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Artificial nighttime lights and the "real" well-being of nations: 'Measuring economic growth from outer space' and welfare from right here on Earth

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Abstract. GDP remains too much of an imprecise measure of the standard of living. There is a need for either substitutes or complements. Nighttime lights are a reasonable indicator of the extent, scale, and intensity of socio-economic activities, but a poor measure of national welfare. However, if nighttime lights are understood to constitute externalities, then their effects can be used to adjust measured growth for welfare. From that angle, nighttime lights appear to exert sub-optimal positive externalities in developing countries, and supra-optimal negative externality in developed countries. This means that even if we assume equal growth rates in developing and developed countries, welfare is enhanced by increasing nighttime lights in developing countries and reduced by increasing nighttime lights in developed countries.
Keywords. Artificial lights and economic growth, Nighttime lights and growth, Growth and welfare, Nighttime lights and real well-being (welfare).
JEL. H23, O15, D62, I12, O47, I31, R13, Q52.

1. Introduction

Recently Coyle (2014) wrote an "affectionate" biography of GDP (gross domestic product). In a JEL review essay Syrquin (2016), while generally supportive, finds fault with the completeness and accuracy of Coyle's account. However, from both Coyle and Syrquin it remains clear that GDP continues to suffer familiar conceptual and measurement problems. Conceptually, although GDP purports to measure the market value of *final* goods and services, it is itself not a *final* statistic in that it is revised many times. Obviously, each revision makes a different statement about the size of the country and the well-being of its people. Moreover, estimating the products of service sectors is not straightforward. When goods sectors dominated GDP, this conceptual problem was not huge, but since most economies are increasingly service economies, it is difficult both to ignore and to calculate the real quantity of services rendered even when we know the nominal value of service sectors. One approximation is the productivity of the service sector, but the precision of the resulting statistic would require an unrealistic assumption that the service sector is always constant (cf. Amavilah, 2016).

GDP measurement problems include the fact that its calculation does not include household production, underground economic activities, leisure-work tradeoffs, positive/negative externalities of production and consumption, or all sorts of inequalities, socio-political justice, and ultimately Easterlin's (2010; 1995; 1973) "income-happiness paradox" (cf. Stevenson & Welfers, 2008). Morever, while GDP problems afflict developing and developed countries alike, the scale,

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extent, and intensity of nighttime light use is a notch higher in the former group of countries than in the latter. Hence, GDP is an inaccurate indicator of the standard of living of developing countries particularly. New measures and/or complements are badly needed, and many attempts in that regard have been made already. In a wide-ranging JEL review article Fleurbaey (2009) focuses on "four alternatives to GDP" as bases for measuring social welfare. He concludes that "a full convergence is not likely to occur soon" (p.1070).

Among the four alternatives, the "capabilities approach" first initiated by Adelman & Morris (1972) and expanded by Sen (1989; 1985; 1984; 1979a; 1979b), researchers at the UNDP such as Anand & Sen (1994), and most recently Temple & Johns (1998), and Anand, Hunter, & Smith (2005) have proposed the human development index (HDI). The HDI is an improved measure of national well-being, because it considers GDP per capita, as well as key representations of human capital in its health (life-expectancy) and education (years of schooling) dimensions. However, even with such improvement, GDP remains the largest and most dominant determinant of HDI. This dominance is not surprising since there is a positive and likely significant correlation between GDP and human capital accumulation and growth. Both life longevity and education are made possible by "investment in people" (Schultz, 1981; 1979; 1961; Becker, 1993), which themselves depend on economic growth.

The objective of this comment is to suggest how one might modify and use the relationship between artificial nighttime lights and GDP to measure the *real* well-being of nations, where "real" is taken to mean "true." In Section 1 below I list a few studies on this subject. Section 2 follows and modifies Henderson, Storeygard, and Weil (HSW, 2012) to show how one might assess real well-being from the relationship between nighttime lights and economic activities. The assessment requires treating nighttime light use as an externality. The third section makes a concluding remark.

2. Nighttime lights and the socio-economic activities of the nations

To deal, really avoid to deal, with GDP problems, attempts have been made at linking a variey of socio-economic activities to night-time lights. For example, Pinkovsky's (2013) study shows that there exists discontinuities in the levels of growth of satellite recorded lights per capita across national borders. The correlation between night-time lights and economic growth strengthens from low growth to high growth countries. The study also finds that international institutional variables like private property rights perform better than local variables like eduction, geography and culture. While the results are reasonable, it is not clear what they mean. For instance, do they mean that within one country highly lit urban areas perform better than poorly lit or unlit rural areas?

Bickenbuch, Bode, Lange, & Nunnenkamp (2013) examine nighttime lights as a proxy for economic activity at the sub-national level when GDP data is poor. They find that the elasticity of GDP with respect to nigh-time lights is unstable, suggsting that night-time lights are a poor proxy for GDP. This result is consistent with Bundervoet, Maiyo, & Sanghi's (2015) investigation of 47 counties in Kenya and 30 districts in Rwanda, which show that Nairobi is the largest source of Kenyan GDP and that three districts and Kigali account for 40% of Rwanda's GDP. In both cases night-time lights overstate the contribution to GDP in lit areas compared to other approaches to measuring GDP. Even if one takes the results for granted, it is not quite clear whether nighttime lights measure production or consumption. The production of goods and services takes place mainly during the day, whereas production and consumption of lights takes place at night. If that were to be correct, then GDP by the production approach (supply-side) would be smaller than GDP by the expenditure (demand-side) approach. It is a fact that in both Kenya and Rwanda workers who produce goods and services, including lights, live in unlit or poorly lit shanty towns of Nairobi and Kigali. This is one reason Sir W. Arthur Lewis (1955) have cautioned development policy that “output may be growing, and yet the mass of the people may be becoming poorer” (quoted by Asongu, p.3; cf. Amavilah, 2014c). Bhagwati (1958) has called the same phenomenon “immiserizing growth.”

While Chaiwat (2016) finds the effects of night-time lights on GDP to be robust, with significant spatial inequality in Thailand, Mellander, Lobo, Stolorick, & Matheson (2015), using fine-grained geo-coded residential and industrial micro-data for Sweden, discover that light radiance and light saturation correlate strongly with population density and weakly with wage rate. Most recently Proville, Zaval-Araiza, & Wagner (2017) observe global long-term relationships between night-time lights and a series of socio-economic indicators like electricity consumption, CO2 emission, GDP, population, CH4 emission, N2O emission, poverty, and F-gas emission. The same study adds that the relationships are not linear and vary considerably spatially, temporally, and intertemporally. This appears to suggest that night-time lights are good indicators of the location, scale, and intensity of socio-economic activities, but they still do not tell us enough about the well-being of nations. Ghosh, Anderson, Elvidge, & Sutton (2013) reviewed 68 papers that attempted to use nighttime satellite imagery as a proxy measure of human well-being. They conclude that the data for nighttime lights has potential, but the quality, coverage, and frequency of coverage need improvement. Moreover, “because of the geographical, cultural, and economic differences in lighting between countries the relation between GDP and light emissions requires further investigation. [It is surprising] that, despite a factor of two difference in the per capita income in southern Italy versus northen Italy, the per capita light emissions were the same...” (p.4714). Backhaus (2016) has echoed the same message that nighttime lights correlate strongly with measures of development like poverty, schooling, and electrification in both cross-sectional and panel data estimations. However, there are significant variations across countries. The study estimates development as a linear function of nighttime lights in Ghana, nonlinear in Malawi, and there is no discernable correlation for Burkina Faso. In Mozambique and Uganda nighttime lights do not reveal any difference between urban (lit) and rural (unlit) areas.

3. Nighttime lights and the “real” well-being of nations

Although economists like Romer (2009) have alluded to the relationship between nighttime lights and economic growth and development for a while now, systematic economic research on the subject is fairly recent. The literature review by HSW (2012), while not exhaustive, clearly shows that HSW are among the first economists to “develop a statistical framework to use data on night lights to augment official income growth measures” (p.994). The framework is well-justified and set up. However, while the data are illuminating in the cases of South Korea versus North Korea, or the crisis events associated with the Rwandan genocide, for example, the conclusions the data suggests are not entirely satisfactory. One, the apparent causality between development and nighttime lights has been ignored. Second, the fastest growing countries are not the ones most lit.

Let’s review the theory. According to HSW, officially-measured GDP growth ($\dot{y}$)equals desired (true) GDP growth ($\dot{y}^*$), give or take the associated random error ($e_{\dot{y}}$), i.e., $\dot{y} = \dot{y}^* + e_{\dot{y}}$ (Equation 1, p.1005). Furthermore, the growth of nighttime lights($\dot{x}$) is related to $\dot{y}^*$ as $\dot{x} = \alpha\dot{y}^* + e_{\dot{x}}$ (Equation 2, p.1005). Hence,

$$\dot{y} = \beta[\alpha \dot{y}^* + e_{\dot{x}}] = \varphi\dot{y}^* + e_{\dot{y}*}, \varphi = \beta\alpha, \; e_{\dot{y}*} = \beta e_{\dot{x}} + e_{\dot{y}*} \quad (1)$$

Solving for y^* leads to

$$\dot{y}^* = \theta\dot{y} + v, \theta = 1/\varphi, v = 1/\varphi e_{\dot{y}*} = 1/(\beta\alpha)[e_{\dot{y}*}] = 1/\varphi [\beta e_{\dot{x}} + e_{\dot{y}*}]. \quad (2)$$

HSW's pure econometric theory of (1) and (2) remains valid, but to make a statement on real welfare from these relationships requires treating $\dot{x}$ as an externality. For example, $\dot{x}$ is a positive externality if it "causes" ($\dot{y}$, $\dot{y}^*$) to increase, and it is a negative externality if ($\dot{y}$, $\dot{y}^*$) decreases as $\dot{x}$ increases. While it remains unclear whether $\dot{x}$ is a consumption or production externality, it is reasonable to argue that a positive externality enhances welfare and a negative externality reduces it.

It is more natural than not to think that as GDP growth increases economies become more lit, and lit economies grow faster. This is the basis for justifying a positive and statistically strong coefficient (0.18-0.33) of the log-lights (Tables 3 and 4, pp. 1015-1015). In this case the growth rate of $\dot{y}^*$, adjusted for the annual $\dot{x}$ is the time difference in Column 6 of Table 6 (p. 1019), i.e.,

$$\textit{Difference} = \dot{x} = [(\dot{x}_2 - \dot{x}_1)/\dot{x}_1] \times 100,\ 1 = \textit{previous time},\ t\text{-}1,\ 2 = \textit{current time},\ t. \quad (3)$$

Eq. (3) is consistent with situations like Iraq and Rwanda in that as $\dot{x}$ fell due to war and genocide, $\dot{y}^*$ also fell, and subsequently national well-being. Or in the case of South Korea versus North Korea, $\dot{x}$ grew faster in the former than in the latter, and hence $\dot{y}^*$ and associated welfare. However, this is neither the only nor the full story. Both lightness and darkness provide benefits; in other words the optimality of lightness and darkness is both local and debatable.

The correlation assumed to exist between $\dot{x}$ and $\dot{y}$ or $\dot{y}^*$ is a subjective one, and based on the idea that lightness is always preferred to darkness. However, since at the microeconomic level the demand for nighttime lights is derived demand, lights are essentially externalities at the macroeconomic level. Hence, what is important is not just $\dot{x}$, but $\dot{x}$ relative to change in darkness ($\dot{x}^*$). In this case, unlike in (3) above,

$$\dot{x} = \frac{(\dot{x}_2\,(L)\cdot \dot{x}_1(U)) - (\dot{x}_1(L)\cdot \dot{x}_2\,(U))}{(\dot{x}_2\,(U)\cdot \dot{x}_1(U))} \quad (4)$$

where L is for lit, U is for unlit, and 1 and 2 are as designated in (3) above.

Eq. (3) implies trade-offs between lightness and darkness. Compensating variations require that the benefits from lights be large enough to sustain initial utility from darkness. Alternatively, the equivalent variations account for the fact that if nighttime lights change product or factor prices, but do not change the income of at least Nairobi slum dwellers (the Rawlsian criterion that fairness requires making the poorest better-off), by how much would Kenya's national wealth have to vary to have the desired effect on the welfare of all Kenyans – not just people in well-lit areas? This is the problem Fleurbaey (2009, p.1069) seeks to address with his U-indexation of "hedonic states (H) and the rest of the functionings" into satisfaction equivalence (cf. Jones & Klenow, 2016; Young, 2012). This means that for GDP growth to have real welfare implications, it must include the effects of $\dot{x}^*$. An easy way to see this is to think of situations in which nighttime lights are pollution – a negative externality. Let's stress the point just a little further.

Nighttime lights affect the environment, safety and health, and energy consumption; it is a costly pollutant that generates benefits as well (Cho, *et al.*, 2015). According to Falchi, *et al.*, (2016) over 80% of the world is light-polluted, and close to 100% of Americans and Europeans experience zero natural lights. Nighttime lights pollute in different ways, but three are noteworthy: One, they disrupt the diurnal patterns of lights with further negative effects on plant and animal physiology and behavior. Two, they affect the health and safety of all living beings. Public health and other experts have linked light pollution to breast and prostate cancer, abnormal sleep behavior, suppressed melatonin production, insomnia, dysfunctional sleep/wake cycles, depression, reproductive health, and obesity (AMA, 2012; Drake, *et al.,* 2004; Gumenyuk, *et al.,* 2014; Elvidge, 1997; Elvidge, *et al.,* 2009; Elvidge, *et al.,* 1999; Small, *et al.,* 2011; Ghosh, *et al.,* 2009; Ghosh, *et al.,* 2010; Haim & Portnov, 2013; Durant, *et al.,* 2015; Small, *et al.,* 2009). Finally, nighttime lights represent inefficient energy consumption – "conspicuous consumption" as Veblen would have called it. For instance, LEDs are cost-effective in monetary terms, but blue-white LEDs are costly in real terms. As Horts (undated) argues "the superfluous and irrational squandering of energy involved [in lighting up] and its harmful environmental effects: the generation of greenhouse gases that produce acid rain and radioactive waste, ... ignore the importance of the night and for learning to value it" (p.38). [Moroever] natural light 'entrains' or regularizes basic and fundamental biological activities across species from plants to us humans. ... To assume that other living organisms are just going to 'adapt' to our newly created lighting schedules for commercial convenience is apathetically ignorant and insane" (Horts, [Retrieved from]; cf., Saleh, 2007). With light growth at 6% per annum over the past 15 years and in view of climate change, much of it attributable to energy production and consumption, it makes little sense that we continue to attribute the "Theogonist" value to light vis-a-vis darkness. Of course, there are biblical underpinnings to people, especially religious people, for preferring lightness to darkness. The Bible teaches that before the creation of the physical world there was a mathematical identity in which God was with the Word, the Word was God. Both God and the Word were surrounded by darkness and silence. It was not until the first day of creation that light came about to separate the scary night from the cheery day. Since the day-night balance created on the First Day was sub-optimal, God enhanced it by creating the Sun on the Fourth Day of creation. The point: It is not difficult to understand why lights are perceived to represent human progress. Are they?

To-date the most light-polluted countries are Singapore, South Korea, Kuwait, Qatar, and United Arab Emirates (UAE). Although these countries are highly lit, their $(\dot{y}, \dot{y}^*)$ differ greatly. Hence, a decent argument can be made about the welfare implications of such differential growth. To stress the same point, note that the least light-polluted countries are all in Africa. According to IMF's World Economic Outlooks (various years since 2014), South Africa, Africa's most lit economy, has not been among Africa's 10 fastest growing economies. Nighttime lights fails to pick up that difference, which means that light pollution reduces the welfare effect of measured growth in high-lit, and increases it in low-lit, countries. In other words, both consumption and production account for (4) above. How would one defend such a claim?

There is no doubt that the existence, distribution, scale, extent, and intensity of many socio-economic activity are highly correlated with artificial nighttime lights. It is not an "open-n-shut" case though that the correlation is welfare enhancing. Excessive lighting is an increasingly widespread form of pollution. To measure its effect on growth and welfare, we need to construct some composite nighttime light pollution index ($\dot{x}^*$) equal to the weighted sum of all components (types) of light pollution (e.g., light trespass, over-illumination, glare, light clutter, and skyglow), so that

$$\dot{x}^* = 1/N\sum_i^n w_i \dot{x}_i,\ i = 1,2,3,\ldots n = \text{light types};\ w_i = \text{weights}. \qquad (5)$$

The mathematical form of (5) is difficult to guess at this point, but I would start the exercise with general forms like the Bowley index and Fisher index. What is clear is that not only does $\dot{x}^*$ differ across economic units, it differs for different reasons. For example, light trespass pollution, even with modern lighting ordinances, is a more serious pollutant in high population density locations than it is in sparsely populated areas. In this way lighting is an inevitable benefit and cost of the urbanization aspect of the industrialization process.

Over-illumination is another type of light pollution. It is the most inefficient in terms of energy consumption. Assuming the price per barrel of oil is \$50, the inefficiency cost of over-illumination at present would be \$36.5 billion per annum (Kyba, *et al.,* 2014). Like for skyglow pollution, the negative and positive externallities of over-illumination appear to be invariant with respect to the level of development (Luginbuhl, 2014; Aube, *et al.,* 2013, Bortle, 2001), and contrast sharply to light clutter, which due to technological change, afflicts developing countries more than developed countries as evidenced by wildlife disturbances and road accidents. So, to make an accurate statement from growth "measured from outer space," welfare gains/losses must be adjusted for $\dot{x}$. This further means nighttime lights are indicators of well (bad)-being as well as arguments in both production and consumption.

If so, we must make explicit the utility (consumption) and profit (production) functions underlying measured growth to allow for a precise statement on the welfare implications of $\dot{y}$ and/or $\dot{y}^*$. From both HSW's Equation 1-3, and our descriptions in (1) and (5), welfare is an expectation in that a country's homogenous households seek to maximize their utility from consuming goods and services, including nighttime lights, i.e., $U(y^*(y), X^*)$. The country's producers' objective is to maximize profit/surplus using a production technology in which artificial nighttimes are both an input and output, i.e., $y = f(X^*, 1 - X^*)$, where $1 - X^*$ are conventional factors and forces of production like labor (L), human capital (H), physical capital (K), and other proximate as well as deep determinants of production (A). In other words, $y = f(X^*, L, H, K, A) + e$. Following Bilancini & D'Alessandro's (2011) work on the implications of externalities for growth and "degrowth," the marginal utility (μ) of $y^*(y)$ and of X^*, respectively, would be:

$$\mu(y^* y)) = \partial U(y^*(y))/\partial y^*(y) > 0;$$
$$\mu(X^*) = \partial U(y^*(y))/\partial X^* = 0, \text{ if } X^* \text{ is no externality;}$$
$$\mu(X^*) = \partial U(y^*(y))/\partial X^* > 0, \text{ if } X^* \text{ is a positive externality;}$$
$$\mu(X^*) = \partial U(y^*(y))/\partial X^* < 0, \text{ if } X^* \text{ is a negative externality.} \quad (6)$$

In (6), as in Bilanchini and D'Alessandro, X^* is a socializable good ("relational good", Equation 4, p. 6) in that the flow of services from it are a combination of social capital (S) and $\dot{x}$ in (3) or accurately in (4) above, so that in level terms from (5)

$$X^* = S^a \dot{x}^b, \; a + b = 1. \quad (7)$$

Eq. (7) is not a brand new idea, it is the same idea Romer (2009) has in mind when he tells the story of students in a West African country who go to study at airports and other places where nighttime lights are reliable, where, once turned on, X^* is a common resource with an externality. Over time, the country's welfare is a solution to the following general maximization problem:

$$W = \int_0^\infty [U(.) + \left(\lambda(f(.))\right) e^{-\rho t}, \quad (8)$$

where W stands for well-being (social welfare) and ρ is the social discount rate.

The specific form of U(.) can be Cobb-Douglas, CES, Klein-Rubin, Store-Geary etc. Similarly f(.) can take many forms such as Cobb-Douglas in Solow-Swan, or newer versions like Romer (1986; 1990), Lucas (2009; 1993; 1988), Tamura (1991), and subsequent variants, extensions, and modifications so well described by Klenow & Rodrigues-Clare (2005), and Amavilah (2014a; 2014b). Here, following Amavilah (2016) the problem in (8) above is about

$$W = max \int_0^{\infty} [(U(y^*(y(X^*)),X^*))) + \lambda(Py^*(y(X^*)) - Cy^*(y(X^*)))e^{pt}\, dt$$
$$= \max \int_0^{\infty} E(U^*) + \lambda(E(\Pi^*))), \qquad (9)$$

where $E(U^*) = f(y^*, y, X^*)$ is the expected discounted social utility, and $E(\Pi^*) = f(P, y^*, y, X^*)$ is the expected discounted social profit/surplus, meaning real social welfare is social utility (consumer surplus) plus social profit (producer surplus). In terms of Hamiltonian dynamics (9) amounts to

$$H = E(U^*) + \lambda\, [E(\Pi^*) - E(\Omega^*)] = E(U^*) + \lambda E(\Pi^{**}), \qquad (10)$$

where $\Pi^{**} = \Pi^* - \Omega^* = \theta gX^* - \theta\, y^*(y(X^*))$, and $\theta gX^* - \theta y^*\, (y(X^*)) = dX^*/dt$, which is the growth in the external effects of nighttime lights relative to darkness as (5) suggests.

The adjustment to (9) or (10) is consistent with Jones & Klenow's (2016) finding that welfare goes "beyond GDP across countries and time", no matter whether GDP is measured in conventional ways, augmented and or proxied by quantitative indicators likes nighttime lights viewed from outer space. Jones & Klenow's Equation 19 (p. 2433) in which the "consumption equivalent of welfare" depends on life-expectancy, leisure, and inequality is particularly clarifying. It is in the spirit of Sen by which welfare is a function of inequality adjusted HDI, and hence the four key points made. However, from our perspective the Jones-Klenow model still overstates welfare in developed countries and understates it in developing countries. An understatement of this kind may be responsible for missing the welfare gains of "the African growth miracle" Young (2012) has observed.

4. Concluding remark

We can examine the necessary and sufficient conditions under which (8)-(10) obtain. However, one obvious observation there is that H or W increases if $\Pi^{**} > 0$, which can be iff $\Pi^* > \Omega^* \Rightarrow \theta gX^* > \theta y^*(y(X^*))$. Thus, while nighttime lights clearly indicate socio-economic activity, and hence complement GDP, they make a weak and unclear statement on the well-being of nations as their effects may be welfare enhancing, reducing, or both. Currently, it would seem that, X^* is a pollutant mainly in the "developed" economies. The negative external effects of nighttime lights should reduce the measured welfare in those countries. In developing economies nighttime lights are still positive externalities and enhance welfare even where measured GDP growth is lower than it is in developed economies. In terms of standard short-run production, economies experiencing little light pollution (mostly developing countries) are in sections of their production functions where the marginal products of (returns to) nighttime lights are still increasing; whereas highlighly light-polluted economies are already facing the law of diminishing returns. Thus, the lights we see from outer space directly measure the existence, scale, extent, and intensity of socio-economic activities. They are a poor measure of H or W, which, I have argued, is measured correctly by adjusting measured GDP growth for the external effects of X^*. In other words, appropriately adjusted for externalities it is possible, perhaps even probable, for a country to experience high economic growth without high welfare, and high welfare without high economic growth.

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