Estimating and Simulating a SIRD Model of COVID-19 for Many Countries, States, and Cities

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Extended results for Paraguay
Based on data through September 11, 2020
Outline of Slides

- Basic data from Johns Hopkins CSSE (raw and smoothed)
- Brief summary of the model
- Baseline results ($\delta = 1.0\%, \gamma = 0.2, \theta = 0.1$)
- Simulation of re-opening – possibilities for raising $R_0$
- Results with alternative parameter values:
  - Lower mortality rate, $\delta = 0.8\%$
  - Higher mortality rate, $\delta = 1.2\%$
  - Infections last longer, $\gamma = 0.15$
  - Cases resolve more quickly, $\theta = 0.2$
  - Cases resolve more slowly, $\theta = 0.07$
- Data underlying estimates of $R_0(t)$
Underlying data from Johns Hopkins CSSE

– Raw data
– Smoothed = 7 day centered moving average
– No “excess deaths” correction (change as of Aug 6 run)
Paraguay: Daily Deaths per Million People
Paraguay: Daily Deaths per Million People (Smoothed)
Brief Summary of Model

- See the paper for a full exposition
- A 5-state SIRDC model with a time-varying $R_0$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta$</td>
<td>1.0%</td>
<td>Mortality rate from infections (IFR)</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>0.2</td>
<td>Rate at which people stop being infectious</td>
</tr>
<tr>
<td>$\theta$</td>
<td>0.1</td>
<td>Rate at which cases (post-infection) resolve</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.05</td>
<td>Rate at which $R_0(t)$ decays with daily deaths</td>
</tr>
<tr>
<td>$R_0$</td>
<td>...</td>
<td>Initial base reproduction rate</td>
</tr>
<tr>
<td>$R_0(t)$</td>
<td>...</td>
<td>Base reproduction rate at date $t$ ($\beta_t/\gamma$)</td>
</tr>
</tbody>
</table>
Estimates of Time-Varying $R_0$

– Inferred from daily deaths, and
– the change in daily deaths, and
– the change in (the change in daily deaths)
(see end of slide deck for this data)
Paraguay: Estimates of $R_0(t)$

Paraguay

$\delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20$
Paraguay: Percent Currently Infectious

Peak I/N = 0.13%  Final I/N = 0.13%  δ = 0.010  θ = 0.10  γ = 0.20
Paraguay: Growth Rate of Daily Deaths over Past Week (percent)

Paraguay

$\delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20$
Notes on Interpreting Results
Guide to Graphs

- **Warning:** Results are often very uncertain; this can be seen by comparing across multiple graphs. See the original paper.

- **7 days of forecasts: Rainbow color order!**
  ROY-G-BIV (old to new, low to high)
  - Black = current
  - Red = oldest, Orange = second oldest, Yellow = third oldest...
  - Violet (purple) = one day earlier

- **For robustness graphs, same idea**
  - Black = baseline (e.g. $\delta = 1.0\%$)
  - Red = lowest parameter value (e.g. $\delta = 0.8\%$)
  - Green = highest parameter value (e.g. $\delta = 1.2\%$)
How does $R_0$ change over time?

- Inferred from death data when we have it
- For future, two approaches:

  1. Alternatively, we fit this equation:

  $\log R_0(t) = a_0 - \alpha(Daily\ Deaths)$

  $\Rightarrow \alpha \approx 0.05$

  $R_0$ declines by 5 percent for each new daily death, or rises by 5 percent when daily deaths decline

- Robustness: Assume $R_0(t) = final\ empirical\ value$. Constant in future, so no $\alpha$ adjustment $\rightarrow \alpha = 0$
Repeated “Forecasts” from the past 7 days of data

– After peak, forecasts settle down.
– Before that, very noisy!
– If the region has not peaked, do not trust
– With $\alpha = 0.05$ (see robustness section for $\alpha = 0$)
Paraguay (7 days): Daily Deaths per Million People ($\alpha = .05$)

Paraguay

$R_0 = 1.4/1.1/1.1$  $\delta = 0.010$  $\theta=0.1$  $\gamma=0.2$  %Infect= 1/ 2/ 8
Paraguay (7 days): Cumulative Deaths per Million (Future, $\alpha = .05$)

Paraguay

$R_0 = 1.4/1.1/1.1$  $\delta = 0.010$  $\theta = 0.1$  $\gamma = 0.2$  $%\text{Infect} = 1/2/8$
Paraguay (7 days): Cumulative Deaths per Million, Log Scale ($\alpha = .05$)
Robustness to Mortality Rate, $\delta$
Paraguay: Cumulative Deaths per Million ($\delta = .01/.008/.012$)

Paraguay

$R_0 = 1.4/1.0/1.0$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%Infect = 1/2/5$

DATA THROUGH 11-SEP-2020
Paraguay: Daily Deaths per Million People \((\delta = \text{.01/0.008/0.012})\)

\[ R_0 = 1.4/1.0/1.0 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 1/2/5 \]

DATA THROUGH 11-SEP-2020
Paraguay: Cumulative Deaths per Million ($\delta = 0.01/0.008/0.012$)

Paraguay

$R_0 = 1.4/1.0/1.0$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$ Infect $= 1/2/5$

$\delta = 0.012$
$\delta = 0.01$
$\delta = 0.008$

DATA THROUGH 11-SEP-2020
Reopening and Herd Immunity

– Black: assumes $R_0(\text{today})$ remains in place forever
– Red: assumes $R_0(\text{suppress}) = \frac{1}{s(\text{today})}$
– Green: we move 25% of the way from $R_0(\text{today})$ back to initial $R_0 = \text{“normal”}$
– Purple: we move 50% of the way from $R_0(\text{today})$ back to initial $R_0 = \text{“normal”}$

NOTE: Lines often cover each other up
Paraguay: Re-Opening ($\alpha = 0.05$)

Paraguay

$R_0(t)=1.0$, $R_0$ (suppress) = 1.0, $R_0(25/50)$ = 1.2/1.5, $\delta = 0.010$, $\alpha = 0.05$

(Light bars = New York City, for comparison)
Paraguay: Re-Opening ($\alpha = 0$)

Paraguay

$R_0(t) = 1.0$, $R_0(suppress) = 1.0$, $R_0(25/50) = 1.2/1.5$, $\delta = 0.010$, $\alpha = 0.00$

(Light bars = New York City, for comparison)
Results for alternative parameter values
Paraguay (7 days): Daily Deaths per Million People ($\alpha = 0$)

Paraguay

$R_0 = 1.4/1.1/1.1 \quad \delta = 0.010 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \%\text{Infect} = 1/2/13$
Paraguay (7 days): Cumulative Deaths per Million (Future, $\alpha = 0$)

Paraguay

$R_0=1.4/1.1/1.1$  $\delta = 0.010$  $\theta=0.1$  $\gamma=0.2$  $\%$Infect= 1/ 2/13

Cumulative deaths per million people

Paraguay (7 days): Cumulative Deaths per Million, Log Scale ($\alpha = 0$)
Paraguay: Daily Deaths per Million People ($\delta = 0.8\%$)

Paraguay

$R_0 = 1.4/1.0/1.1$  $\delta = 0.008$  $\theta = 0.1$  $\gamma = 0.2$  $\%$ Infect $= 1/2/6$
Paraguay: Cumulative Deaths per Million ($\delta = 0.8\%$)

Paraguay

$R_0 = 1.4/1.0/1.1$  $\delta = 0.008$  $\theta = 0.1$  $\gamma = 0.2$  $\%$Infect = 1/2/6
Paraguay: Daily Deaths per Million People ($\delta = 1.2\%$)

Paraguay

$R_0 = 1.4/1.0/1.0$  \( \delta = 0.012 \)  \( \theta = 0.1 \)  \( \gamma = 0.2 \)  \( \%\text{Infect} = 1/1/4 \)
Paraguay: Cumulative Deaths per Million ($\delta = 1.2\%$)

Paraguay

$R_0=1.4/1.0/1.0$  $\delta = 0.012$  $\theta=0.1$  $\gamma=0.2$  %Infect= 1/ 1/ 4
Paraguay: Daily Deaths per Million People \((\gamma = 0.2/0.15)\)

\[
R_0 = 1.4/1.0/1.0 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 1/2/5
\]

DATA THROUGH 11-SEP-2020
Paraguay: Cumulative Deaths per Million $\gamma = .2/.15$)

Data through 11-Sep-2020

$R_0 = 1.4/1.0/1.0 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 1/2/5$

$\gamma \equiv 0.15$
Paraguay: Daily Deaths per Million People ($\theta = .1/ .07/ .2$)

Paraguay

$R_0=1.4/1.0/1.0 \; \delta = 0.010 \; \alpha=0.05 \; \theta=0.1 \; \%Infect= 1/ 2/ 5$

DATA THROUGH 11-SEP-2020
Paraguay: Cumulative Deaths per Million People ($\theta = .1/.07/.2$)

Paraguay

$R_0=1.4/1.0/1.0 \quad \delta = 0.010 \quad \alpha=0.05 \quad \theta=0.1 \quad \%\text{Infect} = 1/2/5$

DATA THROUGH 11-SEP-2020
Data Underlying Estimates of Time-Varying $R_0$

– Inferred from daily deaths, and
– the change in daily deaths, and
– the change in (the change in daily deaths)
Paraguay: Daily Deaths, Actual and Smoothed

\[ \delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20 \]
Paraguay: Change in Smoothed Daily Deaths

Paraguay: \( \Delta d \)

\( \delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20 \)
Paraguay: Change in (Change in Smoothed Daily Deaths)

Paraguay: Delta (Delta d)
\[ \delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20 \]