

# Inclusive Wealth Report 2018

## Methodological Annex: Frontier Approach

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## 1. Overall framework

In our conceptual framework, we are interested in the change of intertemporal well-being at  $t$ :

$$V(t) = \int_t^{\infty} U(C_{\tau})e^{-\delta(\tau-t)}d\tau.$$

Assuming equivalence between wealth and well-being, this is measured by wealth in practice. Denoting produced, human, and natural capital as  $K$ ,  $H$ , and  $N$ , the change in inclusive wealth  $W$  is expressed by:

$$\frac{dW(K, H, N, t)}{dt} = p_K \frac{dK}{dt} + p_H \frac{dH}{dt} + p_N \frac{dN}{dt} + \frac{\partial V}{\partial t},$$

where  $p_K$ ,  $p_H$  and  $p_N$  are the marginal shadow prices of produced, human, and natural capital, respectively. They are formally defined by,

$$p_K \equiv \frac{\partial V}{\partial K}, p_H \equiv \frac{\partial V}{\partial H}, p_N \equiv \frac{\partial V}{\partial N},$$

given a forecast of how produced, human, and natural capitals, as well as other flow variables, evolve in the future in the economy in question. Practically, shadow prices act as a weight factor attached to each capital, resulting in the measure of wealth, or IWI:

$$IWI = p_K K + p_H H + p_N N.$$

In practice, we can use  $W$  and IWI interchangeably, although they can differ in that IWI also uses shadow prices on the margin. In addition, the unit of IWI is dollar (monetary) terms, rather than utility units. Of course, this does not affect sustainability assessment.

Another aspect worth exploring is the effect of human population dynamics. Aside from the simple Malthusian effect (Arrow et al. 2004; Ferreira et al. 2008), wealth per capita may not represent well-being divided by the current population (Arrow et al. 2003). Moreover, as expounded in Arrow et al. (2012), even if we employ well-being divided by future population, i.e., adopting dynamic average utilitarianism, inclusive wealth per capita is shown to be in line with social well-being, under simple assumptions. When these assumptions do not hold, sustainability assessment may change (Yamaguchi 2017).

## 2. Produced capital

Produced capital, also referred to as manufactured or reproducible capital, includes physical infrastructure, land, property, and facilities of private firms, houses, etc. Upon calculation, we follow the method originated by Harberger (1978) and applied by King and Levine (1994) and Feenstra et al. (2013). In particular, we employ the perpetual inventory method (PIM), which is a simple summation of gross investment net of depreciation that occurs in each period. One cannot keep track of investment and depreciation indefinitely into the past, so should start from somewhere. This is called a benchmark year  $t = 0$ , in which the initial capital stock  $K(0)$  is set. Formally, produced capital stock at  $t$  is:

$$K(t) = K(0)(1 - \delta)^t + \sum_{\tau=1}^t I(\tau)(1 - \delta)^{t-\tau},$$

where  $I(t)$  and  $\delta$  stand for investment at  $t$  and depreciation rate. In our computation, the initial capital stock  $K(0)$  is estimated by assuming a steady state of capital-output ratio. That is, if we assume  $0 = \frac{d}{dt} \left( \frac{K}{y} \right) = (I - \delta K)/K - \gamma$  where  $\gamma$  is the economic growth rate, the steady state capital stock would be  $K^{ss} = \frac{I}{\delta + \gamma}$ .

Finally, it is worth noting that the shadow price of produced capital is unity, since national statisticians measure investment in produced capital in dollar terms, which is the unit of inclusive wealth. The dataset we employ is summarised in Table 1.

Table 1: Data sources and assumptions for the calculation of produced capital

Variables	Data sources / assumptions
Investment, $I$	United Nations Statistics Division (2013)
Output, $y$	United Nations Statistics Division (2013)
Depreciation rate, $\delta$	4% (as taking the country average from Feenstra et al. (2013))
Capital lifetime	Indefinite

## 3. Human capital

As we mentioned in the main text of Chapter 1, we employ two approaches to human capital, and report them separately. However, both approaches have in common the education-induced human capital, so we start from there.

### 3.1 Education

Education pays off later in life in the form of increased lifetime income and well-being, both at personal and aggregate levels. In line with the literature on human capital, and for practical reasons, we focus on the return on formal education, but this does not mean that other, non-formal types of education (e.g., early childhood education, vocational training) is not an important contributor to wealth as well. We estimate the value of human capital on the output of education production function. This is generally called the income approach to human capital computation. In contrast, some other estimates use the input side of education production function, typically by educational expenditure (World Bank 2014). For a more detailed excellent review of human capital in general and a detailed account of this, see Chapters 3-4 of IWR 2014.

We estimate the value of human capital based on the idea that educational attainment yield returns to human capital. Following Arrow et al. (2012) and Klenow and Rodriguez-Clare (1997), educational attainment is proxied by the average years of total schooling per person,  $A$ , which is obtained from Barro and Lee (2015). The rate of return on education is assumed to be constant at  $\rho = 8.5\%$ . This is multiplied by the population who has had education,  $P_{5+edu}$ . Thus, the stock of human capital is:

$$H = e^{\rho A} * P_{5+edu}$$

The shadow price of one unit of human capital is calculated using the present value of lifetime income, which is proxied by the average compensation to employees,  $w$ , per unit of human capital, multiplied by the expected number of working years,  $T$ . This brings us to the formula:

$$p_H(t) = \int_0^{T(t)} w(\tau) e^{-\delta\tau} d\tau$$

The dataset we employ is summarised in Table 2.

Table 2: Data sources and assumptions for the calculation of human capital

Variables	Data sources / assumptions
Educational attainment, $A$	Barro and Lee (2015)
Population $P$ by age, gender, time	United Nations Population Division (2016)
Interest rate, $\rho$	8.5% (Klenow and Rodríguez-Clare 1997)
Discount rate, $\rho$	8.5%
Employment	International Labour Organization (2015); Conference Board (2016)
Compensation of Employees	United Nations Statistics Division (2016); OECD (2016); Feenstra et al. (2013); Lenzen et al. (2013); Conference Board (2016)

### 3.2 Health

The state of health affects human well-being via at least three channels: by directly contributing to well-being, raising productivity, and extending life years (UNU-IHDP and UNEP 2014). We have computed the latter third value of health capital, largely because it is still challenging to account for the first and second contributions.

Health capital of an individual of age  $a$  is defined by:

$$H(a) = \sum_{t=a}^{100} f(t|t \geq a)V(a, t),$$

Where conditional density of age of death given survival to age  $a$  is:

$$f(t|t \geq a) = \frac{f(t)}{[1 - F(a)]},$$

and

$$V(a, t) = \sum_{u=0}^{t-a} (1 - \delta)^u$$

is the discount factor. Total health capital of a country is:

$$H = \sum_{a=0}^{100} H(a)P(a),$$

where  $P(a)$  is the population of age  $a$ .

The shadow price of health capital is simply the value of statistical life year (VSLY). For more detailed illustration, see Arrow et al. (2012; 2013) and UNU-IHDP and UNEP (2014).

### 3.3 Shadow price of human and health capital

Within the frontier approach of calculation, we determine shadow prices of education- and health-induced human capital by employing a non-parametric method. We outline this method in this subsection. Previous measurement of that portion of longevity of health capital is based on the assumption that marginal willingness to pay to reduce the risk of death is common for all the age groups. Alternatively, we use non-parametric estimation of shadow prices with inputs being capital assets.

In particular, we assume a production possibility set,  $P$ , with input vector (produced, human, health, and natural capital),  $x$ , output (GDP),  $y$ , and a directional vector  $g = g_y$  with  $g \in \mathfrak{R}^M$ . Formally,

$$P(x) = \{(x, y): x \text{ can produce } y\}$$

$$D(x, y; g) = \max_{\beta} \{\beta: y + \beta g_y \in P(x)\}$$

$D$  is called the distance function, which maximises the output, controlling the coefficient,  $\beta$ . By solving the revenue-maximising problem and parametrising DDF, the shadow price of human and health capital can be derived. For details, see Fare et al. (2005) and Tamaki et al. (2017).

## 4. Natural capital

For natural capital, the current edition of IWR accounts for non-renewable resources (fossil fuel and mineral) and renewable resources (agricultural land, forest, and fishery). We illustrate how we account for the five classes in turn.

### 4.1 Fossil fuels

Our account scope for fossil fuels includes coal, natural gas, and oil. For a given resource, we start from the current stock, and then trace back past stocks by using each year production. In this way, we can construct a consistent time-series dataset that reflects more recent and accurate flow (extraction) variables. In other words, the corresponding stock under study in year  $t - 1$ ,  $S(t - 1)$ , is derived from the production,  $P(t)$ , and the stock in year  $t$ ,  $S(t)$ , by:

$$S(t - 1) = S(t) + P(t).$$

The unit shadow price of a non-renewable resource,  $p_S$ , is the price net of extraction cost, which is sometimes called rental price. Ideally, the marginal cost of extraction should be used for corresponding remaining stock, but it is notoriously hard to obtain. We instead assume that the rental rate of the total price is constant, which is obtained from Narayanan et.al. (2012).

Table 3: Data sources and assumptions for the calculation of fossil fuels

<b>Variables</b>	<b>Data sources / assumptions</b>
<i>S</i> : reserve	U.S. Energy Information Administration (2015)
<i>P</i> : Extraction	U.S. Energy Information Administration (2015)
Prices	BP (2015) <ul style="list-style-type: none"> <li>• Coal: averaged prices from U.S, northwestern Europe, Japan coking, and Japan steam</li> <li>• Natural gas: averaged prices from EU, UK, US, Japan, and Canada</li> <li>• Oil: averaged prices of Dubai, Brent, Nigerian Forcados, and West Texas Intermediate</li> <li>• adjusted for inflation before averaging over time using the U.S. GDP deflator</li> </ul>
Rental rates	Narayanan et al. (2012)

## 4.2 Metals and minerals

The methodology for accounting for minerals is similar to that used for fossil fuels, the other form of non-renewable resources. For rental rates, we retrieved sectoral rental rates of different mineral industries from Narayanan (2012). For other data of reserves, extraction, and prices are obtained from U.S. Geological Survey (2015), which is the most authorised dataset on the subject. The dataset we employ is summarised in Table 4.

Table 4: Data sources and assumptions for the calculation of metal and mineral resources

Variables	Data sources / assumptions
<i>S</i> : reserve	U.S. Geological Survey (2015)
<i>P</i> : Extraction	U.S. Geological Survey (2015)
Prices	U.S. Geological Survey (2015)
Rental rates	Narayanan et al. (2012)

### 4.3 Agricultural land

Agricultural land refers to cropland and pastureland. The methodology for accounting for these two classes is much the same. For the quantity of this natural capital, permanent cropland/pastureland area data from Food and Agricultural Organization (FAO 2015a) is employed.

To quantify the marginal shadow price of a unit of agricultural land, we cannot use the market price as in the case of non-renewable resources, since there does not usually exist a market for agricultural land. Instead, we compute the shadow price as the net present value of the annual flow of services per hectare that the parcel yields, in line with World Bank (2011) and past editions of IWR. More specifically, rental price per hectare of cropland for country  $i$  in year  $t$  can be expressed as:

$$RPA_{it} = \left(\frac{1}{A}\right) \sum_{k=1}^N R_{ik} P_{itk} Q_{itk}$$

where  $A$ ,  $R$ ,  $P$  and  $Q$  are the harvested area in crops, rental rate, crop price, and crop quantity produced, respectively.  $N$  stands for the number of crops, which may be as many as 159 ( $k = 1, \dots, 159$ ) in the current study.  $t$  is the year of analysis, from 1990 to 2014. For the estimation of the rental rate by crop group, we mapped FAO crop classification (HS) with those sectoral rental rates provided by Narayanan et al. (2012).

Note that the above rental price corresponds to an annual flow of services; we need to capitalise it to be employed as the shadow price. Formally, the NPV of this rental price for country  $i$  in year  $t$  is written as:

$$p_{Ait} = \sum_{\tau=0}^{\infty} \frac{RPA_{it}}{(1+r)^{\tau}} = \frac{1+r}{r} RPA_{it}$$

where  $r$  is the discount rate, set at 5% per annum. Finally, to avoid unnecessary volatility in the social value of natural capital, we take the year average of this price for country  $i$ :

$$\bar{p}_{Ai} = \frac{1}{25} \sum_{t=1990}^{2014} p_{Ait}$$

which is used as the shadow price of cropland.

The calculation of pastureland wealth differs from that of cropland in that it is difficult to link rents to a particular amount of land involved in the production process. Thus, we opted to assume the shadow price of pastureland to be equal to cropland, and this is acknowledged to be a limitation of the current accounting. The dataset we employ is summarised in Table 5.

Table 5: Data sources and assumptions for the calculation of agricultural land

<b>Variables</b>	<b>Data sources / assumptions</b>
Quantity of crops produced, $Q$	FAO (2015a)
Price of crops produced, $P$	FAO (2015a)
Rental Rate, $R$	Narayanan et. al. (2012)
Harvested area in crops, $A$	FAO (2015a)
Discount rate, $r$	5%
Permanent cropland/pastureland area	FAO (2015a)

#### 4.4 Forest

In the current forest accounting, we follow IWR 2014 methodology. The forest wealth comprises timber value and non-timber forest benefits (NTFB).

##### *Timber*

We estimate the volume of timber resources commercially available. For the quantity of this specific capital, the total forest area, excluding cultivated forest, is multiplied by timber density per area, and percentage of total volume that is commercially available. The exclusion of cultivated forest could be debatable, as it is regarded as contributing to timber and non-timber values. It is due to the fact that the activity of cultivating forest is categorised as a production activity in the System of National Accounts. In line with this reasoning, we have registered cultivated forest under produced capital in IWR 2014 and 2018.

For the computation of shadow prices, there are several steps involved, following IWR 2014. First, we followed the World Bank's (2006) method of adopting a weighted average price of two different commodities: industrial round wood and fuelwood, which are also country-

specific parameters. The weight attached to the different prices is based on the quantity of the commodity manufactured, while industrial round wood and fuelwood prices are obtained from the value and quantity exported and produced, respectively. Second, we converted the annual estimated values from current to constant prices by using each country-specific gross domestic product (GDP) deflator. Third, we used information on the regional rental rates for timber estimated by Bolt et al. (2002). Such rates are assumed to be constant over time. Fourth, we estimated the average price over the entire study period (1990 to 2014), thereby obtaining our proxy value for the shadow price of timber.

Finally, in the same manner as other resources, wealth corresponding to timber value is calculated as the product of quantity, price, and average rental rate over time.

Table 6: Data sources and assumptions for the calculation of forest resources

<b>Variables</b>	<b>Data sources / assumptions</b>
Forest stocks	FAO (2015b; 2010; 2006; 2001; 1995)
Forest stock commercially available	FAO (2006)
Wood production	FAO (2015b)
Value of wood production	FAO (2015b)
Rental rate, $R$	Bolt et al. (2002)

#### *Non-timber forest benefits (NTFB)*

Aside from provisioning services in the form of timber production, forest capital yields many ecosystem services. Following IWR 2014, we have accounted for this non-timber forest benefits in the following manner.

First, total forest area in the country under analysis excluding cultivated forest is retrieved from FAO (2015b), which we denote  $Q$  (ha). Second, the fraction of the total forest area which is accessed by individuals to obtain benefits is assumed to be  $\gamma$ . The ecological literature has stressed that only the portion of the forest that contributes to well-being should be accounted for. For want of better assumptions, we assume  $\gamma$  to be 10%, following World Bank (2006).

Third, the unit benefit of non-timber forest to intertemporal social well-being is obtained from the Ecosystem Service Valuation Database (ESVD) database of van der Ploeg and de Groot (2010). We denote this by  $P$  (USD/ha/year). The average value per hectare should be different for temperate and boreal, and tropical forest, as shown in Table 7. Accordingly, we weighted the corresponding values by the share of each forest type in the total forest of the country. Fourth, to translate this benefit into capital asset value, we take its net present value, using the discount rate of  $r=5\%$ .

In short, the value of NTFB forest wealth is calculated as:

$$\sum_{t=0}^{\infty} \frac{PQ_t \gamma}{(1+r)^{t-t}} = \frac{1+r}{r} PQ \gamma.$$

Table 7: Accounting of non-timber forest benefits

Select service	Temperate and boreal Forests (USD/yr/ha)	Tropical forest (USD/yr/ha)
<b>Provisioning services</b>		
1 food	23	107
2 water	146	137
3 genetic	2	451
4 medical		475
5 raw materials		
6 ornamental		
<b>Regulating services</b>		
7 air quality	868	223
8 climate		
9 extreme events	0	33
10 water flows	2	14
11 waste	40	343
12 erosion	1	342
13 soil fertility	37	129
14 pollination	418	54
15 bio control	20	13
<b>Habitat services</b>		
16 nursery		17
17 genepool	506	396
<b>Cultural services</b>		
18 aesthetic		
19 recreation	27	257
20 inspiration	0	
21 spiritual		
22 cognitive	0	
<b>Total</b>	<b>2,091</b>	<b>2,990</b>

Source: van der Ploeg and de Groot (2010).

## 5. Fisheries

This edition of the Inclusive Wealth Report is the first to estimate fish capital stock as part of renewable natural capital. Estimating the fish stock is a herculean task, compared to other classes of natural capital, for various reasons. They cannot be estimated based on the habitat area, unlike the case of forest or agricultural land, which can be computed based on area. Moreover, the sheer mobility of the resource not only makes the exercise harder, but also poses a fundamental question: what area can a given fishery be attributed, given that a marine fishery habitat is usually not contained within national borders? In the current exercise, we simplify the matter by assuming that the fish stock belongs to a country where harvest arises and the resource is loaded. Of course, this is a crude treatment in many ways. In particular, just because a fishery biomass is loaded to country A, does not necessarily mean that the fishery belongs to A. Having acknowledged this shortcoming, we have no alternative sound theory to allocate harvest to countries.

In renewable resource economics, and bio-economics in general, there is a long tradition of assuming resource dynamics. The stock is the population growth net of harvest:

$$\frac{dS_t}{dt} = G(S_t) - H_t,$$

where  $S_t$  denotes the renewable resource biomass stock;  $G(S_t)$  is the growth function;  $H_t$  is the harvest. Population, whether it is renewable resource or human being, is often assumed to follow a logistic growth function:

$$G(S_t) = rS_t \left(1 - \frac{S_t}{k}\right),$$

where  $r$  and  $k$  are the parameters which represent intrinsic (relative) growth rate and carrying capacity of the resource stock, respectively. Harvest, in turn, depends on the resource abundance. A simple but empirically supported harvest production function is to assume it is proportional to the product of effort and stock, i.e.,

$$H_t = qE_tS_t,$$

where  $q$  is called catchability coefficient.  $E_t$  stands for effort put in the production process, which is often proxied by the number of vessels or fishermen working hours. Combining these two equations, we obtain a familiar Gordon-Schaeffer model:

$$\frac{dS_t}{dt} = rS_t \left(1 - \frac{S_t}{k}\right) - qE_t S_t.$$

This means that to estimate the fishery stock,  $S_t$ , we can resort either to harvest function, (1), or total resource dynamics, (2). World's fish stocks are commonly assessed by examining the trend in catch or harvest data. Although this catch-based assessment method has attracted a lot of criticism (see for instance Daan et al. (2011)), either due to its technical and conceptual flaws, it is currently still considered as the most reliable method for assessing fish stock (Froese et al., 2012; Kleisner et al., 2013). This is mainly because the only data available for most fisheries are the weight of fish caught each year (Pauly et al., 2013). If effort and harvest are known data, as well as catchability coefficient  $q$ , then  $S_t$  can be estimated solely from the Schaefer production function (Yamaguchi et al. 2016).

However, effort data are sparse worldwide, so we cannot employ this method for inclusive wealth accounting all over the globe. Alternatively, we use the resource dynamics; however, there is no reliable data on  $r$  and  $k$  for most fish stocks. Given this constraint, we followed Martell and Froese (2013) who developed an algorithm to randomly generate feasible  $(r, k)$  pairs from a uniform distribution function. The likelihood of the generated  $(r, k)$  pairs are further evaluated by using Bernoulli distribution to ensure that the estimated stock meets the following assumptions: it has never collapsed or exceeded the carrying capacity, and that the final stock lies within the assumed range of depletion.

In a case where the values of  $(r, k)$  are not obtainable, the stocks are simply estimated according to the following rules:

- If the year under study is after the year of maximum catch, then the biomass stock is estimated as twice the catch;
- Otherwise, the biomass stock is estimated as twice maximum catch, net of catch (2 x Maximum Catch – Catch).

Time series data of catch (tonnage and value) of each country's economic exclusive zone (EEZ) for the period of 1950 – 2010 are obtained from Sea Around Us Project (SAUP 2016). We only evaluate the stock that has a catch record for at least 20 years and which has a total catch in a given area of at least 1000 tonnes over the time span.

## 6. Adjustments

As we outlined in Chapter 1, we treated three adjustments that are not covered by familiar capital assets that nevertheless contribute to social well-being change: carbon damage, oil capital gain, and total factor productivity. We basically follow IWR 2014 methodology for these

adjustments.

## **6.1 Carbon damage**

Following Arrow et al. (2012), we can view carbon damage as a mostly exogenous change in social well-being, as these damages do not directly correspond to each country's carbon emissions. As in IWR 2014, the key methodological steps can be described as follows:

- (1) Obtain the total global carbon emissions for the period under analysis, 1990 to 2014;
- (2) Derive the total global damages as a function of the emissions; and,
- (3) Assign the global damages to the countries according to the potential effect of global warming in their economies.

Global carbon emissions: Two sources of carbon emissions were accounted for: (i) carbon emissions stemming from fuel consumption and cement, which were obtained from the Carbon Dioxide Information Analysis Center (Boden et al. 2011); and (ii) emissions resulting from global deforestation. In this case, we used FAO (2013) data on the changes in annual global forest land. It is further estimated that the average carbon release per hectare is equal to 100 tonnes of carbon (Lampietti and Dixon 1995).

Global carbon damages: The damage per tonne of carbon released to the atmosphere is estimated at US\$50 (see Tol 2009). By multiplying the total amount of global tons of carbon released to the atmosphere by the price per tonne, we obtain the total global carbon damages. Note that this parameter is constant over time.

Assigning carbon damages to countries: To calculate the distribution of the damages that each region suffers, we referred to the study of Nordhaus and Boyer (2000). This study presents the distribution of damages which different regions and the global economy as a whole will suffer as a percentage of the corresponding regional and global GDP. By using country and global GDP information, we were able to re-estimate regional percentage damages in terms of the total global GDP – and not related to the country GDP – as initially presented in Nordhaus and Boyer (2000). Finally, we apportioned the global damages estimated in previous steps two according to this latter percentage.

## **6.2 Oil capital gain and loss**

If the price of oil increases, oil-rich nations enjoy wealth increase. This is not a gain in quantity of natural capital, but so long as countries can tap into this windfall to improve social well-being, this should be accounted for in wealth accounting. An annual increase of 3% in the

rental price of oil is assumed, which corresponds to the annual average oil price increase during 1990-2014 (BP 2015). Conversely, importing-countries may have fewer investment opportunities due to higher oil prices, so oil capital losses are distributed to oil-importing countries.

### 6.3 Total factor productivity

Total factor productivity of a nation is a source of resource that can be accessed even though they are tangible. We take different methods in computing TFP: for frontier analysis, we used a non-parametric analysis called Malmquist productivity index, which in turn is based on the concept of data envelopment analysis. For IWR 2014 methods, we directly use the TFP data calculated conventionally by Conference Board (2017), in line with Arrow et al. (2012) and IWR 2012.

For frontier analysis, let

- $x_t$ : Inputs (produced, human, and natural capital)
- $y_t$ : Outputs (GDP)
- Distance function:  $d(x_t, y_t) = \max\{\delta; (x_t, y_t | \delta) \in T(t)\}$
- Malmquist Productivity Index  $M(Y_{it}, K_{it}, H_{it}, N_{it}, Y_{it+1}, K_{it+1}, H_{it+1}, N_{it+1})$

$$= \left[ \frac{d^t(Y_{it+1}, K_{it+1}, H_{it+1}, N_{it+1})}{d^t(Y_{it}, K_{it}, H_{it}, N_{it})} \times \frac{d^{t+1}(Y_{it+1}, K_{it+1}, H_{it+1}, N_{it+1})}{d^{t+1}(Y_{it}, K_{it}, H_{it}, N_{it})} \right]^{\frac{1}{2}}$$

where  $d$  is the geometric distance to the production frontier caused by production inefficiency, while the frontier denotes the best available technology from the given inputs and outputs.  $i$  refers to the country under analysis, running  $i$  from 1 up to 140 nations in our sample;  $Y$  is the corresponding value of gross domestic product;  $K, H$  and  $N$  stand for produced, human, and natural capital inputs.

## References

- Arrow, K.J., P. Dasgupta, L.H. Goulder, K.J. Mumford, and K. Oleson (2013), 'Sustainability and the Measurement of Wealth: Further Reflections,' *Environment and Development Economics*, **18**(4): 504–516.
- Arrow, K. J., Dasgupta, P., Goulder, L. H., Mumford, K. J., & Oleson, K. (2012). Sustainability and the measurement of wealth. *Environment and Development Economics*, **17**(3), 317-353.
- Arrow, K., Dasgupta, P., Goulder, L., Daily, G., Ehrlich, P., Heal, G., ... & Walker, B. (2004). Are we consuming too much? *The Journal of Economic Perspectives*, **18**(3): 147-172.
- Arrow, K. J., Dasgupta, P., & Mäler, K. G. (2003). The genuine savings criterion and the value of population. *Economic theory*, **21**(2): 217-225.
- Barro, R. & Lee, J. W. (2015). *Education Matters: Global Schooling Gains from the 19th to the 21st Century*. New York, NY: Oxford University Press.
- Boden, T.A., Marland, G., Andres, R.J. (2011). 'Global, regional, and national fossil fuel CO2 emissions.' *Carbon Dioxide Information Analysis Center*. 36335–37831.
- Bolt, K., Matete, M., & Clemens, M. (2002). Manual for calculating adjusted net savings. Environment Department, World Bank, 1-23.
- BP. (2015). *Statistical Review of World Energy 2015*. Retrieved from [http://www.bp.com/Statistical review](http://www.bp.com/Statistical%20review).
- Conference Board. (2016). *Total Economy Database™ (Adjusted version)*.
- Conference Board. (2017). *Total Economy Database™ (Adjusted version)*.
- Daan, N., Gislason, H., Pope, J. G., & Rice, J. C. (2011). 'Apocalypse in world fisheries? The reports of their death are greatly exaggerated.' *ICES Journal of Marine Science*, **68**(7): 1375-1378.
- Färe, R., Grosskopf, S., Noh, D. W., & Weber, W. (2005). Characteristics of a polluting technology: theory and practice. *Journal of Econometrics*, **126**(2): 469-492.
- Feenstra, R., Inklaar, R. & Timmer, M. (2013). *The Next Generation of the Penn World Table*. Retrieved from [www.ggdc.net/pwt](http://www.ggdc.net/pwt)
- Ferreira, S., Hamilton, K., & Vincent, J. R. (2008). Comprehensive wealth and future consumption: accounting for population growth. *The World Bank Economic Review*, **22**(2), 233-248.
- Food and Agriculture Organization of the United Nations (FAO). (2015a). FAOSTAT. Retrieved from <http://faostat3.fao.org/download/Q/QC/E>.
- Food and Agriculture Organization of the United Nations (FAO). (2015b). Global forest resources assessment 2015 – Retrieved <http://www.fao.org/forest-resources-assessment/explore-data/en/>.
- Food and Agriculture Organization of the United Nations (FAO) (2013). *FAO Statistical Yearbook 2013*. Rome.
- Food and Agriculture Organization of the United Nations (FAO). (2010). *Global Forest Resources Assessment 2010 – Main Report*. FAO Forestry Paper. FAO Forestry Paper 163. Rome
- Food and Agriculture Organization of the United Nations (FAO). (2006). *Global Forest Resources Assessment 2005 – Progress towards sustainable forest management*. FAO Forestry Paper 147. Rome
- Food and Agriculture Organization of the United Nations (FAO). (2001). *Global Forest Resources Assessment 2000 – Main Report*. FAO Forestry Paper 140. Rome

- Food and Agriculture Organization of the United Nations (FAO). (1995). *Forest Resources Assessment 1990 – Global synthesis*. FAO Forestry Paper No. 124. Rome.
- Froese, R., Demirel, N., Coro, G., Kleisner, K. M., & Winker, H. (2017). 'Estimating fisheries reference points from catch and resilience.' *Fish and Fisheries*, **18**(3): 506-526.
- Froese, R., Zeller, D., Kleisner, K., & Pauly, D. (2012). 'What catch data can tell us about the status of global fisheries.' *Marine Biology*, **159**(6): 1283-1292.
- Harberger, A. (1978). 'Perspectives on Capital and Technology in Less Developed Countries.' In M. Artis & A. Nobay (Eds.). *Contemporary Economic Analysis*, Croom Helm: London.
- International Labor Organization. (2015). *Key Indicators of the Labour Market (KILM) database*. Retrieved from [www.ilo.org](http://www.ilo.org)
- King, R.G. & Levine, R. (1994). 'Capital fundamentalism, economic development and economic growth.' *Carnegie-Rochester Conference Series on Public Policy*, **40**, 259-292.
- Klenow, P. & Rodríguez-Clare, A. (1997). The Neoclassical Revival in Growth Economics: Has It Gone Too Far? In B. Bernanke & J. Rotemberg (Eds.). *NBER Macroeconomics Annual 1997*. Cambridge, MA: MIT Press, 73-102.
- Kleisner, K., Zeller, D., Froese, R., & Pauly, D. (2013). 'Using global catch data for inferences on the world's marine fisheries.' *Fish and Fisheries*, **14**(3): 293-311.
- Lampietti, J. & Dixon, J. (1995). *To see the forest for the trees: A guide to non-timber forest benefits*. Washington, DC: World Bank.
- Lenzen, M., Moran, D., Kanemoto, K., & Geschke, A. (2013). 'Building Eora: a global multi-region input-output database at high country and sector resolution.' *Economic Systems Research*, **25**(1): 20-49.
- Martell, S., & Froese, R. (2013). 'A simple method for estimating MSY from catch and resilience.' *Fish and Fisheries*, **14**(4):504-514.
- Montenegro, C. E. & Patrinos, H. A. (2014). *Comparable Estimates of Returns to Schooling Around the World*. (No. WPS7020). The World Bank Policy Research Working Paper
- Narayanan, B., Aguiar, A. & McDougall, R. (2012). *Global Trade, Assistance, and Production: The GTAP 8 Data Base*. Center for Global Trade Analysis, Purdue University. Retrieved from [http://www.gtap.agecon.purdue.edu/databases/v8/v8\\_doco.asp](http://www.gtap.agecon.purdue.edu/databases/v8/v8_doco.asp).
- Nordhaus, W.D. & Boyer, J. (2000). *Warming the world: economic models of global warming*. MIT press.
- OECD. (2016). *OECD National Accounts*. Retrieved from <http://stats.oecd.org/>
- Pauly, D., Hilborn, R., & Branch, T. A. (2013). 'Fisheries: does catch reflect abundance?' *Nature*, **494**(7437): 303-306.
- SAUP (2016). [www.seaaroundus.org](http://www.seaaroundus.org)
- Tamaki, T., Shin, K. J., Nakamura, H., Fujii, H., & Managi, S. (2017). 'Shadow prices and production inefficiency of mineral resources.' *Economic Analysis and Policy*, DOI: <http://dx.doi.org/10.1016/j.eap.2017.03.005>
- Tol, R.J. (2009). 'The economic effects of climate change.' *Journal of Economic Perspectives*, **23**: 29–51.
- United Nations Population Division (2016). *World Population Prospects: The 2017 Revision*. Retrieved from <https://www.un.org/development/desa/publications/world-population-prospects-the-2017-revision.html>
- United Nations Statistics Division. (2013). *Nationals Accounts Main Aggregates Database*. Retrieved from <http://unstats.un.org/unsd/snaama/Introduction.asp>

- UNU-IHDP, & UNEP. (2012). *Inclusive Wealth Report 2012: Measuring Progress toward Sustainability*. Cambridge: Cambridge University Press.
- UNU-IHDP, & UNEP. (2014). *Inclusive Wealth Report 2014: Measuring Progress toward Sustainability*. Cambridge: Cambridge University Press.
- U.S. Energy Information Administration (2015). International energy statistics. Retrieved from <http://www.eia.gov/countries/data.cfm>.
- U.S. Geological Survey. (2015). Mineral commodity summaries. Retrieved from <http://minerals.usgs.gov/minerals/pubs/mcs/>.
- Van der Ploeg, S. and R.S. de Groot (2010) The TEEB Valuation Database – a searchable database of 1310 estimates of monetary values of ecosystem services. Foundation for Sustainable Development, Wageningen, the Netherlands.
- World Bank. (2006). *Where is the wealth of nations?* Washington, DC: World Bank.
- World Bank. (2011). *The changing wealth of nations*. Washington, DC: World Bank.
- Yamaguchi, R. (2017). Wealth and population growth under dynamic average utilitarianism. *Environment and Development Economics*, forthcoming.
- Yamaguchi, R., Sato, M., & Ueta, K. (2016). Measuring regional wealth and assessing sustainable development: An application to a disaster-torn region in Japan. *Social Indicators Research*, **129**(1): 365-389.