyard space; and cells per courtyard. One categorical variable was examined: presence of openings in the direction of prevailing winds. Significant variables at $p < 0.2$ were then included in a full multivariable hierarchical linear model to examine the association between absolute ventilation and environmental characteristics at the prison level. Backward elimination was used to remove variables not significant at $p < 0.05$ until a parsimonious, reduced model was achieved. For all hierarchical models, absolute ventilation was normalized by log10-transformation. Data were analyzed using SAS 9.4 (Cary, NC).

Spatial Distribution of Ventilation

Although air changes per hour (ACH) has classically been used as a metric for assessing infection control risks, per person ventilation rates are a better measure of risk of airborne infection.[20] Currently, the World Health Organization (WHO) guidelines recommend a minimum of 60 liters per second per person for the prevention of airborne infections in naturally ventilated health-care settings.[20] Per person ventilation rates were calculated for each cell by dividing the absolute room ventilation by room occupants; beeswarm plots of per person

ventilation are presented for each prison. We compared per person ventilation rates between prisons using a Kruskal-Wallis one-way ANOVA. In order to identify macro- and microenvironments of ventilation within the prisons, quintile values of ventilation rates were calculated and overlaid on architectural floor plans.

Transmission Modeling

Transmission probabilities were estimated using a non-steady-state version of the Wells-Riley equation, which has been used to describe airborne transmission probabilities within a space with defined ventilation characteristics.[2, 15, 21, 22] The probability of infection (P) is given by the following equation:

$$P = 1 - e^{-I p q t / Q}$$

Rudnick and Milton revised the classic Wells-Riley equation to allow the estimation of the probably of infection in a confined space when total exposure occurs in a single time period in the following manner:

$$P = 1 - \exp \left[-\frac{I q p t}{Q \theta} \left\{ 1 - \frac{V}{Q \theta} \left[1 - \exp \left(-\frac{Q \theta}{V} \right) \right] \right\} \right]$$

As given by the above equation, the probability of infection is a function of the number of infectious individuals in a room (I), breathing rate per person (p), quantum generation rate by an infected person (q), total exposure time (t), volume of the confined space (V), time elapsed from when the room becomes occupied (θ), and germ-free ventilation rate (Q). We estimated the probability of TB infection as a function of time (t) in the presence of one infectious individual in general population cells of the three prisons.

Model Parameters

Germ-free ventilation rate (Q) was estimated as the absolute ventilation for each prison cell as described above. The existing literature provides several estimates for the infectious

quanta rate (q). In their classic experiments, Wells et al. estimated q to be 1.25 quanta per hour for smear-positive individuals.[23] Half a century later, Escombe et al. estimated q to be 8.2 quanta per hour;[24] both sets of estimates were for individuals with clinically recognized TB who were receiving treatment. We used the more conservative estimate of 1.25 quanta per hour for our model and adjusted for the proportion of smear-positive individuals reported among these prisons (3.46%). We estimated the relative infectiousness of smear-negative individuals at 0.2.[25] We performed one-way sensitivity analysis for the estimates of quantum generation rate by an infected person (q).

The mean respiratory rate of adults (p) was estimated to be 360 liters per hour corresponding to a normal adult respiratory minute volume of 6 liters per minute. We assumed there was one infectious individual (I) regardless of the number of inmates per cell. Since the total exposure (t) occurred in a single time period, during extended lock-up time, $t = \theta$.[22] The period of infectiousness is critical for projecting the probability of transmission and the impact of early diagnosis. This period is variable among different study populations; by comparing cross-sectional prevalence with TB notifications of Mato Grosso do Sul (unpublished data), we estimated this duration to be on average 120 days.

Interventions

We then explored the effects of improved ventilation and improved case finding to achieve significant reductions in transmission probabilities, using the mean transmission probability across all three prisons as the base case. In order to determine the effects of improvements to case finding, passive case finding was modeled as a 25% reduction in time-to-diagnosis. We examined the impact of improving ventilation of each cell to WHO-recommended minimums of ACH or per person ventilation rates for TB control in health-care settings. For

naturally ventilated buildings, the WHO also recommends ventilation flow rates through spaces with two opposite openings. Cross-ventilation is considered to be more effective than single-sided ventilation design for airborne infection control.[20] Wind-driven natural ventilation rate through a cross-ventilated room is given by the following equation:

$$ACH = \frac{0.65 \times \text{wind speed} \left(\frac{m}{s}\right) \times \text{smallest opening area} (m^2) \times 3600 \frac{s}{h}}{\text{room volume} (m^3)}$$

For each prison cell we estimated cross-ventilated ACH assuming existing architectural (e.g. room volume and area of smallest opening) and environmental conditions (e.g. wind speed).

We modeled the mean probability of infection if all cells had at least 12 ACH (minimum ventilation for airborne infection isolation rooms);[26] 60 liters per second per person (minimal ventilation for naturally ventilated rooms); and cross-ventilation design conditions (optimal ventilation for naturally ventilated rooms).[20]

RESULTS

Architecture, Environment, and Ventilation

Architectural characteristics, occupancy and ventilation estimates for the three prisons are shown in Table 1. EPC, PTL and UPRB had total inmate populations of 426, 505 and 286, respectively. The mean cell occupancy for each prison was 13.2, 5.8 and 11.7 while mean number of beds per cell was 6.4, 2.9 and 5.7 ($p < 0.001$). Inmates in PTL had an average of 20.0 hours of lock-down time whereas inmates in EPC and PTL had 16.8 and 14.7 hours, respectively. Mean floor area, 13.0 – 13.3 m², was comparable across all three prisons. However, number of cells per courtyard and courtyard floor area significantly differed ($p < 0.001$). EPC and UPRB had 3.8 and 4.6 cells per courtyard with 55.0 m² and 54.0 m² of courtyard space, respectively, while PTL had 19.4 cells per courtyard with a mean courtyard area of 316.3 m². Across all prisons, ceiling height, area of openings, portable fans, and daily recreation time were significantly different (all $p < 0.001$).

Mean carbon dioxide concentrations across the three prisons was 749.8 ppm (95% CI: 713.5, 786.1) (Figure 1). EPC, PTL, and UPRB had mean steady-state CO₂ of 989.3 ppm (95% CI: 915.8, 1062.9), 652.4 ppm (95% CI: 618.1, 686.6), and 775.6 ppm (95% CI: 708.6, 842.7), respectively ($p < 0.001$). 18.4% of all cells had CO₂ concentrations greater than the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASRHAE) – recommended limit of 1,000 ppm. 65.3% of all cells with CO₂ concentrations greater than 1,000 ppm were cells in EPC. Carbon dioxide concentrations per number of cell occupants varied significantly across all prisons, ($p < 0.001$) (Figure 2).

Mean per person ventilation across the three prisons was 19.4 l/s/person (95% CI: 17.3, 21.5) (Figure 3). EPC, PTL and UPRB had mean per person ventilation rates of 9.5 l/s/person

(95% CI: 8.3 – 10.8), 23.9 l/s/person (95% CI: 21.1, 26.7), and 16.4 l/s/person (95% CI: 11.9, 20.8), respectively ($p < 0.001$). 49.6% of all cells had less than 12 ACH and 97.9% had less than 60 l/s/person. With existing architectural features, the mean absolute ventilation ranged from 119.1 L/s – 202.3 L/s ($p = 0.008$). There was no significant difference in mean ACH across the three prisons.

The overlay of per person ventilation on EPC's architectural floor plan illustrates the homogeneity in ventilation between courtyards, ($p < 0.001$) (Figure 4). All prison cells in EPC had ventilation rates less than 16.5 L/s/person. Spatial distribution of per person ventilation for general populations cells of PTL shows variability in per person ventilation rates within and across courtyards (Figure 5). 96.2% of all prison cells in UPRB had ventilation rates less than 27.4 L/s/person as evidence in the architectural floor plan with overlaid per person ventilation rates (Figure 6).

Determinants of Absolute Ventilation

In multivariable hierarchical linear analysis, absolute ventilation was positively associated with floor area, ceiling height, opening area, opening to floor area ratio, opening to volume ratio, and area of courtyard space, (all $p < 0.03$) (Table 2). In contrast, decreased number of cells per courtyard was associated with increased absolute ventilation ($p < 0.02$). These findings were consistent in another hierarchical linear model that accounted for both prison and cellblock levels characteristics (Table 3).

Estimated Risk of Tuberculosis Transmission

The mean estimated risks of TB transmission after exposure for 120 days to an infectious cellmate under the existing conditions were 66.0% (95% CI: 0.22, 1.10) for EPC, 69.7% (95% CI: 0.19, 1.21) for PTL, and 53.3% (95% CI: 0.10, 0.97) for UPRB, ($p < 0.001$) (Figure 7).

The effect of improved case finding, calculated as a 25% decrease in time-to-diagnosis, was estimated for existing transmission risk conditions and for one scenario of improved ventilation (Figure 8A). The benefits of improving case finding to achieve a decrease of 30 days result in 9.1% and 9.4% reductions to transmission probabilities for existing and improved ventilation scenarios, respectively. When cells were modeled as having minimum ventilation rates of 12 ACH as recommended for mechanically ventilated airborne infection isolation rooms, mean transmission probability slightly improved from 66.1% to 57.8% (8.3% reduction).

Significant improvements in TB transmission were observed when ventilation was modeled using the WHO standards for control of infectious agents in naturally ventilated healthcare settings (Figure 8B). The effects of improving ventilation to 60 L/s/person and providing cross-ventilation conditions result in 36.1% and 60.3% decreases in transmission risk, respectively.

Sensitivity Analysis

We estimated the mean probability of infection attributable to known estimates of the infectious quanta rate (q) and examined its sensitivity to the duration of infectiousness (Figure 9). The Escombe et al. estimate of 8.2 quanta per hour yielded a 98.9% probability of infection over 120 days of exposure to an infectious case. A significantly lower probability of infection, 66.1%, was observed using the Wells-Riley estimate of 1.25 quanta per hour.

DISCUSSION

In 2013, TB notification rate in the prisons of Mato Grosso do Sul were 1,109.3 per 100,000 (unpublished data). We found severe overcrowding, which combined with the architectural and environmental conditions typical of Brazilian prisons may explain the high rates of TB notifications among prisons. We believe that the present study is the first to perform architectural and environmental measurements and to assess the impact of ventilation for TB transmission in high prevalence TB prison settings. Consistent with other studies that have looked at the influence of architectural conditions on natural ventilation,[15, 27, 28] we found specific design conditions, such as larger opening areas and more generous opening to floor area ratio, are associated with higher rates of ventilation and could potentially serve to ameliorate risk of airborne transmission. Despite the presence of some favorable conditions, prisons in Mato Grosso do Sul have overall low ventilation rates, contributing to high estimated risk of TB transmission.

A recent study conducted in a South African prison found that reducing severe overcrowding, improving ventilation, and implementing active case finding incurred significant benefits for the ongoing transmission of TB.[2] Although ventilation was not directly measured, current estimated transmission risk was 90% after 120 days of exposure. Improvements to ventilation resulted in 25% reductions to annual risk of TB infection. The present study had lower mean transmission risks given the variability in ventilation rates. However, our results yield higher benefits associated with improving ventilation. More data is needed to inform context specific environmental recommendations for TB control.

The present study provides important new descriptive information to help understand the architecture, environment, ventilation, and TB transmission risk in prison settings of Brazil. Area

of open windows and doors, presence of cross ventilation design, floor area, and ceiling height has been shown to impact ventilation.[15] Similarly, present multivariate analyses demonstrate that spacious floor areas, high ceilings and generous opening area were associated with higher absolute ventilation in prison cells, albeit insufficient to achieve recommended values set by the WHO. Though these findings may be intuitive, the models also suggest the important association of decreased number of cells per courtyard and larger floor area of courtyards with improved absolute ventilation, which are unique to prison settings. Therefore, these factors should be considered in the design, construction or renovation of prison structures.

The WHO has established guidelines for minimal ventilation rates in health care settings to reduce the risk of airborne infections. Because of the extremely high rates of TB observed in these Brazilian prisons, we sought to evaluate the impact of applying these standards to correctional facilities. In this context, improving ventilation to the WHO recommended threshold of 12 ACH does not confer a large benefit, in part because this guideline was created for mechanically ventilated airborne infection isolation rooms (AIIR).[26] Despite the lack of applicability of the WHO's ≥ 12 ACH recommendation, the literature has interpreted this guideline as the optimal ventilation rate for TB control in congregate settings.[2, 27] In contrast, standards for natural ventilation are far more appropriate for quantifying reduction in TB transmission in prison settings.

We found that transmission risk greatly improved when ventilation was increased to meet the WHO recommended natural ventilation rate of 60 L/s/person. Natural ventilation is highly variable[15, 28] and consequently it is difficult to design structures with desired airflow patterns to achieve optimal per person ventilation rates. The significance of cellblock level factors, cells per courtyard and courtyard floor area, in determining absolute ventilation can aid in identifying

microenvironments within prisons where ventilation is insufficient.. However, achieving seemingly unrealistically high ventilation rates in single-sided ventilated cells poses a unique set of challenges in overcrowded spaces. In order to address difficulties associated with naturally ventilated spaces, the WHO has quantified absolute ventilation under optimal cross-ventilation design conditions while taking into account the architectural and environmental specifications inherent to each space.[20]

By estimating the impact of cross-ventilation, we found that the transmission risk would significantly decrease to a low level of 5.79%. Retrofitting existing structures to improve ventilation or designing new prisons with correct ventilation conditions is likely to have a major impact on TB transmission. However, high ventilation rates does not ensure that indoor air will mix uniformly[29] and thus further analysis is needed to assess the conditions created under a cross-ventilation design. Improvements to simple natural ventilation systems are typically low-cost and consequently incur large benefits by decreasing the number of airborne infections in resource-limited settings.[20, 29] But security considerations must be taken into account when designing prison cells with more openings that could serve as entry or exit points.

Previous studies in low-resource prison settings have been limited by the availability or access to environmental data. Our study strength is the inclusion of context specific information to each prison: architectural design and elements pertaining to the built environment of individual cells and communal spaces as well as existing carbon dioxide-estimates of ventilation in each cell. The use of carbon dioxide as a natural tracer gas after at least 14 hours of overnight confinement ensured that ventilation rates calculated for each cell, reflected well-mixed and near-equilibrium conditions. Only one measure of CO₂ was recorded per cell; therefore, we cannot assess variability that would be expected in naturally ventilated settings (e.g., as a result

of wind speed variability). Nevertheless, ventilation rates were low across all three prisons and across multiple days of measurements.

The use of model-based analyses has several limitations. We used a conservative estimate for the quantum generation rate parameter despite varying estimates and individual variability of infective quanta production. The analysis was also based on the assumption that there was equal infectivity and contact risks within each cell. Therefore estimated transmission risk was restricted to events occurring within cells for time of confinement, and events such as close contact with highly infectious individuals outside the cell (e.g. transmission events occurring in the courtyard or when prison staff or outside visitors enter the cells or courtyard spaces) are not captured. Inmates frequently move to different cells within the same or different courtyards in a way that fundamentally alters transmission dynamics.[10] We could not capture the extensive contact networks that are created from constant movements of inmates in Brazilian prisons.

The increasing importance of TB transmission occurring in prisons calls for informed infection control strategies. Prevalence of TB in the prisons of Mato Grosso do Sul, Brazil, and the world, is exceptionally high, illustrating the need for innovative control strategies to minimize TB transmission. These neglected populations are subject to substandard living conditions that pose a direct hazard to inmates and contribute to the TB burden experienced in the general population.[3, 7, 13] Strategies adopted in prison settings continue to be essentially medical and educational with recent literature pointing to an interest in early TB diagnostic interventions.[30] However, the effectiveness of these measures is limited if they are not associated with interventions aimed at improving environmental conditions as our findings suggest that over 50% of cellmates would be infected within a few months. Our findings suggest that combining early diagnostic strategies with improve ventilation will have synergistic benefits.

In summary, improved ventilation through informed architectural design and the use of quantitative measurements in context specific settings could be used to develop and implement environmental control settings suitable for resource-constrained prisons. Environmental interventions are needed in order to change the existing conditions of prisons in Mato Grosso do Sul and the world as TB continues to threaten our communities.

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APPENDIX I: TABLES

Table 1. Description of the sample, by prison (N=141 cells)^a

Cell Characteristic ^b	EPC (n=32)	PTL (n=85)	UPRB (n=24)	p-value ^c
Occupancy	13.2 ± 5.9	5.8 ± 2.7	11.7 ± 6.0	<0.001
Beds	6.4 ± 4.1	2.9 ± 1.5	5.7 ± 1.7	<0.001
Absolute ventilation (L/s)	119.1 ± 54.0	128.7 ± 74.4	202.3 ± 217.5	0.008
Air changes per hour (ACH)	12.6 ± 4.6	15.0 ± 12.5	21.8 ± 26.7	0.066
Steady-state CO ₂ (ppm)	989.3 ± 204.1	652.4 ± 159.0	775.6 ± 158.9	<0.001
Temperature (°C)	27.6 ± 1.0	22.2 ± 1.5	21.1 ± 0.3	<0.001
Relative humidity (%)	77.7 ± 5.4	72.7 ± 4.8	84.8 ± 2.9	<0.001
Floor area (m ²)	13.1 ± 6.9	13.3 ± 4.7	13.0 ± 3.6	0.959
Ceiling height (m)	2.9 ± 0.2	3.2 ± 0.2	2.9 ± 0.2	<0.001
Opening area (m ²)	4.3 ± 0.8	2.8 ± 0.3	5.1 ± 3.9	<0.001
Openings facing prevailing winds	14 (43.8)	40 (50.0)	8 (33.3)	0.346
Interior concrete walls	2.5 ± 1.1	2.3 ± 1.0	2.0 ± 0.5	0.144
Interior obstructions	7.2 ± 4.5	7.0 ± 3.7	5.9 ± 2.3	0.371
Portable fans	7.5 ± 8.0	2.6 ± 1.5	5.7 ± 2.8	<0.001
Cells per courtyard	3.8 ± 1.4	19.4 ± 6.1	4.6 ± 1.7	<0.001
Courtyard area (m ²)	55.0 ± 17.1	316.3 ± 94.7	54.0 ± 15.9	<0.001
Recreational time (hrs)	7.2 ± 4.5	4.0 ± 2.4	9.3 ± 1.0	<0.001

^a 1,047 inmates in 141 cells.

^b Table values are mean ± SD for continuous variables and n (column %) for categorical variables.

^c P-value is for t-test (continuous variables) or χ^2 test (categorical variables).

Table 2. One-level^a hierarchical linear model of factors associated with absolute ventilation (L/s) (\log_{10})

Characteristic	Full Model		Reduced Model	
	Coefficient (95% CI)	<i>p</i> -value	Coefficient (95% CI)	<i>p</i> -value
Floor area (m ²)	0.051 (0.01, 0.09)	0.009	0.045 (0.01, 0.08)	0.005
Ceiling height (m)	0.892 (0.20, 1.59)	0.012	0.700 (0.08, 1.32)	0.028
Opening area (m ²)	0.083 (0.01, 0.16)	0.032	0.082 (0.01, 0.15)	0.025
Opening area to floor area ratio	12.973 (6.57, 19.37)	<0.001	11.955 (5.80, 18.11)	<0.001
Opening to volume ratio	32.904 (14.95, 50.86)	<0.001	30.491 (13.65, 47.33)	<0.001
Openings facing prevailing winds	0.092 (0.01, 0.18)	0.034		
Interior concrete walls	-0.048 (-0.14, 0.04)	0.304		
Interior obstructions	-0.006 (-0.03, 0.02)	0.574		
Portable fans	0.004 (-0.01, 0.02)	0.642		
Cells per courtyard	-0.023 (-0.04, -0.01)	0.006	-0.016 (-0.03, -0.01)	0.023
Courtyard area (m ²)	0.003 (0.001, 0.004)	<0.001	0.002 (0.001, 0.003)	<0.001

^a Prison level effects.**Table 3.** Two-level^a hierarchical linear model of factors associated with absolute ventilation (L/s) (\log_{10})

Characteristic	Full Model		Reduced Model	
	Coefficient (95% CI)	<i>p</i> -value	Coefficient (95% CI)	<i>p</i> -value
Floor area (m ²)	0.048 (0.01, 0.10)	0.045	0.023 (0.01, 0.03)	0.020
Ceiling height (m)	0.522 (0.39, 1.83)	0.043	0.378 (0.10, 1.36)	0.041
Opening area (m ²)	0.062 (0.03, 0.15)	0.019	0.024 (0.01, 0.14)	0.017
Opening area to floor area ratio	7.424 (3.56, 18.41)	0.009	6.893 (2.43, 16.86)	0.006
Opening to volume ratio	17.785 (12.24, 47.81)	0.004	14.642 (13.79, 39.53)	<0.001
Openings facing prevailing winds	0.109 (0.03, 0.19)	0.010		
Interior concrete walls	-0.018 (-0.14, 0.11)	0.776		
Interior obstructions	-0.020 (-0.04, 0.003)	0.094		
Portable fans	0.006 (-0.02, 0.03)	0.636		
Cells per courtyard	-0.019 (-0.06, 0.02)	0.044	-0.013 (-0.03, -0.02)	0.033
Courtyard area (m ²)	0.001 (-0.001, 0.003)	0.026	0.001 (-0.001, 0.002)	0.004

^a Prison and cellblock level effects.

APPENDIX II: FIGURES

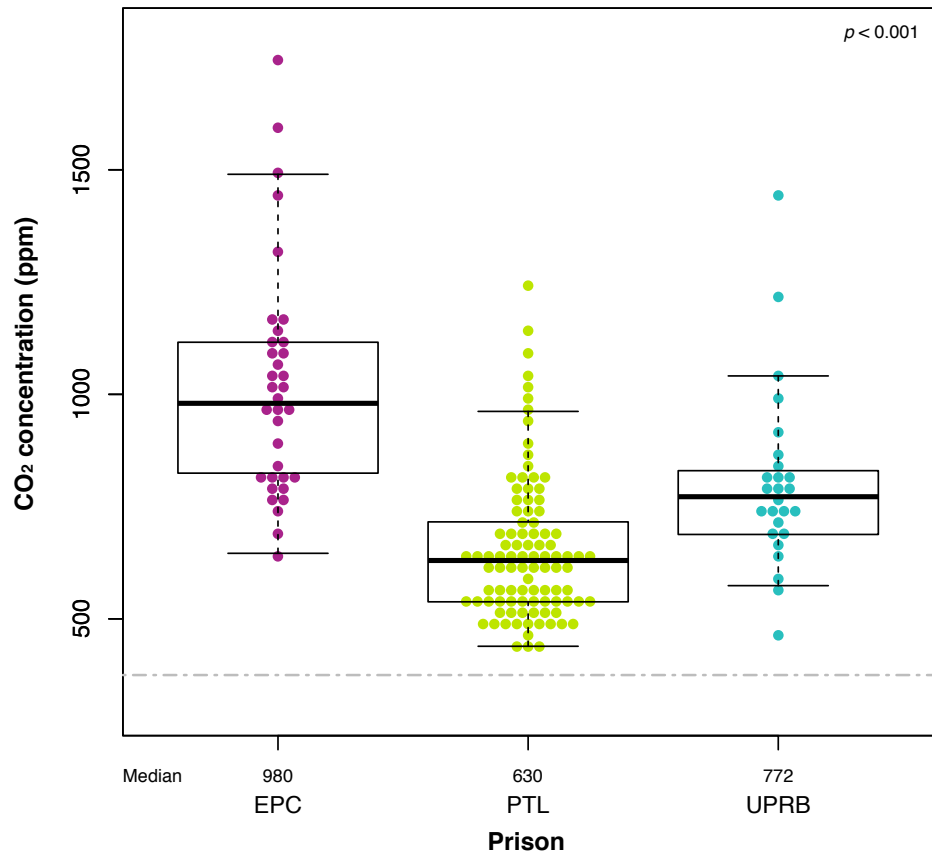


Figure 1. Carbon dioxide (CO₂) concentrations (dots) for individual cells in three prisons of Mato Grosso do Sul, Brazil, 2013. The boxplots show median and quartiles values. The horizontal dashed line indicates the average outdoor carbon dioxide concentration (410 ppm). P-value was calculated using the Kruskal – Wallis ANOVA test.

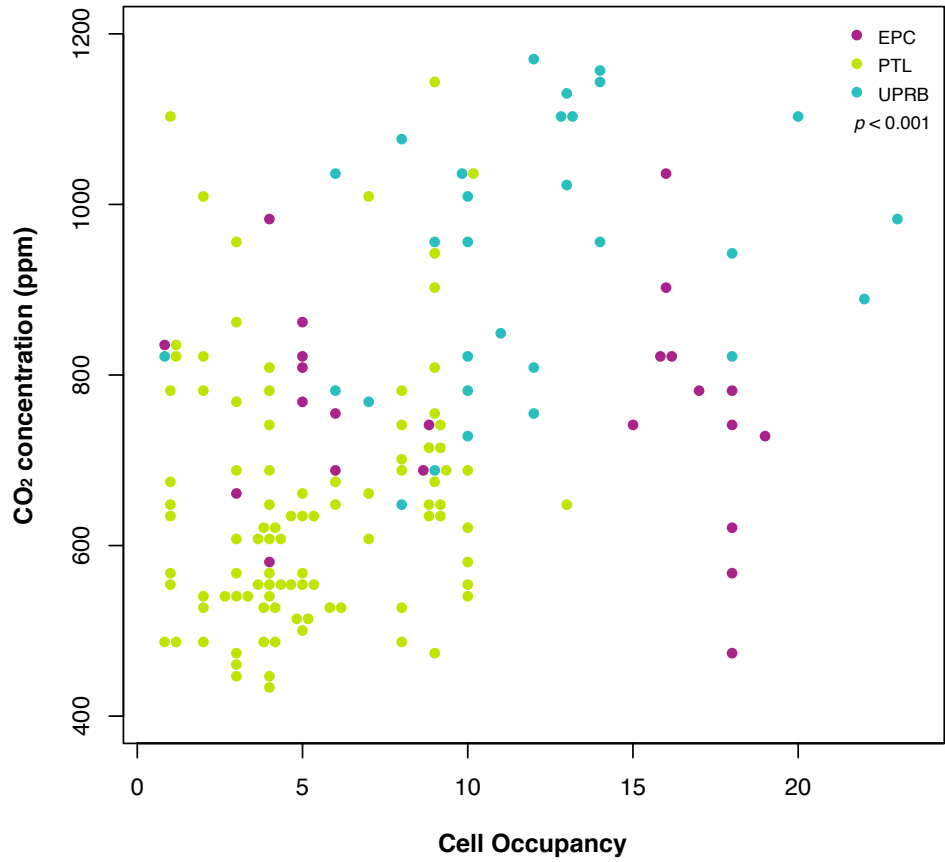


Figure 2. Carbon dioxide (CO₂) concentrations per number of cell occupants (dots) for individual cells in three prisons of Mato Grosso do Sul, Brazil, 2013. P-value was calculated using the Kruskal – Wallis ANOVA test.

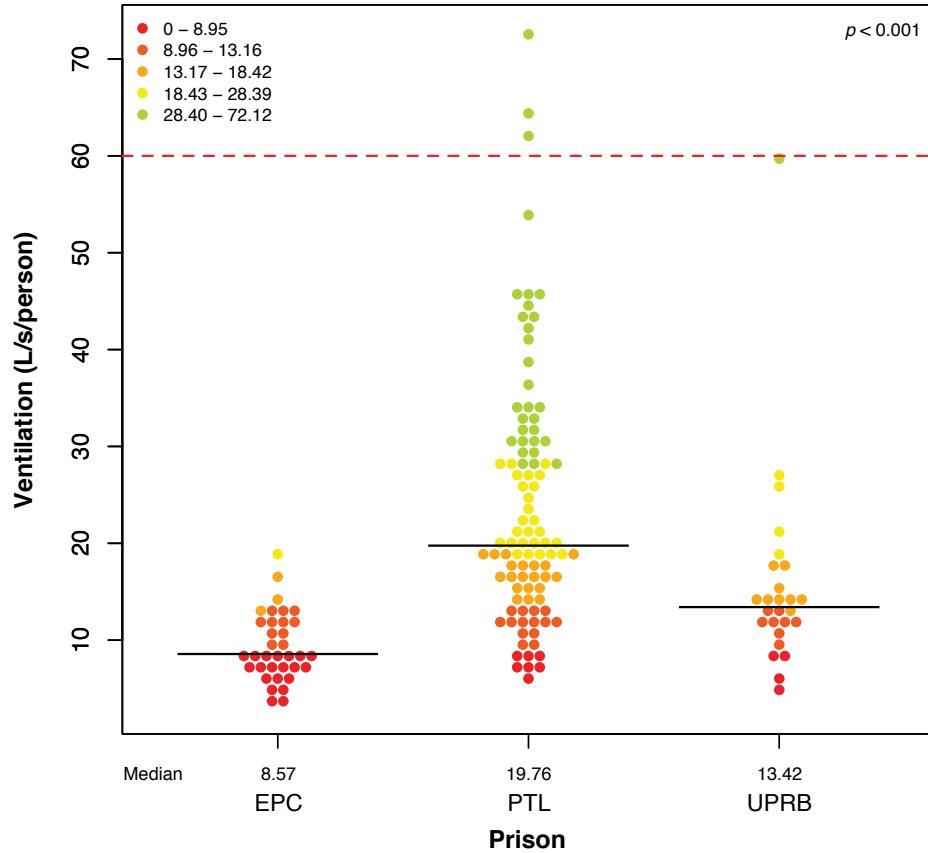


Figure 3. Ventilation (L/s/person) (colored dots) and median values (dark horizontal line) in general population cells of three prisons of Mato Grosso do Sul, Brazil, 2013. The horizontal dashed line indicates the WHO recommended 60 L/s/person for naturally ventilated, general wards. P-value was calculated using the Kruskal – Wallis ANOVA test.

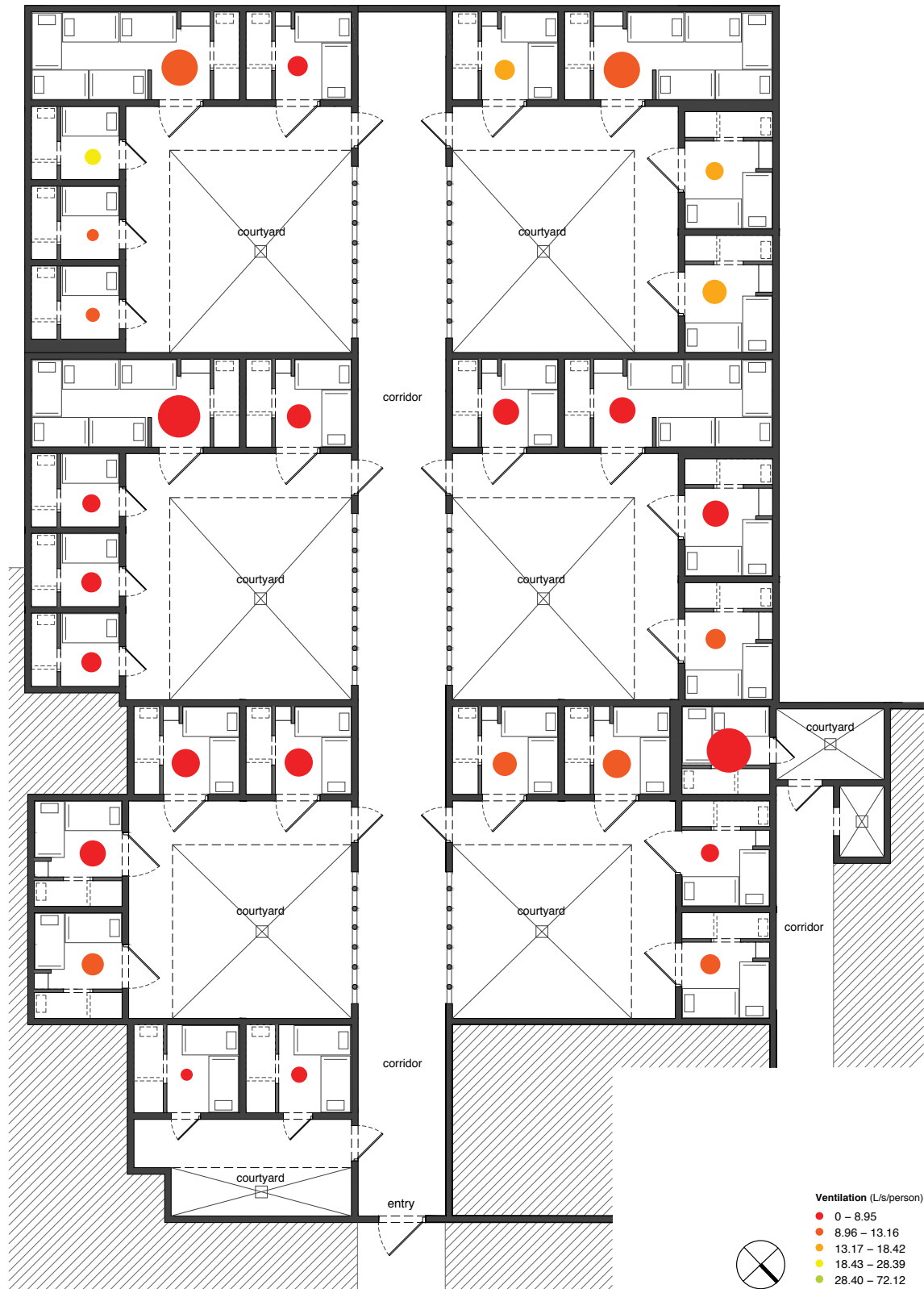


Figure 4. Architectural floor plan of EPC with overlay of per person ventilation (colored dots). Colored dots are proportional to the number of inmates per cell.

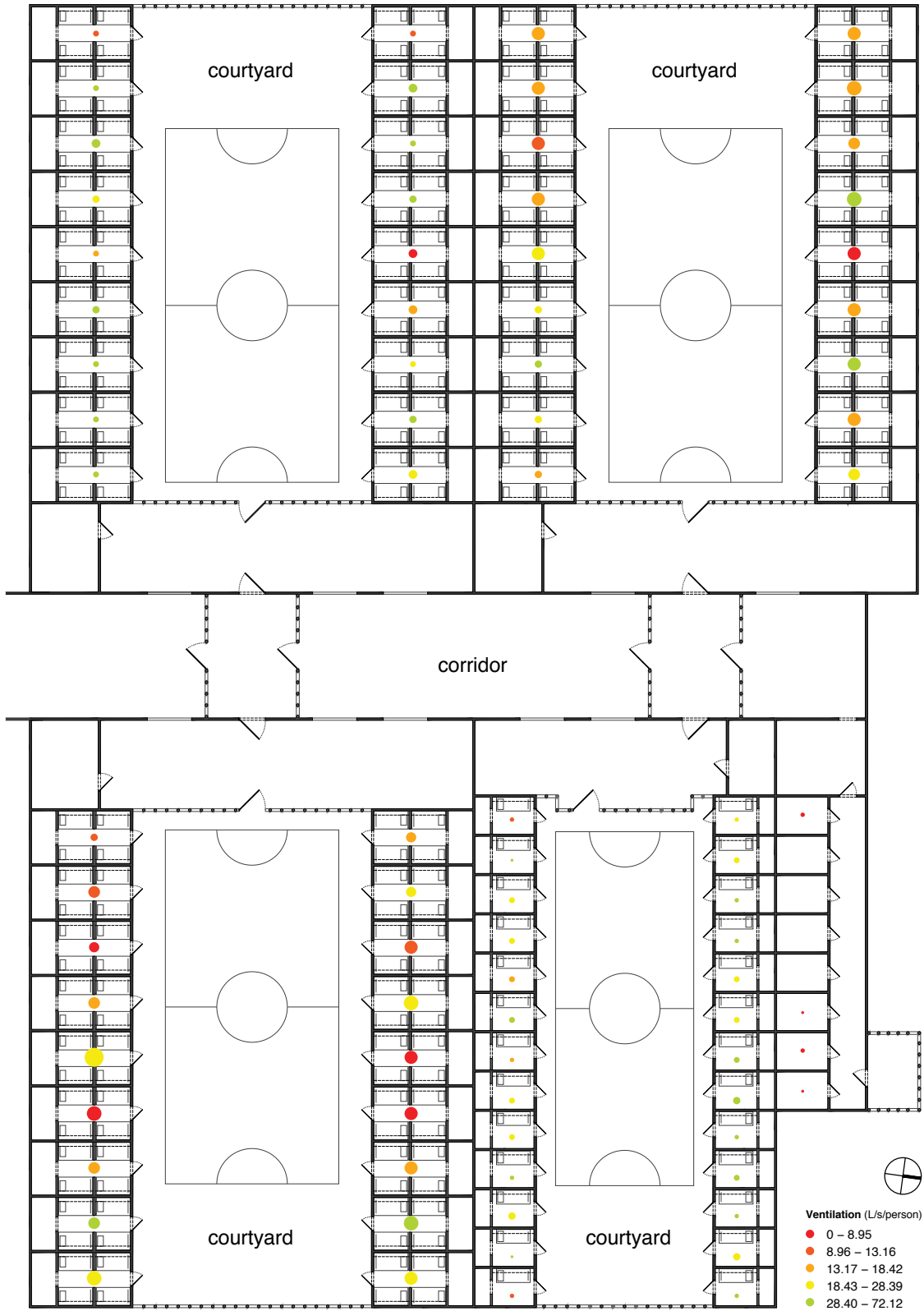
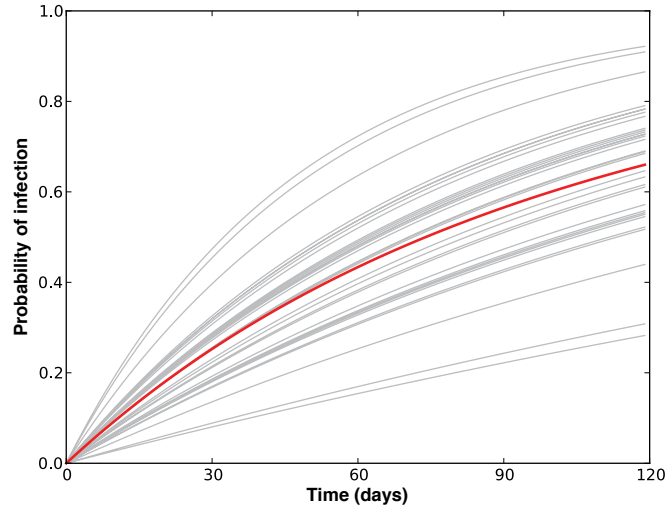


Figure 5. Architectural floor plan of PTL with overlay of per person ventilation (colored dots). Colored dots are proportional to the number of inmates per cell.

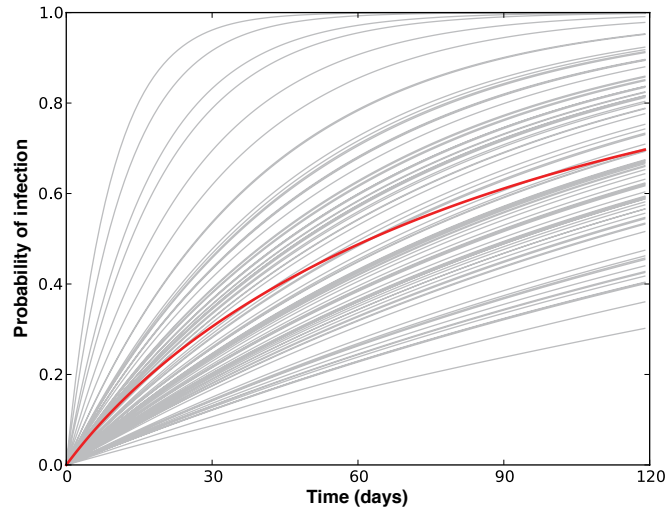


Figure 6. Architectural floor plan of UPRB with overlay of per person ventilation (colored dots). Colored dots are proportional to the number of inmates per cell.

A)



B)



C)

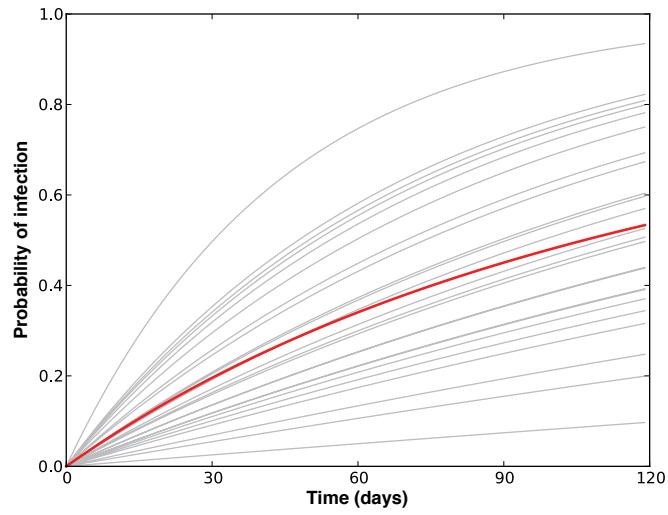


Figure 7. Mean probability of tuberculosis infection by time spent in a prison cell with one infectious case in EPC (A), PTL (B), and UPRB (C), Mato Grosso do Sul, Brazil, 2013.

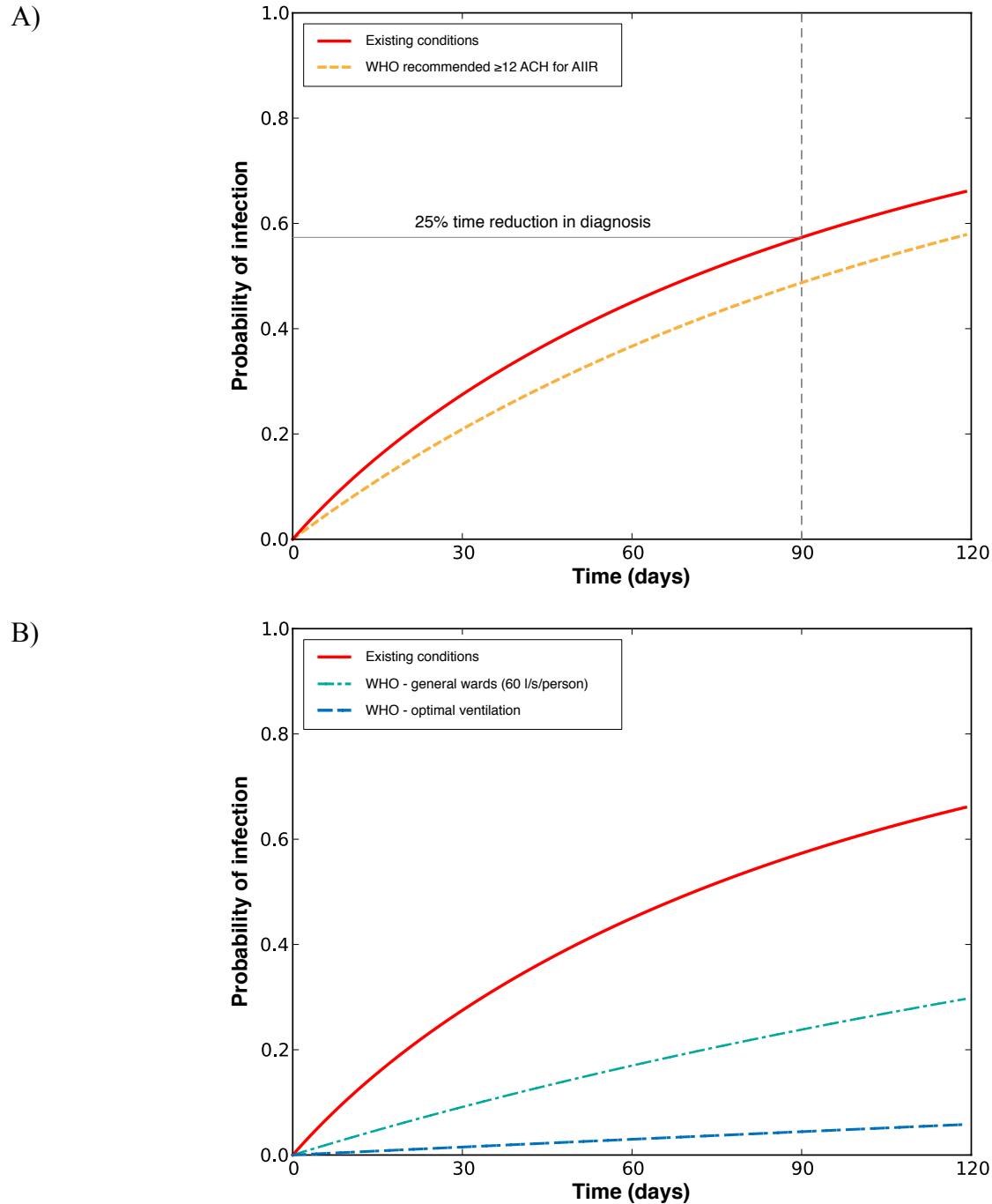


Figure 8. The effects of improving cell ventilation and time to diagnosis on tuberculosis transmission probabilities by time period of infectiousness up to 120 days. Two values of ventilation scenarios are shown (A): the current estimated mean absolute ventilation (m^3/h) and the mean of improving ventilation in all cells to ≥ 12 ACH. The vertical dashed line represents a 25% reduction in time to diagnosis. Three values of ventilation scenarios are shown (B): the current estimated mean absolute ventilation (m^3/h); the mean of improving ventilation rate in all cells to 60 L/s/person; and the mean of improving ventilation rate in all cells to reflect optimal ACH under a cross-ventilation design.

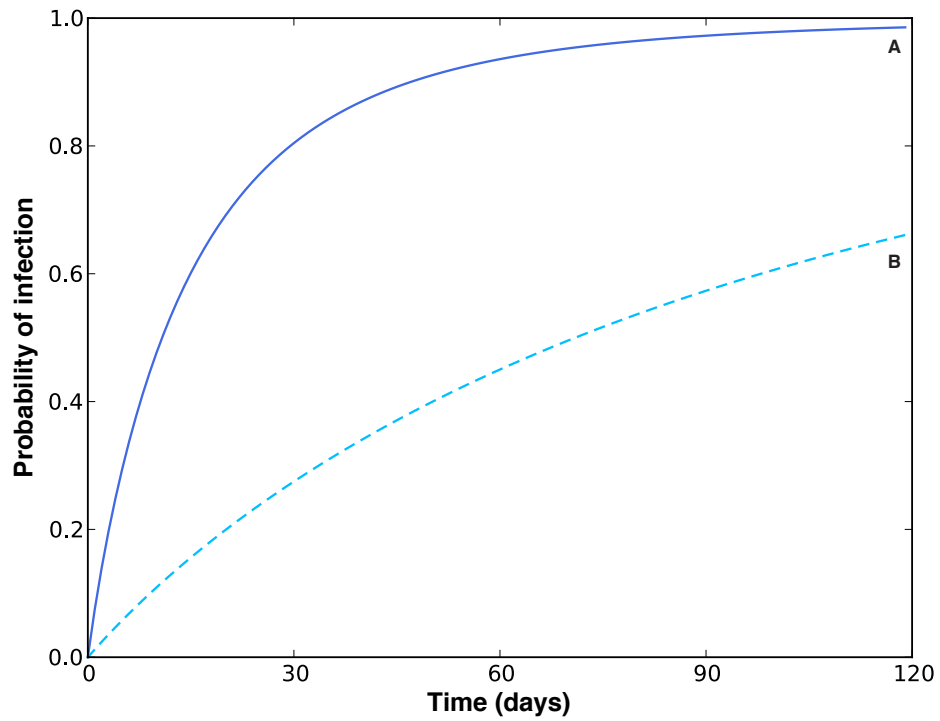
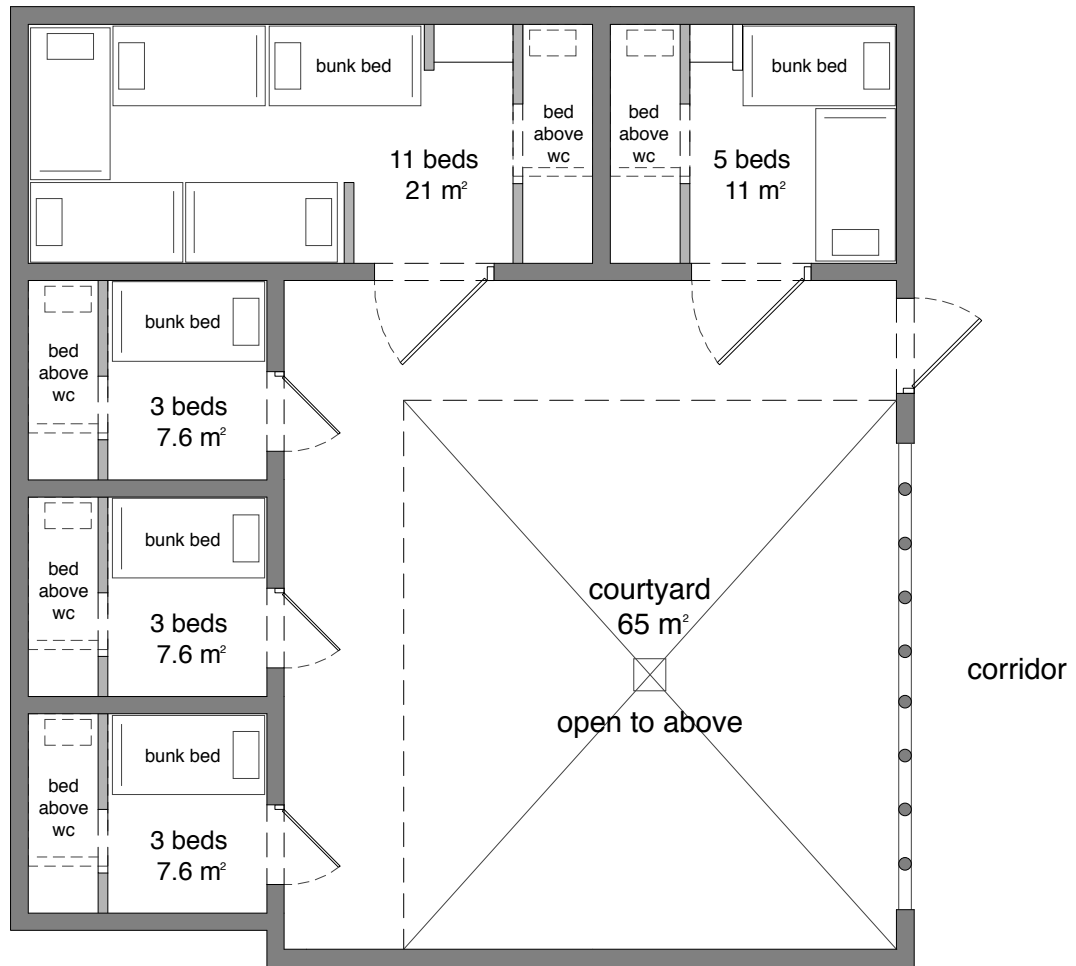


Figure 9. Sensitivity analysis demonstrating how the probability of infection varies as a function of the quanta per hour (q) and length of time in days using the Escombe et al. estimate of q at 8.2 quanta/hour (A) and the Wells-Riley estimate of q at 1.25 quanta/hour (B).

APPENDIX III: SUPPLEMENTAL MATERIAL

Figure S1. Architectural floor plan of a typical courtyard and photographs of EPC	32
Figure S2. Architectural floor plan of a typical courtyard and photographs of PTL	33
Figure S3. Architectural floor plan of a typical courtyard and photographs of UPRB	34

A)

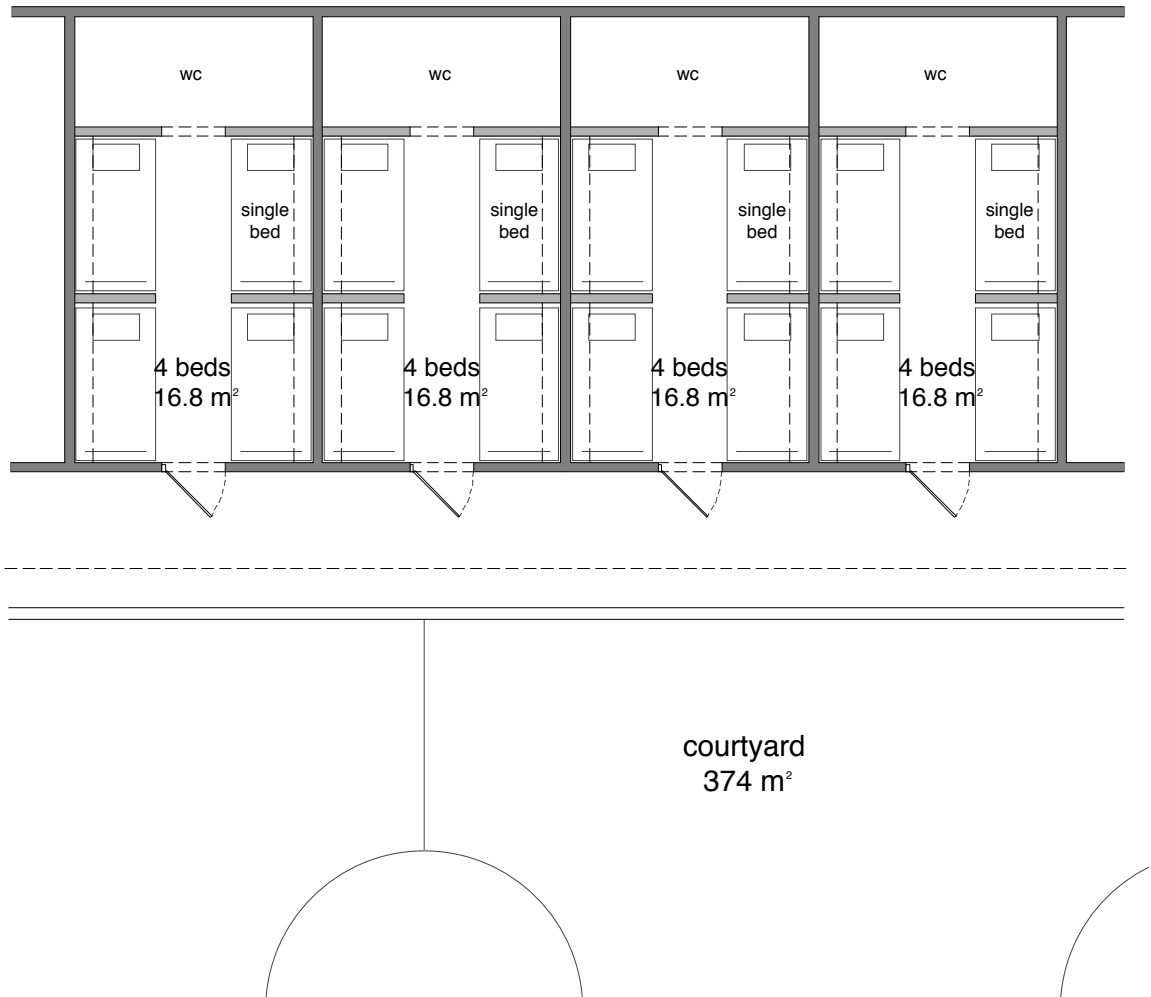


B)



Figure S1. Architectural floor plan of typical general population cell courtyard in EPC (A). Photographs illustrating existing built conditions, 2013 (B).

A)

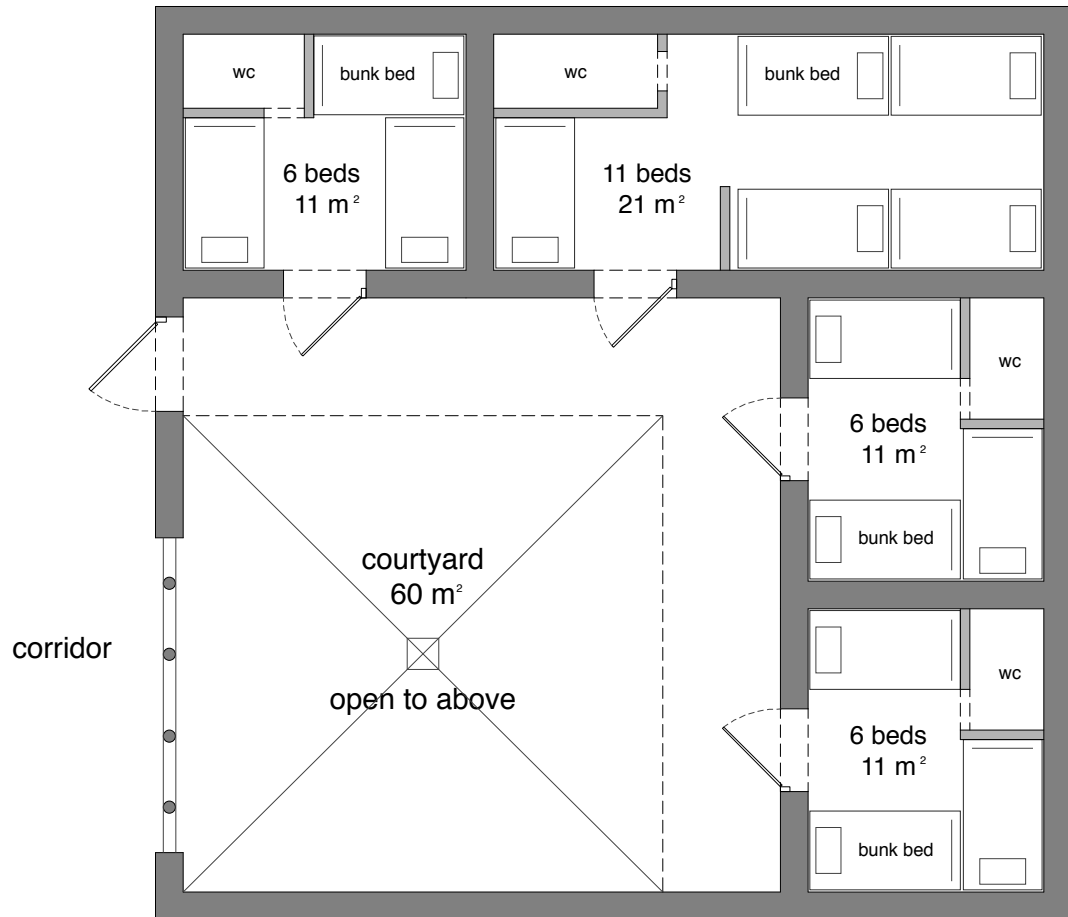


B)



Figure S2. Partial architectural floor plan of typical general population cell courtyard in PTL (A). Photographs illustrating existing built conditions, 2013 (B).

A)



B)

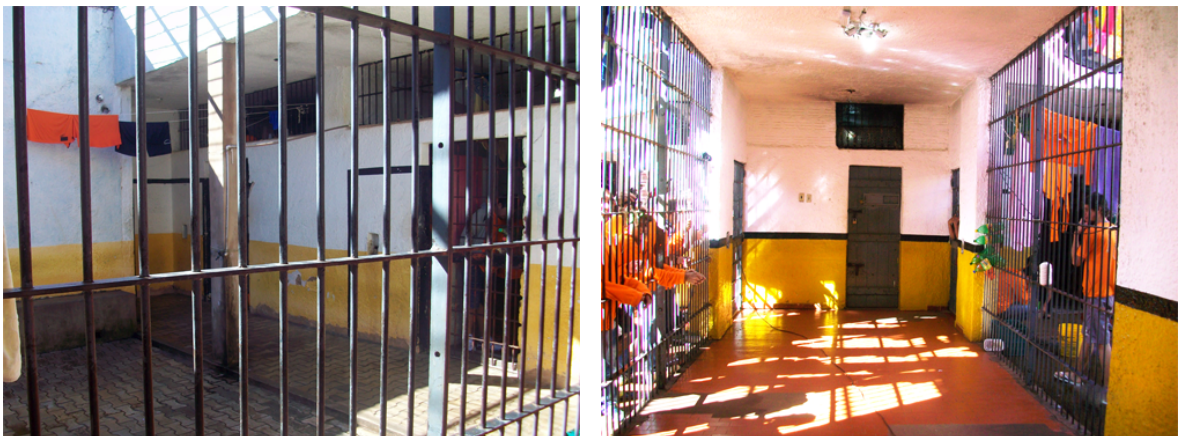


Figure S3. Architectural floor plan of typical general population cell courtyard in UPRB (A). Photographs illustrating existing built conditions, 2013 (B).