Supplementary Materials: 'National REDD+ outcompetes gold and logging: the potential of cleaning profit chains.' Overman, Cummings, Luzar and Fragoso.

S1. Guyana background.

Guyana is considered a High Forest Low Deforestation (HFLD) country (Da Fonseca et al. 2007) and ranks 151st worldwide in per capita GDP (CIA 2015). Guyana has 83.3% forest cover (18.4M ha), with much of its non-forest area covered by natural savannah. It has a population of around 750,000 people, the large majority of whom live in the Caribbean coastal zone (Guyana Bureau of Statistics 2002, GFC and INDUFOR 2015). The country has been at the forefront of REDD development since 2006 and is a partner country of both the UN-REDD Programme and the World Bank's Forest Carbon Partnership Facility (UNFCCC 2017, FCPF 2017, The REDD desk, 2016). In late 2009, Guyana signed a five-year bilateral performance-based REDD+ agreement with Norway worth $250M to facilitate REDD+ readiness and low-carbon projects, and is currently in the process of extending the collaboration (Government of Norway 2016, Joint Concept Note 2015, The REDD desk, 2016). One of the results of the Norway-agreement is Guyana's UN-submission 'The reference level for Guyana's REDD+ program' (GoG 2015), the core document for this paper.

S2. Costs of deforestation and logging a tree, and calculating annual emissions.

Clearing a hectare of forest in Guyana (detected nationwide from time-series satellite imagery with 5-meter resolution) will reduce revenue in the next assessment by $5,201 due to forfeited REDD+ revenue incurred by the associated emissions. The value is derived from the reported mean carbon density of Guyana's forests, which is 283.7 $tC.ha^{-1}$ (above- and belowground live biomass components, 16% variation across forest types, Government of Guyana [GoG] 2015), multiplied by the C – CO_2 conversion factor [the ratio of the molecular weights: (12 + 2*16) / 12 = 3.667], and the price per tCO_2 (US$5 in this paper), which gives $5,201 per hectare. Conversely, not clearing a hectare yields this same amount (more explanation in S3 below).

Logging. Pearson et al. (2014) conducted detailed field studies in six timber-producing countries, including Guyana, to relate the annual extracted volume of logs with total associated emissions (from the log itself, incidental damage and residue [stump, roots, branches, damage to adjacent trees] and infrastructural damage [skid trails, logging roads, loading decks]), with the goal of quantifying degradation emissions from logging. In Guyana the mean dbh of logged trees in four sampled concessions was 54 cm, producing 1.3 tC in extracted volume, accompanied by 3.3 tC collateral damage and 3.4 tC infrastructural damage, for a total of 8 tC per logged tree. Hence logging a tree corresponds on average to $147 in lost REDD+ revenue [8 * (44/12) * $5 = $147]. Pearson et al.'s findings were used in Guyana's UN-FREL submission (GoG 2015).
The country's emissions rate in a given year *x* derives from converting cleared hectares and logged volume in year *x* into CO_2 units, and dividing this annual total by the country's total CO_2 stock in year *x-1* (forest area * carbon density * (44/12)).

S3. Missed gold revenue from under declaration and recovery inefficiency.

Guyana has a post-mining tax system, where extracted gold is self-declared and bought by the government at the daily gold price minus 7% taxes. From 2001 through 2012, declared gold was ~2 kg per deforested hectare (weighted mean of annual gold production, divided by mean annual deforestation (excluding deforestation from mining infrastructure), Bank of Guyana 2015, GoG 2015), worth ~$70,000 (Kitco 2016). Using an average mining depth of 10m (Swiecki 2011), this figure for declared gold implies that during 2001—2012 a medium scale operation (processing up to 1,000 m^3 soil per day) earned on average \$700 per day in gold to cover costs (e.g. wages for six workers, fuel, state tax, permit holder fee, and repayment of any equipment loans), and make a profit. A small operation (200 m^3/day) would earn \$140 per day. These figures are improbably low to run mining operations. Yet since mining did occur, this means more than 2 kg/ha gold was produced by operations, but did not subsequently end up in the Treasury (ignoring *where* along the gold supply chain gold went missing).

Few accurate data are publicly available on the cost and yield of alluvial mining in Guyana. One study on operating costs in 2005 (cited by Thomas 2009) results in mining sector costs 2.4 times higher than the value of declared gold that year. A professional operation in a remote alluvial site in Guyana in the early 1990s stated an overall gold recovery grade of 0.456 $g.m^{-3}$ with a 0.1 $g.m^{-3}$ cut-off grade (at a gold price of \$350 /oz., Swiecki 2011). The cut-off grade is the minimal gold content of soil for economically viable mining. Substituting \$350 with the historic period's average gold price of \$996, it implies a professional operation requires soils with a minimum 0.035 $g.m^{-3}$, or 3.5 $kg.ha^{-1}$, to be (minimally) profitable. If we take 0.456 $g.m^{-3}$ as the highest gold grade in Guyana, it implies economically mineable grounds contain between 3.5 kg and 45.6 $kg.ha^{-1}$ recoverable gold (rich grounds are not depleted since the 1990s since still advertised in 2011, Swiecki 2011).

If the average ground across Guyana over 2001—2012 contained 25 $kg.ha^{-1}$ (rounded mean of 3.5 and 45.6), and the average recovery efficiency of all operations was half that of this professional operation, then mean recovery of the small and medium gold mining sector was 12.5 $kg.ha^{-1}$. Anchoring this back into reality, it implies that gross gold yield per day averaged \$4,323, respectively \$865 for medium and small-scale operations. It would imply that the State missed out on royalty revenue over 4.79 times the declared amount (2.16 $kg.ha^{-1}$), through under declaration along the supply chain and inefficient recovery of gold.

Clearly, the 12.5 $kg.ha^{-1}$ is not an accurate or precise number but it *is* very far from the declared 12-year country wide average amount (2.16 $kg.ha^{-1}$), which simply does not cover operational costs, indicating large losses of gold revenue for Guyana. Moreover, the large returns and low risks on smuggling (see next) push towards the higher end of the 4.79 estimate.

Based on our estimate (479%), missed state revenue may have averaged $76 million per year (4.79 * $15.8M, Table 2, ranging from $8M in 2001 to $245M in 2012, the latter equating to 35% of the 2014 State Budget). Adding the full gold value (without production costs and fees) of 4.79 times the declared amount, implies that average private net profit over this period was, or could have been with professional mining, $264,200 per hectare, i.e. not 7x but 65x more than the gross revenue for the state ($4,100, Table 3).

Is cross-border smuggling worthwhile?

Smuggling stems from peoples' general inability to resist high return-low risk opportunities. Guyana's 7% tax on gold is higher than in neighboring countries (Suriname 3-4%, Venezuela 3%, Brazil 1%, Heemskerk 2010, Otto et al. 2006), risk is minimal with porous borders, poor interior law enforcement and corruption (Falloon 2001, Harvard Law School 2007, Stabroek News 2015), and high gold prices may tip the scale toward smuggling. For example (taking the 'worst' country to smuggle to), at a $1,000 oz^{-1} gold price, declared gold per hectare (2.16 kg, or 69.4 troy oz.) would fetch only ~$2,400 more in Suriname, but $14,000 more with a 12.5 $kg.ha^{-1}$ recovery. If State taxes can be avoided altogether (Stabroek News 2015), the extra profit doubles to $28,000 ha^{-1} (on top of profits made from the other 93% of the gold value). These are attractive sums, more so in a country with ~\$200 per month minimum wage. Guyana also has diamonds. Diamonds are 5.5 times lighter than gold (3.5 vs. 19.3 $g.cm^{-3}$) and worth at least around 150 – 3,000 times more (Ajediam 2017).

Professionalism

Our example (Swiecki 2011) demonstrates the high merit of professional efficient mining with exploration. Swiecki reported that reserves estimated by exploration were just 5% under actual production. This is very different from the often hit-and-miss approach in Guyana's gold mining sector (Lowe 2006). Further, this operation was profitable under a \$350 gold price, with costs as low as \$77 oz^{-1} (the cut-off grade, 0.01 $g.m^{-3}$ at \$350 oz^{-1}, implies soil processing costs of \$1.13 m^{-3} (1 troy oz. = 31.1 g). The average recovery of 0.456 $g.m^{-3}$ implies an ounce of gold was obtained from 68.2 m^3 soil. 68.2 * 1.13 = \$76.75 oz^{-1}). At the other end, many operations were forced to close down with gold prices around \$1,250 (Kaieteur News 2014, Guyana Times 2015, largely due to over optimism regarding the gold price remaining high). Costs may have gone up since the 1990s, but such large differences in production cost (\$1,250 vs. \$77 oz^{-1}) show that professional, and rational, mining practices would optimize and stabilize the sector, and remove a current motivation, if not obligation, for smuggling. REDD+ will further reduce state acceptance of inefficient gold extraction given the \$5,200 ha^{-1} opportunity costs of deforestation to the State (at a \$5 carbon price; at \$40 it becomes \$41,600 ha^{-1}, CPLC 2017).

References (Supplementary materials)

Ajediam 2017. Carat diamonds price index, September 2017. http://www.ajediam.com/diamond_price_index.html

Bank of Guyana, 2015. Annual Reports 2001 – 2012. https://www.bankofguyana.org.gy/bog/economic-financial-framework/publications/annual-reports

CIA, 2015. The World Factbook. https://www.cia.gov/library/publications/the-world-factbook/geos/gy.html

CPLC (Carbon Pricing Leadership Coalition), 2017. Report of the high-level commission on carbon prices. Commission Chairs: Joseph E. Stiglitz and Nicholas Stern. https://static1.squarespace.com/static/54ff9c5ce4b0a53decccfb4c/t/59244eed17bffc0ac256cf16/1495551740633/CarbonPricing_Final_May29.pdf

Da Fonseca, G.A.B., Rodrigues, C.M., Midgley, G., Busch, J., Hannah, L. Mittermeier R.A., 2007. No forest left behind. PLoS Biol **5(8)**, e216. doi:10.1371/journal.pbio.0050216

Falloon, M., 2001. Gold mining: an industry on the verge of crisis? Stabroek News. http://www.landofsixpeoples.com/gynewsjs.htm

FCPF (Forest Carbon Partnership Facility), 2017. REDD+ Country Participants. https://www.forestcarbonpartnership.org/redd-countries-1

GFC and INDUFOR, 2015. Guyana REDD+ Monitoring Reporting & Verification System (MRVS). Year 5 Summary Report. 1 January 2014 – 31 December 2014. Version 1. www.forestry.gov.gy/wp-content/uploads/2015/10/MRVS-Summary-Report-Year-51.pdf

GoG [Government of Guyana], 2015. The Reference Level for Guyana's REDD+ Program. http://redd.unfccc.int/files/guyanas_proposal_for_reference_level_for_redd__-_final_sept_2015.pdf

Government of Norway, 2016. Guyana and Norway agree on how to take partnership dialogue forward. https://www.regjeringen.no/en/aktuelt/press-release-guyana-and-norway-agree-on-how-to-take-partnership-dialogue-forward/id2520691/

Guyana Bureau of Statistics, 2002. 2002 Population & Housing Census - Guyana National Report. Ch 6. http://www.statisticsguyana.gov.gy/census.html#popcenfinal

Guyana Times, 2015. 2000+ mining permits relinquished. http://www.guyanatimesgy.com/2015/09/27/2000-mining-permits-relinquished/

Harvard Law School, 2007. All that Glitters: Gold mining in Guyana. Human Rights Program. http://hrp.law.harvard.edu/wp-content/uploads/2013/02/959_file_AllThatGlitters_FINAL_.pdf

Heemskerk, M., 2010. The gold marketing chain in Suriname. WWF Guianas.

http://mariekeheemskerk.org/data/images/wwf2010

Joint Concept Note, 2015. Joint Concept Note on REDD cooperation between Guyana and Norway. Third update. http://www.regjeringen.no/en/aktuelt/norge-vil-gi-300-millioner-til-guyana/id2410147/

Kaieteur News, 2014. Gold slide… Mining operations drop 40 percent, equipment sales decline – GGDMA. http://www.kaieteurnewsonline.com/2014/06/25/gold-slide-mining-operations-drop-40-percent-equipment-sales-decline-ggdma/

Kitco, 2016. Historical gold prices. http://www.kitco.com/charts/historicalgold.html

Lowe, S., 2006. Situation analysis of the small-scale gold mining sector in Guyana. World Wildlife Fund. http://uog.edu.gy/faculties/fot/repository/sites/default/files/Situation Analysis of Au mining- Guyana - S. Lowe 2006.pdf

Otto, J., Andrews, C., Cawood, F., Doggett, M., Guj, P., Stermole, F., Stermole, J., Tilton, J., 2006. Mining royalties : a global study of their impact on investors, government, and civil society. Worldbank; http://siteresources.worldbank.org/INTOGMC/Resources/336099-1156955107170/miningroyaltiespublication.pdf

Pearson, T., Brown, S., Casarim, F., 2014. Carbon emissions from tropical forest degradation caused by logging. Environ. Res. Lett. **9**. doi:10.1088/1748-9326/9/3/034017. http://iopscience.iop.org/1748-9326/9/3/034017/pdf/

Stabroek News, 2015. GGMC criticised over reported big gold smuggling. http://www.stabroeknews.com/2015/news/stories/08/31/ggmc-criticised-over-reported-big-gold-smuggling/

Swiecki, R., 2011. Alluvial mining of gold. http://www.minelinks.com/alluvial/mining.html

The REDD desk, 2016. REDD in Guyana. http://theredddesk.org/countries/guyana (accessed 23.04.16)

Thomas, C.Y., 2009. Too Big to Fail: A Scoping Study of The Small and Medium Scale Gold and Diamond Mining Industry in Guyana. Univ. of Guyana. http://www.guyanaminers.org/sites/default/files/documents/files/Gold%20and%20Diamond%20Mining%20Study.pdf

UNFCCC, 2017. Country submissions. http://redd.unfccc.int/submissions.html?topic=6 (last accessed 20.03.17)