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Causes and Consequences of a Tropical Forest Gold Rush in the Guiana Shield, South America

Statistical and spatial analyses of both historical time series and remotely sensed data show a link between the spatial distribution and growth of gold production across the Guiana Shield in northeast Amazonia. Results indicate that an exponential rise in production across an expanding area is primarily a delayed response to the 1971–1978 market flotation of international gold prices. The subsequent 10-fold (2-fold) average nominal (real) price increase has provided a compelling economic incentive to mass exploitation of lower-grade gold deposits. The ground-based and remotely sensed distributions of mining activity are strongly attached to these deposits that dominate the region's gold geology. The presence of these gold-bearing formations in conservation and sustainable timber zones has sparked social conflict and environmental degradation across the region. Left unmanaged, more than a quarter-million square-kilometer area of tropical forest zoned for protection and sustainable management could ultimately be compromised by the price-driven boom in gold mining through poorly integrated resource use planning, lack of reclamation effort, and control of illegal operations. Serious public health issues propagated through the unregulated mining environment further erode the financial benefits achieved through gold extraction. This study demonstrates in part how international economic policies successfully stabilizing more conspicuous centers of the global economy can have unintended but profound environmental and social impacts on remote commodity frontiers.

INTRODUCTION

The Guiana Shield is the largest contiguous region of exposed Precambrian (>0.6 Ga old) rock in South America, covering more than 2 million square km of northeast Amazonia (1). Its equatorial location and historic absence of large-scale deforestation render it the largest repository of tropical forest vegetation on Precambrian terrain worldwide (34%), an area equivalent to more than one-third of remaining neotropical forest cover (2). It generates one of the highest specific discharges of freshwater in the world but some of the smallest natural suspended sediment loads. It is uniquely characterized by widespread plant endemism and high beta diversity that has evolved atop a quiescent geological landscape affected by relatively few large-scale natural disturbances (3). The age and structure of the underlying geology also strongly contrast with many other tropical forest regions that are characterized predominantly by Phanerozoic sedimentary deposits (4). The Guiana Shield shares significant geological features with other former components of the paleo-continent Gondwana, including West Africa, Western Australia, and south-central Amazonia. Consonant with this shared geological history are parallels in the type of mineral resources in these regions (5, 6). Gold, diamonds, iron, and bauxite represent the most significant mineral resources in these regions that have driven mining activity for centuries (7, 8).

Although production of most minerals in the Guiana Shield has slowly declined over the last quarter century (9), the region has seen exponential growth in gold extraction. Over this period, annual gold output from the region has increased 60-fold from 900 kg in 1979–1980 to just less than 55 000 kg in 2004. The boom in gold mining in this region is even more perplexing because it has occurred despite dampening global demand and increased, albeit controlled, sell-off of large government gold reserves held principally by industrialized countries (Fig. 1).

Understanding the factors driving an expansion of gold mining is crucial in striking the right balance in policy development and for efforts to achieve sustainability and avoid widespread environmental degradation. The environmental and social consequences of poorly managed and regulated gold mining in the region can be severe. Studies have shown that poorly managed mining can create significant impacts through deforestation; accumulation of mercury in rivers, wildlife, and people (10–15); heightened suspended sediment loads (16); transmission of malaria, HIV, and other diseases (9, 17); and significant cultural erosion and social conflict in neighboring rural communities that often capture only a nominal share of financial benefit but bear the weight of environmental and social costs (18, 19). The massive growth in gold mining across the region represents an even greater environmental challenge to an area characterized by some of the lowest rates of natural mechanical weathering in the world (6) and some of the largest blocks of remaining wilderness (20). Situated across highly porous international borders, illegal and poorly managed resource extraction is difficult and expensive to monitor and regulate (21).

The social and environmental impacts of gold mining are particularly resonant when compared with other major mineral commodities. Unlike bauxite, diamond, or iron mining, gold is excavated at a much wider range of operational scales. It regularly employs both physical and chemical refining methods that can introduce significant environmental changes that are both mobile and cumulative. Gold deposits are found within both hard rock (lode deposits) and sedimentary (placer deposits) environments, spreading impacts across upland terrestrial, riverine, and aquatic habitats. Consequently, a region-wide boom in mining can create significant environmental and social challenges as both upland terrestrial and downstream aquatic systems are altered. For a more in-depth comparison of the major impacts attached to different commodities mined in the region, see Hammond (7).

Yet the ultimate causes of a gold rush in the Guiana Shield and regional distribution of its effects have remained obscure despite the overwhelming importance of the mining sector to many national economies and livelihoods, the environmental significance of the region's forests (3, 20), and the very high likelihood of more intense and widespread mineral exploration of the region's gold-bearing rock formations. Heemskerk (22) cogently argued that international gold price was not a driver of

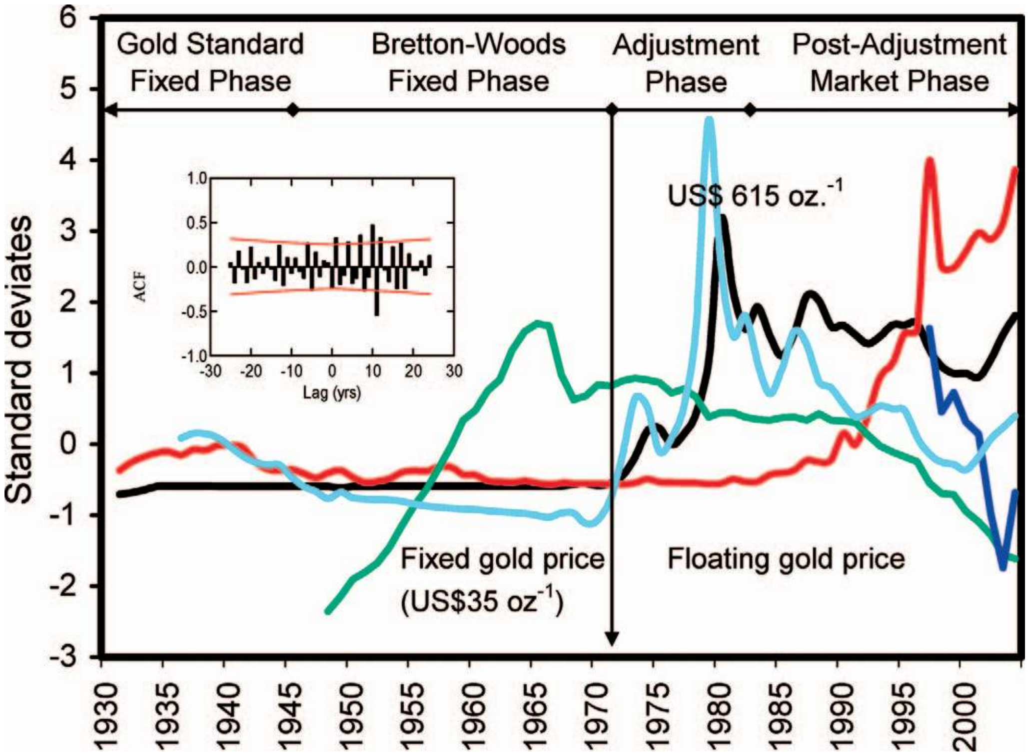


Figure 1. Historical transitions in nominal (black) and real (light blue) world gold price, declared production in the Guiana Shield (red), global gold reserves (green), and consumer demand (dark blue). Annual production for combined statistics from Venezuelan Guayana, Guyana, Suriname, French Guiana, and Brazil (0 = series average) from 1930 to 2005. Annual average gold price identifies pre– and post–Bretton Woods transitional phases from fixed to floating gold price. Global gold reserves are official holdings only. Consumer demand includes jewelry, investment, dental, and industrial components over the period 1998 to 2005. Inset: Cross-correlogram (maximum lag = 25 y) of transformed price *vs.* production over time series. Price leads production over positive lags.

participation among Surinamese artisanal miners. However, analyses of price-production relationships across the spectrum of operational sizes, at regional scales and through the full range of gold price change over the transition from fixed to floating regimes, have not been undertaken.

To explore the links between the rapid growth in production, how this is distributed across the region, the factors driving this change, and the ultimate consequences of this change, we compiled and analyzed together for the first time a number of historical time series and spatial coverages for the region. Quantifiable attributes linked to the gold-mining sector, *viz*. annual production, gold price, ore grade, and official reserves, were obtained for an interval spanning nearly 75 y from 1931 to 2005.

METHODS

Historical Effects

Global production vs. Guiana Shield production. We quantitatively assessed the relationship between worldwide and Guiana Shield gold production trends before and after abandonment of the Bretton-Woods fixed gold price mechanism through a broken-stick regression technique. Global production here excludes production from the Guiana Shield. Generally, strong linear relationships between global and Guiana Shield–scale values indicate that global production drivers are controlling trends. In this case, an increase in gold production in the region may not be symptomatic of a regional "gold rush" but reflect general changes to the global gold-mining sector. Curvilinear or nonlinear relationships indicate that factors driving production at the smaller scale of the Guiana Shield may be in response to or at variance with those controlling production across the full geographic spread of gold-bearing deposits.

Guiana Shield production vs. world gold price. We employed cross-correlation analysis to examine the lead-lag relationship between changing world gold price and declared gold production across the shield regions of Venezuela, Guyana, Suriname, French Guiana, and the northernmost Brazilian states of Amapá, (north) Pará, Roraima, and (north) Amazonas for the 72-y period spanning 1930–2005. An annual average gold price (23) was assigned to each year of the time series. Annual production statistics for the countries composing the shield area were extracted, compiled, and cross-referenced from a range of sources (24, 25) to obtain the most credible record of declared gold production for the region. Undeclared production is believed to have met or exceeded that declared in some countries (e.g., Suriname [11, 22]), and it is assumed here that decadal-scale trends in undeclared production parallel those of declared amounts. Many production centers are also located on international boundaries (e.g., Maroni-Marowijne river), and gold can be produced in one country but ultimately sold across the border if purchasing prices are superior (e.g., due to varying currency exchange or tax rates). In other cases, uncoordinated changes in national resource-use policies can shift mining focus from one country to another. To offset these effects, we pooled annual shield-based production from each country in the region.

Cross-correlation analysis. Cross-correlation with average annual gold price reflects a relationship with total declared production from the region. Individual national gold production series, however, show a similar trend over the period analyzed (9). Prior to constructing the cross-correlation, weak stationarity was achieved by sixth order–polynomial differencing (lag = 1) of the reciprocal square root of production and price data according to the difference transformation (26):

$$\nabla_s^d \log x_1$$

where d is the order of the polynomial trend and number of differences taken, s is the step width of difference, and x is value at time t in the series.

A 95% confidence interval was adopted in identifying significant autocorrelation function values (ACF_L) across examined lags (L) (27).

Comparing lagging moving averages for gold price against leading moving averages for production data can also show the relationship between growth in price and regional production between 1933 and 2004. Assigning the average of a time window consisting of t years prior to the assigned year (y_0) weights the relative performance leading up to y_0. Conversely, assigning an average based on t years following the assigned year emphasizes the state of y_0 relative to future performance. Because changes in gold price are hypothesized to lead regional production based on cross-correlation results, lagging and leading moving averages were calculated, respectively. A 12-y window for assessing moving averages was selected based on the maximum lag showing a significant autocorrelation function in the price-production cross-correlation.

Chow test of structural change. A Chow test (28) was used to determine whether the structure of the log-transformed and differenced gold price and production relationship was significantly different prior to and after abandonment of the Bretton-Woods fixed-price policy in 1971. The Chow test is a modification of the ordinary least squares F-test of the form:

$$\frac{(SSE - SSE_1 - SSE_2)/k}{(SSE_1 - SSE_2)/(n_1 - n_2 - 2k)} \approx F_{k_1 n_1 + n_2 - 2k}$$

Where k is pooled sample size and n_1 and n_2 are sample size for pre- and postbreak sample periods, respectively.

Guiana shield mine ore grade. Ore grade available for a set of 59 abandoned, active, and planned mines was empirically assessed using various published figures for recovered and assayed ore grades (7, 24, 29–31). Recovered grades were used for historical mining events. They are based on total gold weight recovered from total ore processed over the life of a mine. This accurately reflects operational decision making, because it encapsulates the full cost and production attached to a mining event. Assay data were used to grade mines that have recently been commissioned or opened and in either case have not yet reached the end of their full economic life. These are averages derived from pit and/or drill hole samples spread across a target geological formation. Because production data are incomplete or unavailable at these early stages, we believe that using the same data used by the mining companies to decide whether or not to mine a particular deposit is a reliable leading indicator of economically viable ore grade. One caveat of this approach is that deviations either way from the assayed ore grades are common and could alter the pre– and post–Bretton-Woods comparison if these are substantial. Generally speaking, however, recovered ore grades at three large mines in Venezuela (Las Cristinas), Guyana (Omai), and Suriname (Gros-Rosebel) have not strongly deviated from assayed grades due to the enhanced technologies employed in reliably quantifying this critical, decision-making factor. A separate variances t-test was used on ore grade for periods before ($n = 44$) and after ($n = 15$) the Bretton-Woods 1971 break point.

Gold demand. Global gold demand has traditionally been driven by its role as an anchor for national currency value but also by consumer use in jewelry, dentistry, and industrial applications and more recently as both a speculative form of investment and a hedge against losses in rapidly shifting global financial markets. The change in global gold reserves (32) and more recent consumer demand (33) were used to depict the trend in gold demand for comparison against shield production levels.

Spatial Effects

Using spatial coverages for legal mine locations (24, 29, 31), major rock formations (7), and surface drainages (6), we delimited the spatial relationships between gold-bearing lithologies, past mining activity, and relative catchment positions. More recent legal and illegal mining sites (1999–2004) were identified and added to existing ground-based coverages through spectral analysis of LANDSAT ETM+ imagery (34, 35).

Once identified, geological predictors of mining effort were assessed for their degree of overlap with areas designated for protection and allocated to sustainable timber production across the region using timber concession and protected area (36), coverages generated for the Guiana Shield. Raster-based coverages derived from scanned images were vectorized, georeferenced, rectified, and projected using ArcInfo and ArcView GIS. Quality control over spatial attributes was applied using vectorized topographic coverages, remotely sensed radar imagery (JERS-1), and global positioning system coordinates of several mine areas collected in Guyana, French Guiana, and Suriname. The spatial overlap between different land-use units was estimated by intersecting coverages using ArcView's geoprocessing routine. The spatial association of mining and geological coverages was determined by radial projection of 5-km–wide annuli from rock formation edges and counting the number of mine locations ($n = 895$) located within each of these bands at a 1:250 000 scale. Increasing map scale did not alter the distribution of mine distances. Five-kilometer bands were chosen to minimize instances in which mines of varying area fell within more than a single interval. Nearly 99% of mines fell within the same distance interval when comparing point positions of mines forming the analyzed coverage and area maps of these same mines in Guyana and Venezuelan Guayana (31, 37). The set of coverages used to analyze the spatial relationship between gold mining activity and other land-use features in the region is derived from a wide range of sources created to meet different objectives with varying, often undocumented, levels of precision. Consequently, true positional accuracy can vary between coverages. To reduce the artifactual effects of positional inaccuracy on results, instances in which land-use features overlapped less than 1% of their respective areas are not presented here. A comprehensive, high-resolution digital elevation model was not available for the region. Digitized topographic coverages and elevational models (USGS ETOPO5), paper maps, and mine elevation data (0.2- to 10-km resolution) were used to assess the affect, if any, of varying topography on distances analyzed using radial annuli. Only 7 of the 895 mine locations analyzed were affected when considering slope using this approach. The radial annuli method was similarly used to assess the spatial distribution of gold-bearing geological structures relative to protected areas.

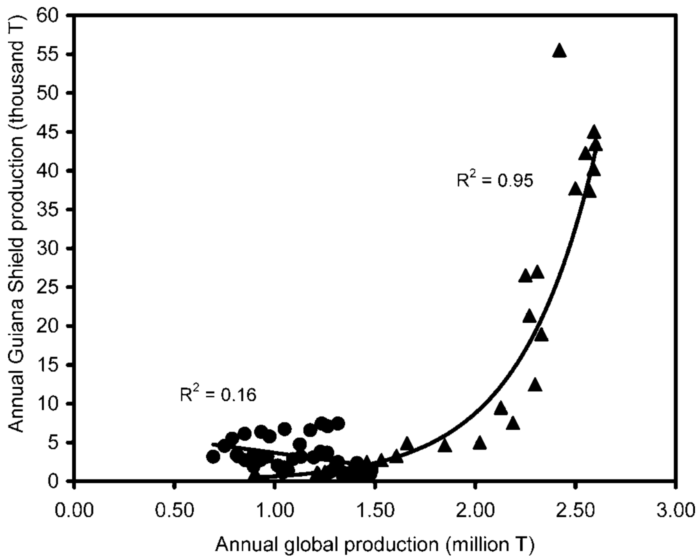


Figure 2. Relationship between annual worldwide (less Guiana Shield) and Guiana Shield gold production before (circles) and after (triangles) abandonment of Bretton-Woods fixed exchange rate mechanism in 1971. Coefficients of determination (R^2) reflect linear and exponential models for pre- and postabandonment periods, respectively.

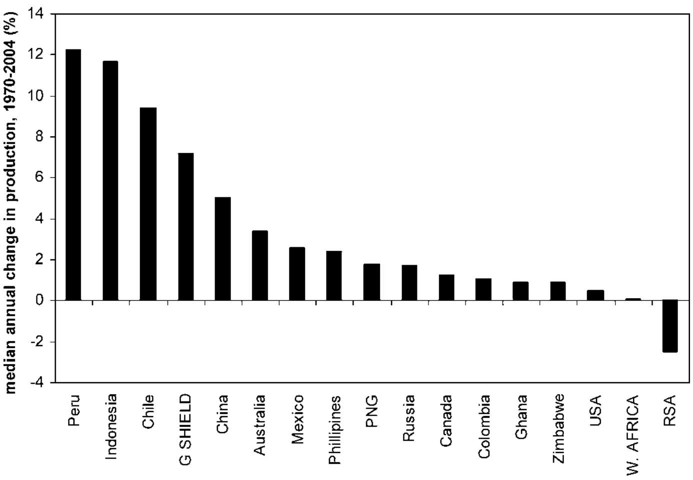


Figure 3. Rank of annual change in gold production between 1970 and 2004 for the 15 largest world gold producers over the period and the Guiana Shield (Venezuelan Guayana, Guyana, Suriname, French Guiana, and Brasilian municipios in states of Roraima, Amapa, north Pará, and north Amazonas). Data source: United States Geological Survey.

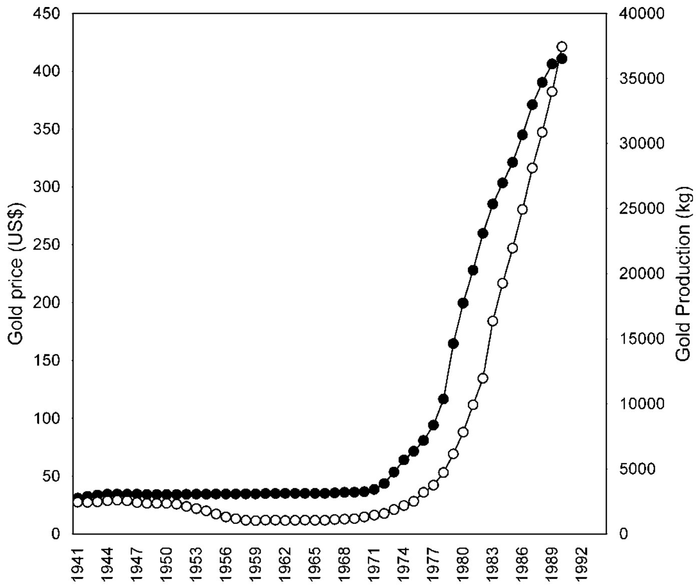


Figure 4. Relationship between nominal gold price (filled circles) and Guiana Shield production (open circles) adjusted by a 12-y floating average. Price and production for each year reflect average for leading and lagging 12-y periods, respectively.

RESULTS AND DISCUSSION

Historical Patterns

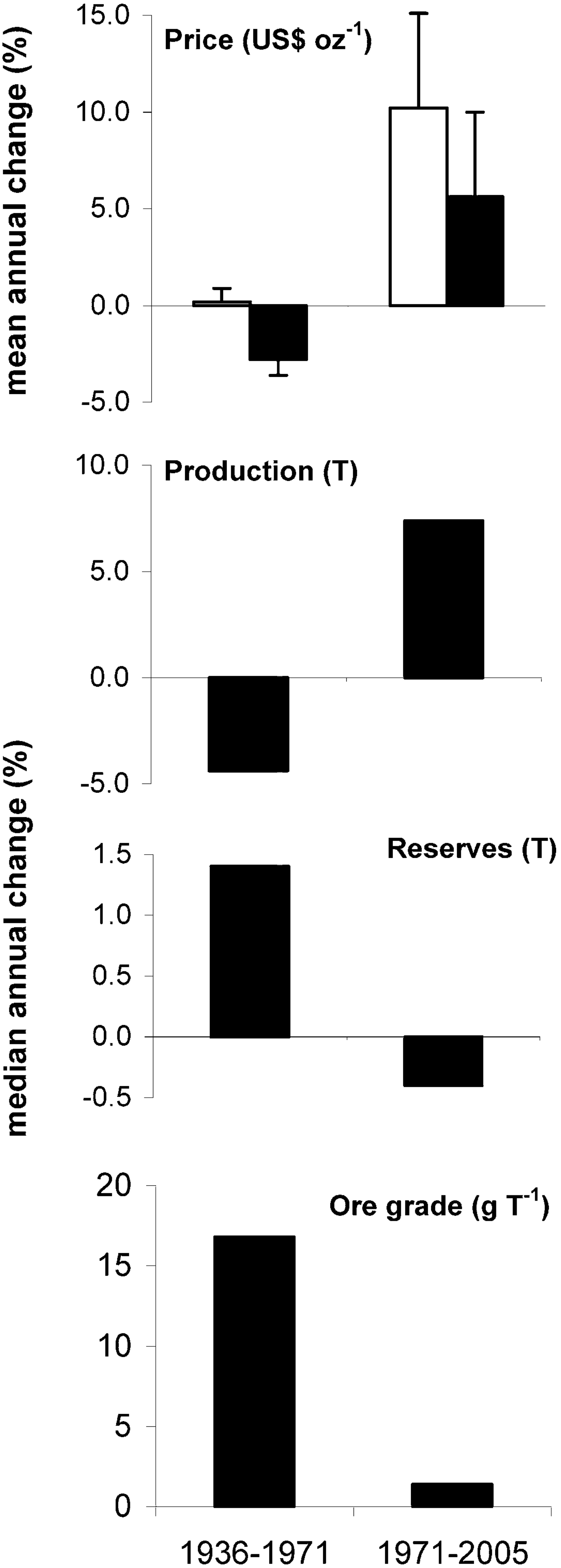
The functional relationship between global and regional gold production changed drastically after the transition from fixed to floating USD–denominated gold prices that took place from 1971 to 1978 (Figures 1 and 2). Global production has traditionally been heavily weighted by mining of higher-grade deposits in South Africa and elsewhere, but the relative contribution from this source has been in steady decline as heavily tapped sources have been exhausted (25) (Fig. 3). Conversely, the number of opportunities for investment in mining previously uneconomic, lower-grade deposits has increased with these higher prices. The Guiana Shield represents one of the largest repositories of these low-grade, greenstone-derived sources (5, 38). It currently ranks as the fastest-growing region of gold production among those with Precambrian terranes and third, after Peru and Indonesia, among regions with tropical forest cover (Fig. 3). This is primarily due to exponential growth from 1990 to 2004 in Guyana, Suriname, French Guiana, and Venezuelan Guayana bolstered by earlier growth in northern Brazil from 1980 to 1995. By comparison, median annual growth rates from combined production in West African tropical forest countries (Cameroon, CAR, Republic of Congo, Cote d'Ivoire, DRC, Equatorial Guinea, Gabon, Ghana, Liberia, and Sierra Leone) are nearly 1.5 orders of magnitude lower than that recorded for the Guiana Shield (Fig. 3). West Africa's largest gold-producing country, Ghana, recorded a median annual growth rate in production from 1970 to 2004 that was more than seven times lower than the Guiana Shield (Fig. 3). In absolute terms, traditional gold-producing heavyweights outside the tropics remain the largest sources of production. The rates of growth in production, however, have lagged those in many tropical countries (Fig. 3). This variance in growth rates is due to relatively little production sourced from these regions prior to the 1970s.

Gold Price and Monetary Policy as a Root Cause

We cross-correlated the annual gold production and price time series to identify lead-lag relationships. Production from the shield region significantly shadowed world gold price of the previous year ($ACF_1 = 0.36$) but also at 4-y ($ACF_4 = 0.25$), 7-y ($ACF_7 = 0.37$), and 10- to 12-y ($ACF_{10,11,12} = 0.48, -0.56, 0.36$) intervals (Fig. 1, inset). The strongest band of significant cross-correlations between price and production occurred across the 10- to 12-y lag. Comparing production and price data offset by respective backward and forward 12-y moving average windows shows the parallel growth with a lag-log phase transition point occurring in the early 1970s (Fig. 4).

We subsequently blocked and transformed price, production, and ore grade time series into equal-sized subseries that depicted annualized changes before and after abandonment of the Bretton-Woods fixed-price policy (Fig. 5). Splitting the data using 1971 as a threshold moment indicates that price and production (Chow test, $F_{2,69} = 6.71$, $p = 0.002$) underwent a structural change in their relationship after the Bretton-Woods abandonment and the subsequent adjustment from fixed to floating price environments. Production in the region relative to global production shows a similar transition from lagging to exponential growth when using the 1971 Bretton-woods abandonment as a cut-off point (Fig. 2).

The root explanation for this lead-lag response is one structured around global monetary policy decisions of the late 20th century. The final abandonment of a fixed gold price policy that formed part of the Bretton-Woods Agreement (1945 to 1971) to fix currency exchange rates based on the U.S. dollar altered the role of gold in the global economy (39). Spurred by increasing inflationary pressures on the U.S. dollar, abandonment of the fixed gold price policy and its role in anchoring exchange rates occurred through a hectic process of reducing the fraction of the U.S. currency underpinned by gold. The disastrous Smithsonian Agreement, signed by a number of Organization of Economic Co-operation and Development members in 1971, attempted to alleviate these pressures by increasing the gold price and allowing currencies to float within a broader band. However, expansionary U.S. monetary policy continued to place pressure on this policy, with the eventual abandonment of fixed exchange rates by 1978 and with it the rapid development of a foreign exchange market and floating gold prices. At this time, full flotation led to a market run on gold and the peak historical market prices experienced in 1980 (Fig. 1). The lagging production response to the abrupt change from a fixed to floating mechanism and the more varied



postadjustment market phase restructured the 20th century global gold economy. Analyses presented here suggest this change invigorated production in the shield region a decade later (Figs. 1, 2, and 5). The decadal lag between price and production seen in the cross-correlation is logical given the abrupt rise in nominal market gold prices. Very little investment was made in mining the region's low-grade deposits prior to the price change brought on by the abandonment of the Bretton-Woods policy. Consequently, the mining presence necessary to catalyze production in tandem with the rise in market prices was not readily available, creating a decadal price-production lag. In addition, life expectancies of mining operations have historically ranged between 10 and 15 y, a periodicity also consistent with the observed lag. The high volatility in correlations observed over the 10- to 12-y lag reflects the rapid closure and opening of large mines that individually exert disproportionate influence on overall production levels in the region both before and after the fixed-to-floating transition. Price-lagging production trends over this period also appear to have occurred across other gold-bearing Precambrian terranes as the price environment changed (8, 40). In many instances, both within the Guiana Shield and across other Precambrian gold mining regions, many new, low-grade deposits have been assayed and higher grade mines have been re-opened to profitably exploit lower-grade portions previously considered uneconomic (7, 31, 41).

Proximate Causes

Many proximate factors have interacted with gold price to create conditions promoting a widespread boom in mining (Fig. 6). Several of these, such as investment in mining innovation and exploration, can be interpreted as responding to a changing price environment combined with exhaustion of higher-grade deposits worldwide. Thus, significant price-production correlations at shorter lags detected here may reflect an interaction of price with these influences, including varying investment risk (42), exploration-production costs, and mine life expectancy and overlap (9).

Policy changes that stimulate capital investment in gold-mining operations or alter the balance of small-, medium-, and large-scale operators can also substantively influence the direction and rate of production changes. Virtually all of the gold-mining areas in the Guiana Shield rest in government-administered lands, lending considerable weight to the effects of changes in national government policies on gold production.

Asymmetries in national regulatory policies and enforcement of these regulations has spurred a region-wide source-sink phenomenon as very small (artisanal) and small operators migrate to locations where regulation and enforcement is relatively weak, unmined deposits are more accessible, and tax rates and government mining incentives are favorable (43). Weak border controls across vast remote frontiers of the central shield region have further catalyzed the spread of illegal miners attracted to lower-grade deposits by high gold prices. Combined with high unemployment, low opportunity costs of labor, and weak regulatory enforcement capacities, high market prices have also spawned a boom in small-scale participation from both urban and rural residents (22, 44).

Production from large-scale operations in the region may also have been sustained during brief periods of price weakening and declining global demand by favorable market hedging of future gold prices that can maintain profitability in large-scale

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Figure 5. Change in real (empty bars) and nominal (filled bars) world gold price (±1 SE), Guiana Shield production, government-held reserves, and ore grade leading up to (1936–1971) and following (1971–2005) abandonment of Bretton-Woods fixed gold price policy.

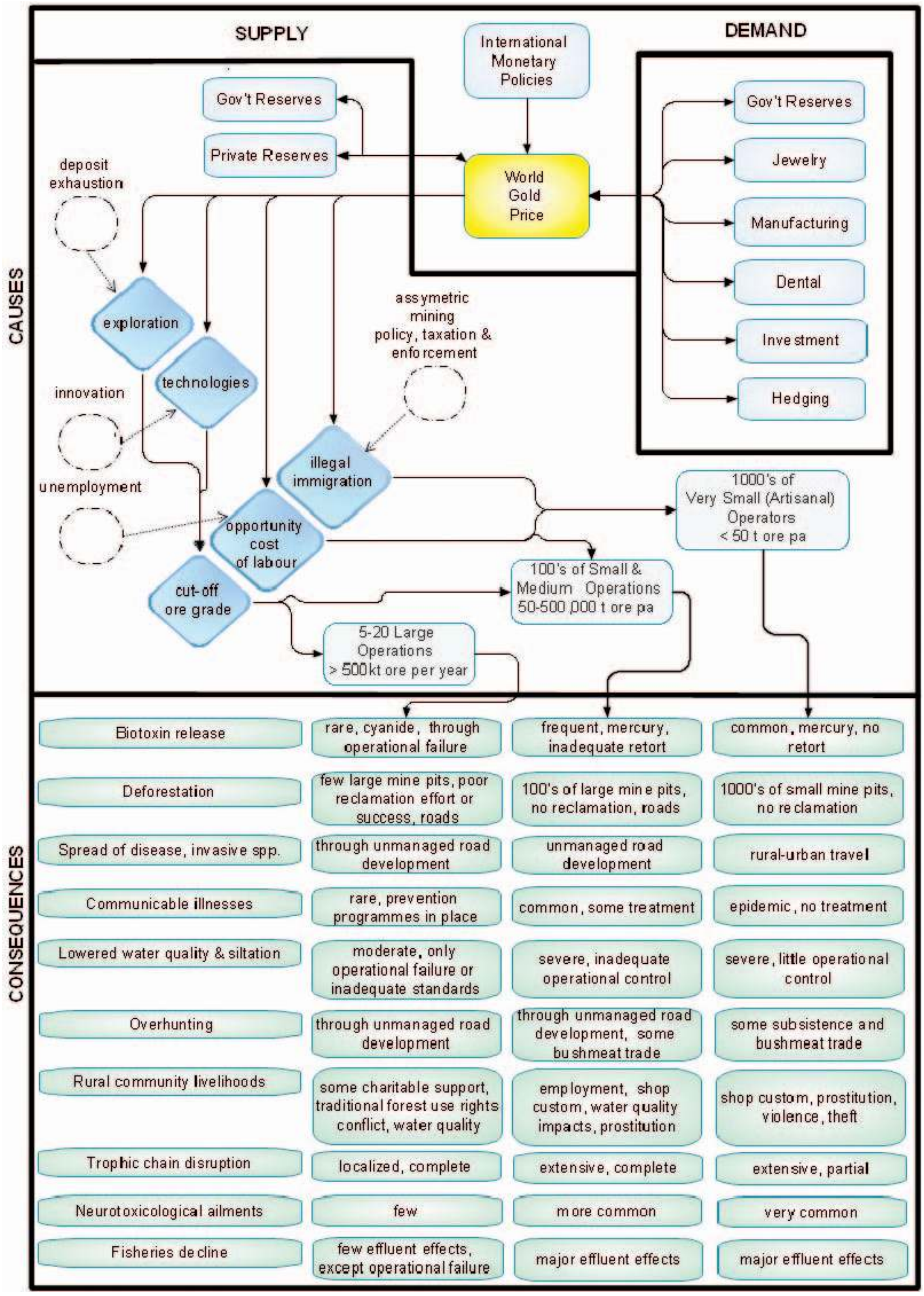

Figure 6. Schematic summarizing relationships between root and proximate causes of gold mining and its consequent impacts in the Guiana Shield.

operations during less favorable price periods (42). At the same time, smaller-scale gold mining represents a compelling alternative to widespread unemployment, making mining at this operational scale also less sensitive to annual market price fluctuations (22, 45).

However, with average nominal gold prices from 1971 to 2005 remaining nearly 10 times the Bretton-Woods fixed price (≈USD 35 oz^{-1}) (Fig. 5), the extent of unmined, low-grade deposits that dominate the region have principally interacted with gold price to drive the rush to mine. During the Bretton-Woods period, the fixed gold price limited profitability to only the most replete, or high-grade, gold-bearing deposits. As a consequence, mining in the Guiana Shield prior to abandonment of Bretton-Woods largely targeted grades exceeding 5 to 10 g t^{-1} (Fig. 5). This has declined by a half to full order of magnitude (Fig. 5) as open-cast mining and hydraulic dredging of lower-grade ores have become profitable under the elevated prices of a post–Bretton-Woods era. Ore grade at mines opened before 1971 was significantly higher than that operating or planned after gold price flotation (separate variances $t_{14,43} = 8.82$, $p < 0.001$) (Fig. 5).

Early exhaustion of localized, high-grade deposits during fixed-price phases has now focused the search for investment opportunities on lower-grade deposits. Elevated market prices and high-grade deposit scarcity have combined with cost-saving exploration and operational technologies to create conditions suitable for widespread mining in the region's tropical forests (Fig. 6).

Spatial Consequences

The spatial distribution of impacts from the post–Bretton-Woods gold rush is predictable due the overwhelming control exerted by two Precambrian geological features on gold mining activity in the region. We estimate that more than three-

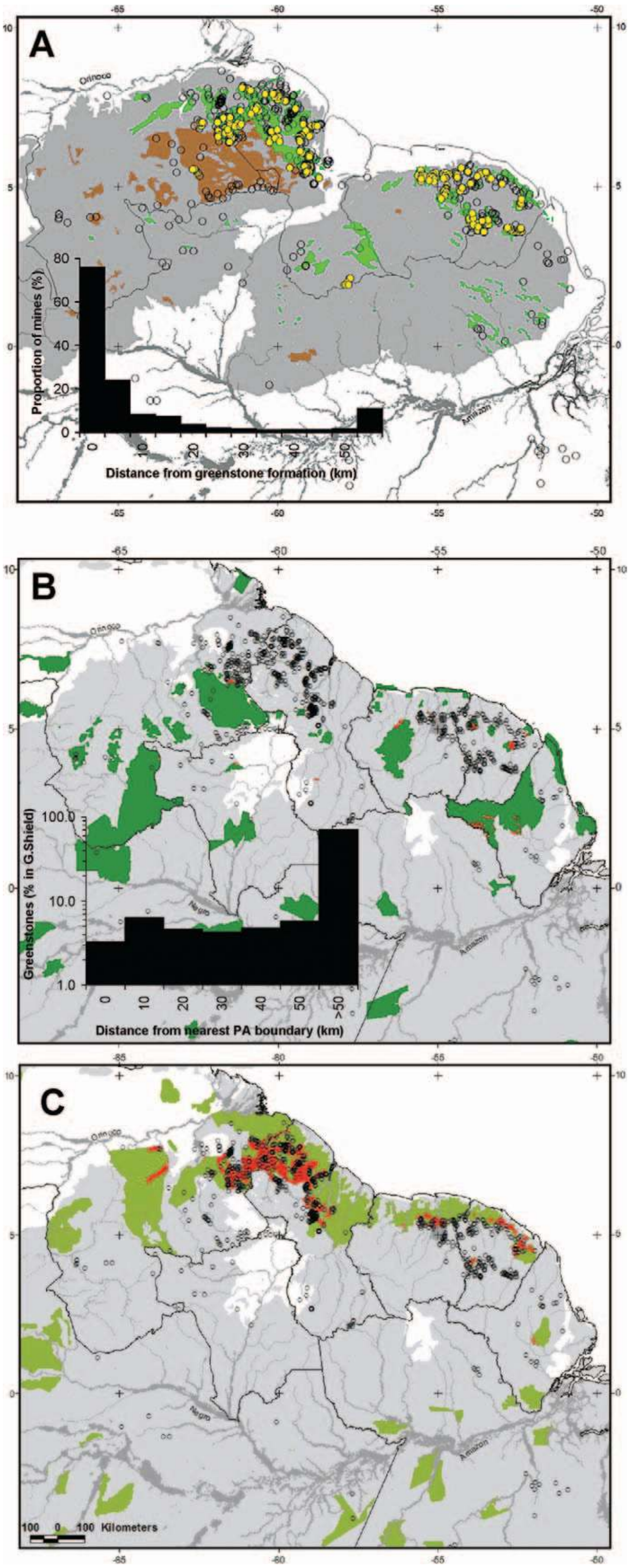

Figure 7. Spatial distribution of mining effort, associated geology, and overlap with conflicting land-use allocations. (a) Greenstone (green) and Roraima sedimentaries (brown) associated with registered gold mines (empty circles: 1890–1990; gold: 1999–2004) across the Guiana Shield (shaded region is exposed Precambrian rock). Inset: distribution of mine to greenstone distances. (b) Designated (green) protected areas and overlap with greenstone formations (red) and mine locations (1890–2004). Inset: distribution of greenstone to protected area distances. (c) Areas designated for timber production (light green) and overlap with greenstone formations (red). Grey shaded and empty area in B, C is forest and savannah cover, respectively.

quarters of gold mining activity since 1880 has taken place within 10 km of the nearest Precambrian greenstone formation and intruded gold-bearing structures (Fig. 6a, inset). Additional activity occurring at greater distances is principally associated with (paleo-) placer deposits downstream from greenstones and associated metamorphic rocks (Fig. 7a) (7, 29). Remotely sensed mining scars indicate that contemporary spatial patterns remain consistent with historical trends towards greenstone-sourced deposits (Fig. 7a). Modern patterns of mining, however, are expanding from traditional greenstone sites into new, lower-grade ones (open *vs*. yellow circles in Fig. 7a). A smaller fraction of activity (>50 km) is also associated solely with the upland sedimentary Roraima Formation that dominates southeastern Venezuela and western Guyana (Fig. 7a), typically in combination with placer diamond extraction (29).

Although many of the effects of mining in the Amazon have been known for some time (45), the large-scale spatial distribution of these impacts has not been well articulated. Our analysis indicates that greenstones, and to a lesser extent outlying remnants of the Roraima formation, provide a simple yet powerful locator of past and future mining impacts on environmental quality in the region. Most countries have already allocated substantial portions of the shield's forested area for environmental protection and as flagship tourist attractions, including several of the largest tropical parks in the world (Fig. 7b) (36). A number of these have absorbed significant impacts from illegal, small-scale gold mining or are certain to be degraded in the absence of additional protective measures (21, 46, 47). Mining activity in French Guiana alone led to more than 40 km^2 of forest cover loss in 2001, a 20-fold increase in the area deforested in 1990 (35) and rising to nearly 115 km^2 in 2006 (48) . Much of this deforestation is overlapping with existing areas allocated for protection or forest management objectives, other than mining (Fig. 7b).

Many existing protected areas in Brazil, French Guiana, Suriname, and Venezuela overlap with greenstone formations (Fig. 7b). Lack of overlap in Guyana is due to a relatively low fraction of national forest area currently afforded legal protection (36). Overall, we estimate that more than 2600 km^2 of the region's current protected area rests directly atop these primary mining targets (38). Our estimate that more than 10% of the region's greenstone area resides within 10 km of the nearest protected area raises equal concern to the long-term viability of these zones because the environmental impact of these mining operations typically radiates beyond mining sites. This is well illustrated by the encroachment of gold mining upon one of the oldest protected areas in the region, the Brownsberg Nature Reserve in Suriname, which has resulted in 5% forest cover loss and ablation of adjacent creek mainstems (49).

Sediments and mercury sourced from gold mining wash into downstream habitats and bioamplify through trophic structures (10, 12, 13). Recent monitoring of the Approuague River in French Guiana showed significantly higher values of water turbidity up to 7 km downstream from mining sites. This high turbidity was associated with a decreased richness of pelagic and benthic invertebrate communities. Fish community trophic structure is also altered in turbid waters, with decreases in the biomass of carnivorous fishes (50).

The extent of these mobile impacts is considerable. The French National Forest Agency calculated that among the 31 340 km of French Guianan waterways, 1333 km (3%) are directly affected by mining operations and 4671 km (15%) are expected to be polluted by increased concentrations of suspended solids (48).

Although deforestation from mining appears modest in comparison with other documented tropical forest land uses, it represents the fastest growing cause of forest loss in a region more typically known for having the lowest deforestation rates in the world (51–53). The rehabilitation of abandoned mine sites is rarely undertaken in the region (36), and natural forest regrowth is slow in a region characterized by world-class soil infertility and a preponderance of large-seeded, poorly dispersed endemic trees (9, 54). Where reclamation programs are in place, prospects for success are limited by a dearth of scientific information to guide the postclosure recovery of completely modified, and often highly contaminated, tropical forest environments.

Similar to many commercial logging operations (55), unrestricted hunting, fishing, and live-specimen collecting in adjacent forest areas are used to offset costs of smaller-scale mining in the case of some operations, degrading local faunal resources and subsistence livelihoods (56). Depletion of local fauna through poaching can create significant changes in the processes affecting recruitment of timber and nontimber plant species (57), constraining prospects for sustainability under natural forest management approaches relying on dispersal services from animals to replenish future timber stocks (58).

Efforts to work towards sustainable forest management across many parts of the region are also under pressure from the post–Bretton-Woods gold rush. We estimate that nearly 256 000 km^2, or 15%, of all forest area allocated for sustainable forest management in the Guiana Shield rests atop greenstone formations (Fig. 7c). Inclusion of greenstone-bearing catchments in sustainable forest management areas across the shield region currently limits forest management effectiveness when surface and subsurface land uses overlap. Similar to protected areas, this conflict is most pronounced where riparian buffer zones are created as part of forest management strategies to reduce sedimentation but the same waterways represent primary mining targets. Ironically, efforts to design and manage roads that limit logging impacts still catalyze poorly regulated gold mining in these areas and their associated effects (9, 59). Consequently, generation of social and environmental costs is not dampened but simply transferred from timber to mining sectors.

Different Players, Different Impacts

Gold is mined in the region at a range of operational scales. Very small, or artisanal, operations are typified by relatively small volumes of ore processed (<500 t per year, *sensu* Healy and Heemskerk [60]) by one to five people relying more heavily on their own labor than capital equipment inputs, although small pump-driven hydraulic jets are increasingly common. Gold is typically beneficiated using manual, gravity-driven separation and mercury amalgam with poor recovery. Small to medium operations employ more significant technologies managed by teams of 5 to 20 people, typically funded by invested capital, and process significantly larger volumes of ore (>500 to 500 000 t per year) (Fig. 6).

Technologies include high-capacity hydraulic, jet, and suction dredging combined with excavation and mechanized beneficiation. Mercury use is substantially greater due to higher ore processing rates, but recovery can also be greater when such technologies as retorts (collecting stoves) are introduced and correctly operated. Large operations are undertaken after substantive investment in exploration and capital equipment, typically by market-capitalized, international mining companies. They employ dozens to hundreds of skilled staff operating advanced mining technologies to process tremendous volumes of ore (>500 000 t per year). In most instances, cyanide is utilized through heap-leach processing to remove gold from low-grade ores (61).

The trend in gold production from the Guiana Shield quantified in this paper is a composite of these different operational scales, but the accrual of environmental and social costs from the spread of gold mining is not uniform across this scale (Fig. 6). Better managed and more visible to the public, large operations also denude very large patches of forest, often catalyze uncontrolled encroachment through rapid development of well-maintained but poorly managed supply roads and create large volumes of toxic fluid waste (62). They also can create significant conflict where operations (and their benefits and impacts) are not adequately addressing indigenous communities' traditional use rights (63). Environmental disasters or significant occupational health problems can ensue when controls fail in these very large operations, and the consequences are felt primarily by these communities (64) (Fig. 6). The number of very large gold mines operating in the region has increased since the 1970s, but remain relatively few given the higher investment required. Despite their small numbers, their contribution to government revenue, foreign exchange earnings, and national employment can be substantial, providing significant social enhancement support through public purpose projects and creating relatively few public health issues. Offsetting these benefits is the volatility in their delivery as large mines open and close, creating a boom-bust cycle of employment, cash flow and nonmonetary benefits that can lead to an expansion of small mining operations in the wake of their closure or contribute to social unrest and political instability with the rapid rise in unemployment (62).

In contrast, the health, environmental, and social impacts of very small and medium operations are widespread, difficult to monitor, and less easily mitigated (Fig. 6). Increased disease transmission rates created by unregulated gold mining at these scales has been described in wider Amazonia for HIV and related sexually transmitted diseases (17, 65), malaria (66), leishmaniasis (67), and several arboviruses (68). Mercury exposure due to poorly managed or infrequent use of retorts and its consequent toxicological effects is widely documented for artisanal and small mine operators in the region (11, 69). Mercury poisoning has rapidly spread beyond mining areas through traditional reliance on freshwater fish in the region (70) and proximity to air (69) and waterborne (71) effluent and its ultimate discharge into commercial offshore fishing zones (12).

These small to medium operational scales account for the bulk of expansion in forest area affected by mining in the region. For example, in Guyana, declared gold from small to medium operations accounted for one-quarter to one-third of total annual production but showed similar upward trends as those from large operators (72). Small- and medium-scale operator license applications also increased 20-fold from several hundred in 1980 to more than 14 000 in 2000, while the forest area covered by mining permits at these scales expanded from just more than 800 km^2 to 13 000 km^2, or 6% of the national land area, by 2000 (72). Interestingly, the ratio of applications for river and land mining permits in Guyana reversed from 1.5:1 in the mid 1980s to 1:4 by 2000, suggesting exhaustion of higher grade alluvial placer deposits and a transition to lower-grade paleo-placer and hard rock deposits under a more favorable price environment (72). A similar trend is recorded in Suriname, although Healy and Heemskerk (60) note that many applications were submitted as a speculative play on increasing gold prices but without plans to operate the permitted sites. No accurate survey has been undertaken of the number of legal and illegal artisanal miners operating in the tropical forests of the region. However, combining reasonable estimates for various countries suggests a population floating between 50 000 and 250 000 over the last two decades (16, 19, 21, 43–45, 60, 65, 73, 74). Remote sensing of mining areas as depicted here bring geographic shape to the rapid expansion of small- and medium-scale mining and provides a good indication of the changes occurring in concert across the region.

CONCLUSIONS

We conclude that the current rush to mine low-grade deposits in the Guiana Shield is, at its largest scale, an indirect consequence of changes in gold's historical role in underpinning exchange rates attached to the Bretton-Woods Agreement and its poorly managed abandonment in the early 1970s. The decision to abruptly abandon gold price regulation as part of the Bretton-Woods fixed exchange rate unknowingly preconditioned this remote economic frontier to explosive growth in lower-grade mining before adequate sectoral structuring could develop. As higher-grade auriferous ores were depleted before and during the Bretton-Wood years, the 10-fold (2-fold) average nominal (real) price increase appears to have "unbottled" low-grade mining in the Guiana Shield (Fig. 1). A price environment favoring low-grade ore mining has interacted with a number of proximate causes to create a regional mining dynamic characterized by thousands of mines operating at a wide range of scales and spreading rapidly across the region. Low-grade ores in Precambrian shield regions are now estimated to account for half of the remaining giant (>100 t Au) gold deposits worldwide (5), and countries in other regions of similar geological terrain appear to have experienced similar, albeit not as explosive, production responses to the gold price transition of the 1970s (8, 75),

Combined, the breadth of operational scale employed in the gold-mining sector poses significant challenges in avoiding and mitigating impacts (Fig. 6). At smaller operational scales, weak regulatory policies and enforcement capacities and illegal immigration combined with broader national-scale patterns of unemployment and poor education in the region have fostered the rush to mine low-grade deposits across the Guiana Shield. Faced with managing large areas of forest wilderness under these conditions and with few operational resources, agencies charged with stewarding land use have had little success in effectively mitigating impacts of the ongoing and expanding gold rush. Delivering carefully crafted incentives that will promote significant improvements in regulation of mining operations, effective protection of established protected areas, and better coordination of conflicting land-use allocations through balanced land-use zoning processes would assist in reducing the mounting social and environmental costs of gold mining as it continues to rush across one of the last and largest tropical forest frontiers. Global-scale policies intending to address stability and growth in major world economic centers can inadvertently stimulate significant environmental and social cost accrual in remote commodity frontiers, such as the Guiana Shield, where some of the poorest people live. Targeted support for establishing better integrated international monetary policy that considers accounting for consequent cost transfers from economic centres to poorly poised commodity frontiers would improve prospects for sustainable development.

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