The wealth of nature

Increasing national wealth and reducing risk by measuring and managing natural capital

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green economy coalition

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This paper was led by the Institute for New Economic Thinking at the Oxford Martin School and the Smith School of Enterprise and the Environment in partnership with the Green Economy Coalition.

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The **Green Economy Coalition (GEC)** is the world's largest movement for fair, green economies. The GEC brings together over 50 organisations including trade unions, environmental NGOs, development NGOs, business and international institutions, and has hubs in seven locations around the world. Together with their global network, the GEC convenes multi-stakeholder dialogues, gathers evidence and shapes policy on five themes of the green economy transition: Valuing Nature, Tackling Inequality, Greening Economic Sectors, Reforming Financial Markets and Measuring & Governing.

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Executive Summary

Human prosperity and wealth has increased dramatically over the last 200 years. There have been marked reductions in poverty and increases in access to food, water, energy and housing across the globe. Earth now supports over 7.5 billion people at an average per capita income of over US$10,000 annually (World Bank, 2010). The poverty trap predicted by Malthus, (1798), has thus far, been avoided.

However, globally, there are many frailties. Scientific research shows that some natural capital is in a poor state, with strongly adverse trends. There is clear evidence of wide-spread ecosystem degradation and declining resilience in food and water systems. Societal risks arising from interruptions of supply chains, extreme weather, species losses and erosion of topsoil and reduced agricultural yields are being documented around the world.

This report considers the linkages between natural capital and human prosperity. It finds that the erosion of natural capital poses threats to continued national and global prosperity, yet political and economic systems are unprepared for responding to that risk for three reasons. First, natural capital is not being accurately measured or valued in the context of ecological tipping points and thresholds. Second, aggregate economic models are ill-equipped for seeing the dependencies between 'capitals'. Most cost-benefit analyses and economic methodologies used in everyday decisions assume that natural capital can be easily substituted by man-made capital, when in fact it cannot. Third, we lack appropriate political and economic institutions to manage natural capital effectively; even national wealth accounts provide an incomplete picture of the value of natural capital.

The paper identifies two key opportunities that emerge from these three challenges. First, *all* natural capital – including minerals, resources, fossil fuels, but also valuable ecosystem assets and natural infrastructure – could support greater prosperity if it were more appropriately valued and hence more efficiently used. Economic values must extend beyond a market-price-only approach and be incorporated into guidance on cost-benefit analysis that helps guide government policy. Further, natural capital could be accurately reflected in comprehensive national wealth accounts, which serve as a better guide to economic progress than measures such as Gross Domestic Product (GDP). Better valuation alone, however, does not ensure future prosperity.

Second, governance regimes based on scientifically-informed political decisions should protect *critical* natural capital, such as a stable climate and well-functioning ecosystems. Such capital underpins our prosperity, but is often subject to uncertain thresholds. Governance of *critical* natural capital stocks should be informed by biophysical limits, potential irreversibility, thresholds and risks to essential life support functions. At the global level, the targets in the Sustainable Development Goals (SDGs), adopted by the United Nations General Assembly in 2015 and applicable to all countries, provide a foundation for such a governance framework.

Ten recommendations to give effect to these findings are presented on accounting and valuation, measurement, economics and governance of natural capital. Some existing key actors – such as national treasuries and scientific institutions – have important roles to play in data management and economic valuation. Further economic research on substitutability is required. Business and finance can increase the demand for natural capital measurement by making innovative use of the resulting metrics. Finally, other key actors – such as natural capital committees – do not exist in many countries and might be created in order to oversee the governance of the protection of natural capital to increase wealth and prosperity.

1. Economic prosperity and the collateral damage to nature

1.1 Summary

Since the industrial revolution, rapid population growth has been accompanied by economic progress, resulting in wide-spread increases in wealth and prosperity across the globe (section 1.2). As humanity progressively succeeded in overcoming local environmental and energy limitations, it became a dominating force of the earth's biophysical processes. This has not led to a depletion of oil and mineral reserves to the point that these socioeconomic advances would be undone, as feared as recently as a few decades ago (e.g. Meadows et al. 1972). But it has placed significant pressure on unpriced natural capital (section 1.3), causing the overuse of renewable resources and leading to concerns that this now threatens future economic prosperity by undermining the earth's life support systems.

1.2 Increases in economic progress

While for millennia human population numbers were characterised globally by low growth rates and setbacks from disease and famine, the industrial revolution transformed the collective productive capabilities of humankind and marked the beginning of exponential population growth. For the world population to exceed one billion people it took all of human history until about 1800 (HYDE 3.1 data base, see Klein Goldewijk et al. 2010), but it required only a little more than a decade for it to grow from six billion people in 1999 to seven billion people in 2011 (UN, 2017).

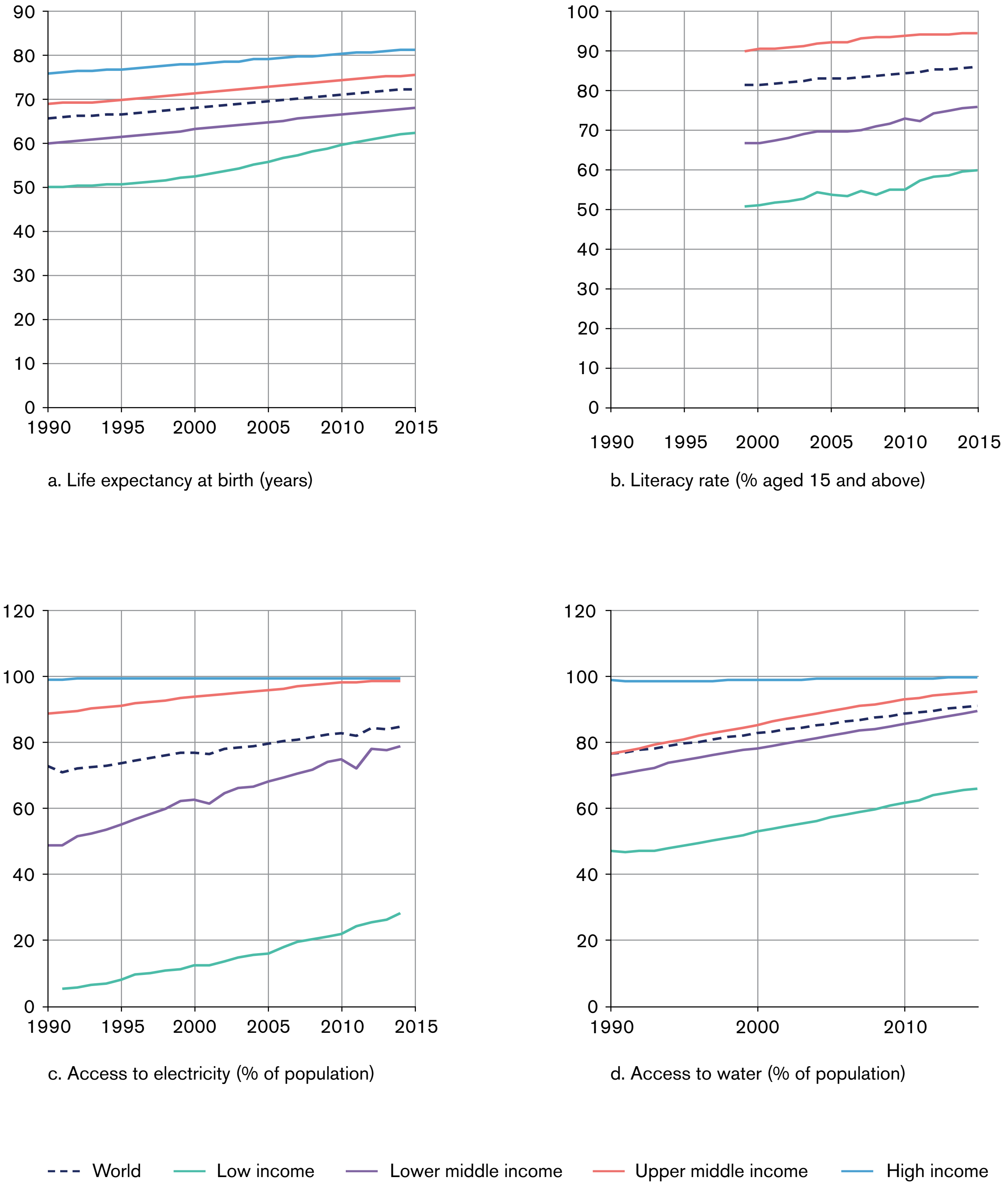
In many respects, the socioeconomic prospects and possibilities for the over 7.5 billion people living today have never been better. Great strides have been made in addressing basic needs and improving human welfare. Between 1990 and 2015, the prevalence of extreme poverty was reduced by more than half (UN, 2015a) and its complete eradication is considered within our reach (Sachs, 2005). Over the past 25 years, most regions of the world experienced sustained economic development, despite the 2008 economic crisis. World GDP per capita increased by around 40% (from around US$7,200 in 1990 to US$10,250 in 2015, both in constant 2010 dollars). The increase was particularly remarkable in middle income countries, where GDP per capita more than doubled during the same period.

This significant increase in GDP has been associated with an improvement of living conditions in most areas of the globe. There are many examples (see UN, 2015a), but we consider four here. First, people are living longer (Figure 1a). World life expectancy at birth has risen by around 6 years between 1990 and 2015, from 65.4 years to 71.7 years. The life expectancy gap between poor and rich countries also reduced, thanks to a major improvement in life expectancy in low income countries, from 49.8 years in 1990 to 62.1 years in 2015.

Second, more people are able to read (Figure 1b). Access to education has improved, and the world literacy rate has correspondingly increased by around 5 points between 2000 and 2015, in particular thanks to improvements in lower income and lower middle-income countries: the literacy rate increased from 50% to 60% in low-income countries between 2000 and 2015, and from 66% to 76% in lower middle-income countries.

Third, access to electricity has expanded (Figure 1c). While only 5% of the population had access to electricity in low-income countries in 1990, around 25% did in 2015. In lower middle-income countries, access to electricity raised from around 50% to 80% during the same period.

Figure 1. Development indicators by groups of countries: (a) life expectancy; (b) literacy; (c) access to electricity; and (d) access to water



Source: World Bank – World Development Indicators. Data on literacy rates unavailable before 1990.

Finally, more people have access to improved water sources (Figure 1d), with radical improvements over the last 25 years in developing countries. These four examples demonstrate significant improvements in economic development and human health – and increases in wealth – over the past 25 years.

Yet progress in key development indicators remains uneven across regions and countries (UN, 2015a). As discussed in greater detail later, the international community has defined through the Sustainable Development Goals (SDGs) its ambitions for a more just and prosperous world, which is free of poverty and on a sustainable development path (UN, 2015b). Closing the existing gaps of meeting basic human needs and fulfilling the aspiration of enabling universal human welfare represents the outstanding opportunity but also continuous challenge of our time. It will also require re-evaluating how we use natural resources to achieve socioeconomic progress.

1.3 Collateral damage to nature

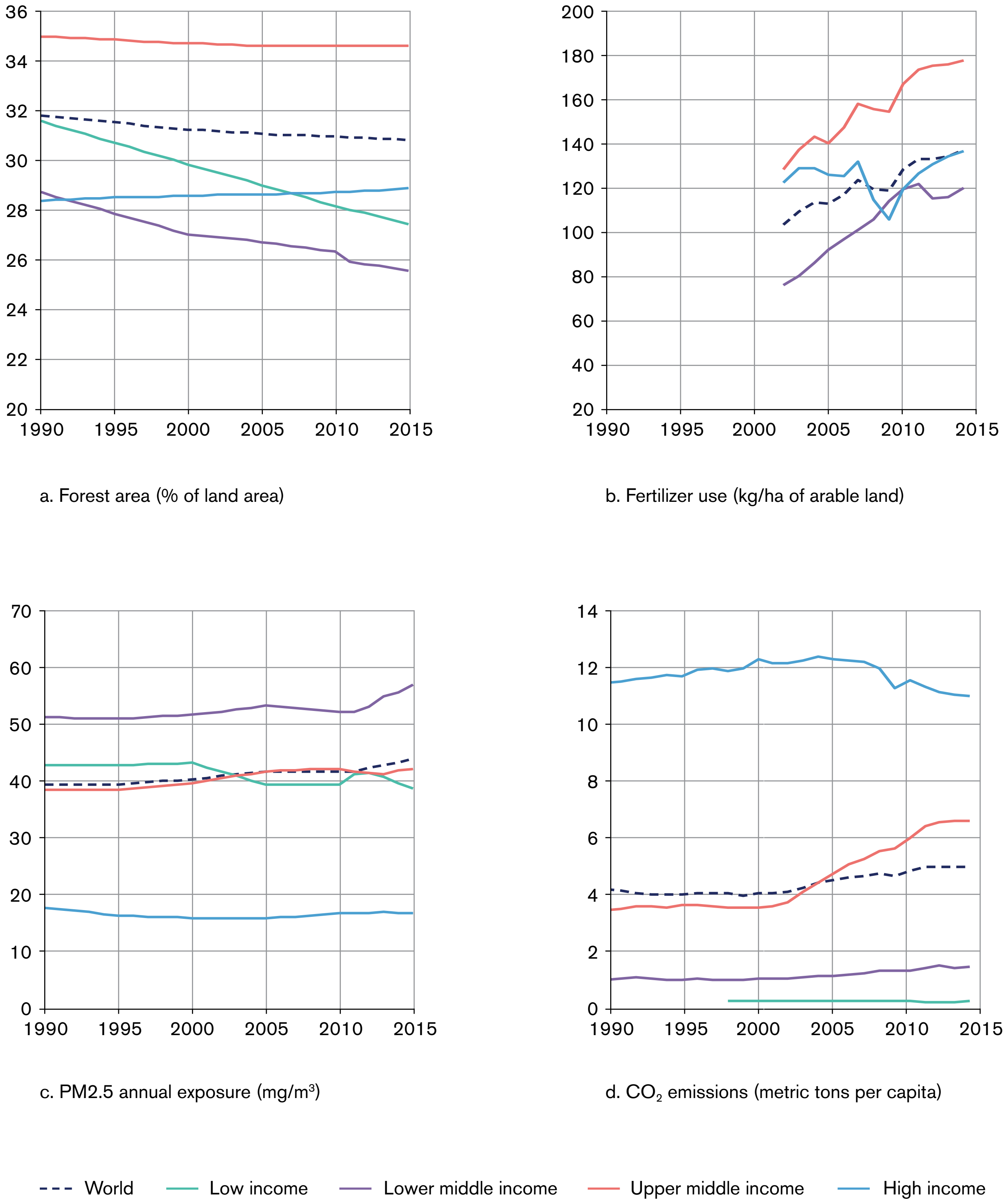
Natural capital provides the foundation for human life and economic activities. It comprises renewable renewable and non-renewable assets. The natural capital stock of a country or region entails the natural resource endowments from which benefits can be derived. *Renewable* natural capital stocks (e.g. fisheries, forests and other ecosystems) deliver goods and services in perpetuity, provided they are properly managed. Hence, it is the rate at which these resources are utilized that matters. By contrast, *exhaustible* resources, such as minerals or oil, are finite and their use leads inevitably (even with partial recycling) to a decline in the useful stock of the resource, constraining its use for future generations.

The advances in human welfare are rooted in the growing ability of human societies to overcome local environmental limitations and energy constraints through innovation and trade. As human economic activities were drawing down natural capital stocks, growing concern emerged that this would ultimately limit further economic progress. However, with regards to non-renewable capital stocks, past concerns about resource limits and scarcity in the *Limits to Growth* (Meadows et al., 1972) have not materialised. More recent concerns from the *Club of Rome* about "peak minerals" also appear misplaced; analysis of data from the United States Geological Survey from 1957 onwards suggests that reserve ratios are being maintained (Hepburn et al., forthcoming).

Instead, it is the increasing overuse of renewable resources and the accumulation of waste products (arising in part from the use of non-renewable resources) in the environment that is a primary sustainability concern, as it is directly linked to the erosion of earth's life support functions. Figure 2 illustrates this by looking at trends in forest cover, fertilizer use, air pollution through particulate matter (PM2.5) and CO_2 emissions. While the trends and absolute values differ considerably among country groups clustered by income, the global aggregates of these environmental indicators show that the environmental footprint either remains at a similar level or increases over time. While forest cover has been increasing in high-income countries, there has been deforestation in low income and lower middle-income countries (Figure 2a). The nitrogen cycle is also under pressure, with growing use of fertilizer, particularly in middle-income countries (Figure 2b). Air quality is also a major concern in many cities in developing countries. In lower middle-income countries, exposure to PM2.5 has increased by nearly 10% over the past 5 years (see Figure 2c). While per capita CO_2 emissions have started to decline in high-income countries, they have increased by more than 80% since 2000 in upper-middle income countries (see Figure 2d).

Humans no longer just modify their immediate environment, but the aggregate impact of human activities has taken on global proportions, as the use of natural resources has been accelerating since the industrial revolution and in particular since the mid-1950s (Steffen et al., 2004, 2007). The accelerated rate of species extinctions and widespread loss of biodiversity represents a longstanding concern (Pimm et al. 1995), given that the web of species interactions influences ecosystem properties and functioning. It is well established that human activities have altered biogeochemical processes, impacting the Nitrogen (N) and Phosphorous (P) cycles (Vitousek et al. 1997). Despite resulting productivity increases in agriculture and other human managed ecosystems, the overall terrestrial net primary productivity (NPP) of biomass has remained largely constant at around 54 GtC per year during the last 30 years (Haberl et al. 2013). With growing and multiple demands placed on land, the proportion of NPP that is appropriated by human activities has approximately doubled over the last century, reaching 14.8 GtC in 2005 or about 25% of the potential NPP (Haberl et al. 2014), diminishing the amount of biomass available to other species. Comprehensive scientific assessments suggest that more than 60% of the globally examined ecosystem services are degraded (MEA, 2005).

Figure 2. Environmental indicators by groups of countries: (a) forest area; (b) fertilizer use; (c) exposure to air pollution (PM2.5); and (d) CO_2 emissions



a. Forest area (% of land area)

b. Fertilizer use (kg/ha of arable land)

c. PM2.5 annual exposure (mg/m³)

d. CO_2 emissions (metric tons per capita)

Source: World Bank – World Development Indicators. Before 2010, statistics for PM2.5 were only collected every five years (for 1990, 1995, 2000, and 2005). Between these years, the data was linearly extrapolated. From 2010 onwards, data is available every year. Data on fertilizer use unavailable before 2002.

The human impact on marine environments is also intensifying. McCauley et al. (2015) highlight local level species loss and decline of species abundance within marine ecosystems, and warn that intensification of ocean fisheries in conjunction with other environmental pressures may greatly accelerate loss rates in the future if left unaddressed. In 1974, 90% of the commercial fish stock was considered to be within biologically sustainable levels, whereas this was only the case for 68.6% in 2013 (FAO, 2016). While attention is often focused on the decline in large predatory fish, a recent study found that up to double the amount of small, low trophic level fisheries have collapsed, which may cause ripple effects through the food chain and trigger ecosystem-wide impacts (Pinsky et al. 2010).

Climate change most exemplifies the global fingerprint of human activities. It is interacting with other pressures on marine and terrestrial environments, while also introducing new risks (IPCC, 2012 and 2014). Physical changes associated with the human-induced increase in atmospheric greenhouse gas concentration, such as changes in temperature and precipitation patterns, shifting exposure to climatic extremes, sea level rise and ocean acidification have implications for natural capital and the services we derive from it (IPCC 2014). A broad array of species responses, such as changes in the distribution range, animal behaviour or plant phenology, which correlate significantly with the direction of climate change, are being documented (Parmesan, 2006). Through its impact on natural and human systems, climate change has been well recognised as a major threat to sustainable development, if no remedial measures are undertaken (e.g. AfDB et al. 2003, World Bank 2010).

The multiple impacts of climate change serve as a reminder that different forms of natural capital often interact in interlocking systems of *natural infrastructure.* For example, forests and floodplains combine to provide flood and erosion protection, often very cost-effectively compared to alternative physical structures (WRI, 2013). Forests provide an array of other benefits, including carbon storage and sequestration, local climate regulation, water filtration and biodiversity. Damaging one part of the natural infrastructure can irremediably affect the rest of the system.

Box 1: The Anthropocene and planetary boundaries

To signify that the impact of human activities on natural processes has reached geological scale proportions, scientists have proposed the arrival of new epoch, the Anthropocene (Crutzen and Stoermer 2000, Crutzen 2002). Since the mid-1950s, the acceleration in economic development has been accompanied by an acceleration in the use of natural resources and associated environmental impacts, as evident in the global trends of a variety of indicators (Steffen et al. 2007).

Rockström et al (2009) proposed nine planetary boundaries to guide human action at the global level. In addition to a boundary on (i) climate change, they proposed global quantified limits on (ii) the rates of biodiversity loss, (iii) the Nitrogen- and Phosphorus-cycles, (iv) stratospheric ozone depletion, (v) ocean acidification, (vi) global freshwater use, and (vii) change in land-use. They estimate that we have already crossed three boundaries (climate change, biodiversity loss and impact on the nitrogen cycle) and propose an additional two planetary boundaries on atmospheric aerosol loading and chemical pollution, but did not quantify these.

The planetary boundaries have to be understood as value judgements, informed by the currently available scientific knowledge. Efforts are being made to further refine some of global quantifications of individual boundaries, for example for biodiversity (Mace et al 2014). Steffen et al. (2015) provide an update on planetary boundary categories and values.

1.4 Conclusion

Because humans are dominating biophysical processes at local to global scales, transforming the global environment, scientists have proposed environmental limits to safeguard the earth's life support systems (Box 1). Current economic systems have had very limited success in decoupling socioeconomic progress from impacts on renewable forms of natural capital. In principle, we should reap the harvests of renewable natural capital indefinitely. In principle, there are reasons for concern about exhaustible natural capital. And yet, in practice the opposite of both statements appears to be true. This is partly because exhaustible natural capital is often valued at market prices. Market prices of resources roughly reflect scarcity, even if they often do not fully reflect all social costs (such as pollution). Increasing prices provide stronger incentives for mineral reuse and recycling, substitution, demand reductions and/or supply increases by greater exploration and production. The results of these forces is that real prices and reserve-to-production ratios have not changed much over the past fifty years (Hepburn et al., forthcoming).

In contrast, such price signals are often absent or significantly distorted for renewable natural capital. As we will see, the lack of appropriate prices is related to a number of challenges in the measurement, valuation and management of such natural capital. And yet, accounting of natural capital is argued to be essential for sustainable development (UNEP, 2011, World Bank, 2011). While pricing is not the only answer – as demonstrated in fisheries, forestry and discussed in section 3 below – it is perhaps unsurprising that priced exhaustible natural resources are not currently at risk of exhaustion, while unpriced renewable resources are often being depleted at rates that exceed their regenerative capacity.

2. The mismanagement of natural capital

2.1 Summary

Following the observation in section 1 that the erosion of critical natural capital risks future economic progress, this section details the underlying challenges, before we consider possible solutions in section 3. We identify three core areas in turn: (i) scientific measurement, (ii) accounting; and (iii) economics. First, our understanding and ability to measure the state of nature, including its risks to future prosperity, is inadequate. This is true notwithstanding dramatic recent improvements in data gathering through a range of new tools (e.g. satellite monitoring and increasingly cheap local sensors). Second, our accounting of natural capital has been weak. Institutions – political and economic – have thus far been unable to fully value natural capital and incorporate it into government accounts and decision making. Third, our economic understanding of the degree to which nature can be depleted without economic output being harmed remains partial. Best estimates indicate that the substitutability of some kinds of natural capital may be rather low, suggesting that governance regimes need to be put in place to protect critical natural capital to prevent major risks to future prosperity. While these challenges are difficult, they are not intractable, as discussed in section 3.

2.2 Measurement: the complexity of biophysical data

The measurement and assessment of the biophysical components of natural capital is rapidly improving. Examples include the assessment of the chemical composition of the atmosphere, more accurate temperature measurements, better cataloguing of different species and mapping their geographical distribution or monitoring the net primary productivity of entire ecosystems. Advances in measurements have been made across spatial and temporal scales.

This progress provides a foundation for efforts that seek an integrated understanding of the interactions between physical, biological and chemical characteristics of natural systems. For example, models used to project climatic changes simulate interactions between ocean, atmosphere, and terrestrial ecosystems are calibrated against their ability to accurately represent past and current climates. Various initiatives are underway to monitor and provide an integrated understanding of the state of natural systems (climate, ice cover, water resources, ecosystem distribution and productivity). Examples include the Global Terrestrial Observing System (GTOS) or the Global Earth Observation System of Systems (GEOSS). Such efforts will help to rapidly detect changes in environmental properties and improve the accuracy of models.

Despite this unprecedented amount of scientific data, our understanding of the interaction between different components of natural capital often remains limited and incomplete. For example, the loss of one species may go unnoticed, while the disappearance of another may alter the entire structure and functioning of an ecosystem. Determining which types of natural capital are critical to life support systems is difficult. Of particular concern are the existence of thresholds or tipping points in natural systems (Box 2), which, once crossed, lead to non-linear responses and potential changes in the properties of life support systems, that are irreversible over time-scales meaningful to human activities. These measurement and assessment challenges make the management of natural capital difficult.

Box 2: Measuring and assessing non-linear systems with tipping points and surprises

Research in Earth systems science now provides ample evidence that progressive depletion of natural capital may lead to non-linear system responses with potentially severe adverse consequences. Human experience with incremental environmental changes and associated impacts in the recent past may not be a good guide for the future. As conditions become further removed from the present-day, the risk of unwanted surprises increases.

Climate change is one example. The ultimate objective of the United Nations Framework Convention on Climate Change (UNFCCC) is the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (UN, 1992). In order to inform this objective, scientists of the Intergovernmental Panel on Climate Change (IPCC) attempt to identify key vulnerabilities of climate sensitive systems, based on the importance of the system, the magnitude and rate of impact, whether the impact is irreversible, the potential for adaptation and other criteria (Schneider et al. 2007). The possible existence of tipping points in some biophysical and social systems could mean that a small change could have large-scale effects on the properties of the system, if a threshold is crossed (Lenton, 2013). For example, a small increase in the global average surface temperature could trigger substantial ecological or physical changes, such as the die-back of the Amazon rainforest or the disintegration of the Greenland and West Antarctic ice-sheets (Lenton et al. 2008). Disasters illustrate the importance of also understanding tipping points in social systems, as they occur when the capacity of livelihoods and economic sectors to cope with a particular hazard is overwhelmed (O'Brien et al., 2012). The IPCC has evaluated the risk for large-scale, system altering and potentially irreversible impacts for different levels of global warming (e.g. IPCC 2007, 2014). Taking such information into account, the 2015 Paris Agreement of the UNFCCC aims to limit global warming to "well below 2°C" above preindustrial levels (UNFCCC, 2015).

The multiple interactions and interdependencies in natural systems make it often difficult to foresee the consequences of human interference. For example, a recently released field study found a 75% decline in the flying insect biomass between 1989 and 2016 across Germany (Hallmann et al., 2017). Global estimates suggest pollinators contribute a current market value of US$ 235-577 billion on global crop production (IPBES, 2016). While the loss of pollinating insects is a given concern, there may be other long-term and less well understood effects on ecosystem structure and functioning resulting from knock-on effects on birds and other species. Another assessment shows that the diversity of mammals can influence carbon storage in a tropical forest through trophic level interactions (Sobral et al. 2017), illustrating sometimes surprising interlinkages between biodiversity and ecosystem conservation and climate protection.

2.3 Accounting: inadequate prices for natural capital

Estimating and tracking physical flows is an important start. However, for government decision making it is helpful if economic valuations are attached to physical flows.[1] To achieve this, the benefits derived from environmental goods and services need to be monetised.

In some instances, this is relatively straightforward. Where natural resources provide direct inputs into the economy (e.g. timber, coal, oil, gas), these flows can be easily monetised because market prices are available. As discussed in section 1, the existence of markets – and market prices – for these components of natural capital considerably simplifies the challenges of accounting.

Much more difficult, however, is the valuation of the nonmarket goods and services provided by nature, often "for free". Environmental economists have attempted to use various survey and econometric techniques to elicit values (willingness to pay, or willingness to accept compensation for loss) for these goods and services. There have even been

[1] Philosophical debates continue about the question of whether putting a price on the cost of a particular resource also implicitly reduces nature to "mere money". One view is that such economic valuations need not, and should not, claim to capture all forms of value – religious, spiritual and others – of natural capital. They are attempting to do something far more mundane, which is to codify the ways in which humans already make economic choices.

questionable attempts to assign a value to unpriced natural capital at the global scales. Costanza et al. (1997) estimated that the total value of ecosystem services amounted to an average of US$33 trillion per year, substantially exceeding the world's Gross National Product (GNP) at the time of about US$18 trillion. In a recent update, Costanza et al (2014) estimate the loss in ecosystem services due to land-use changes between 1997 and 2001 amounted to US$4.3 to US$20 trillion per year.

Efforts are ongoing to strengthen the understanding of the economic dimensions of biodiversity and ecosystem services as various scales (e.g. TEEB, 2010). The UK Office of National Statistics is an example, where government agencies are providing national level estimates of monetary value of natural capital (ONS, 2016). Scientific assessments not only focus on the economic value embedded in ecosystem services, but also how targeted investments in natural capital can enhance the quality of ecosystem goods and services, as has been done recently for China (Ouyang et al. 2016).

While these estimates are significantly better than nothing, they remain crude. At more granular levels, valuations are frequently not available at all. It is difficult to manage nature to increase prosperity if the underpinning basis of measurement and valuation are not present.

2.4 Economics: the theory of substitutability of natural capital

To what degree can natural capital be replaced by a different form of capital in the production process while maintaining economic output and wealth in the long run? Natural capital that is readily *substitutable* can be converted, but natural capital that is a *complement* to other inputs cannot be replaced, or productivity and/or human welfare would be reduced. This question is clearly central to the management of natural capital. It has been addressed conceptually by economists in the debate over so-called weak and strong sustainability (see Box 3). However, clear empirical answers on the limits to the substitutability of nature are lacking.

In aggregate, economic activity is not possible without natural capital – without food and water humans die, so consumption and production stop. However, this does not imply that there are no possibilities for substitution at the margin. Economic theory can helpfully inform us about the degree of substitutability of natural capital at the margin. An introduction to the key concepts is presented in the Appendix, and a detailed review of the theoretical and empirical literatures on the substitutability of natural capital has been prepared to accompany this report (Cohen et al, 2017). We consider the theory and the empirics in turn.

First, we find that conclusions from the theoretical literature about the substitutability of natural capital must be treated with caution. In particular:

- When there are multiple capitals used in production or consumption, complex substitutability and complementarity relationships can arise. Missing observations on natural capital inputs can lead to biased estimates of substitutability. This is particularly relevant for natural capital since it is often difficult to measure and observe.
- Economic analysis of substitutability traditionally applies only to small or *marginal* changes. While this has been plausible historically, and may remain so in some domains for some time, humans are now making large changes to natural capital (see Box 1).
- If potential tipping points associated with the decline of natural capital are ignored – which is implicitly the case in mainstream policymaking and national accounts – natural capital will appear more substitutable in production functions than it actually is.
- Even where natural capital is critical, firms may not act accordingly because of uncertainty and incorrect market prices. This skews estimates of substitutability that are based on firm behaviour.
- Estimates of substitutability are appropriate for a particular place and at a particular time. Substitutability at a large (e.g. sectoral) scale or over a long time period does *not* necessarily imply substitutability on a local (e.g. firm) scale or over a short time period, and vice versa.
- Technological change does not simply increase substitutability. It can make certain types of natural capital more complementary – and hence even more necessary for human prosperity.

Second, our empirical analysis presented in Cohen et al (2017), subject to the caveats above, suggests that overall substitutability of natural capital, in the aggregate, is either low or moderate. There are further reasons for caution here:

- Any point estimate of the substitutability of nature relates to a specific geographical scale. At the national level, data on aggregate natural capital is generally available. However, the process of aggregation renders the entire exercise somewhat questionable – subsoil assets such as oil and gas are simply not the same sort of production input as climatic conditions or water purification from a forest; adding them together does a disservice to their different functions.

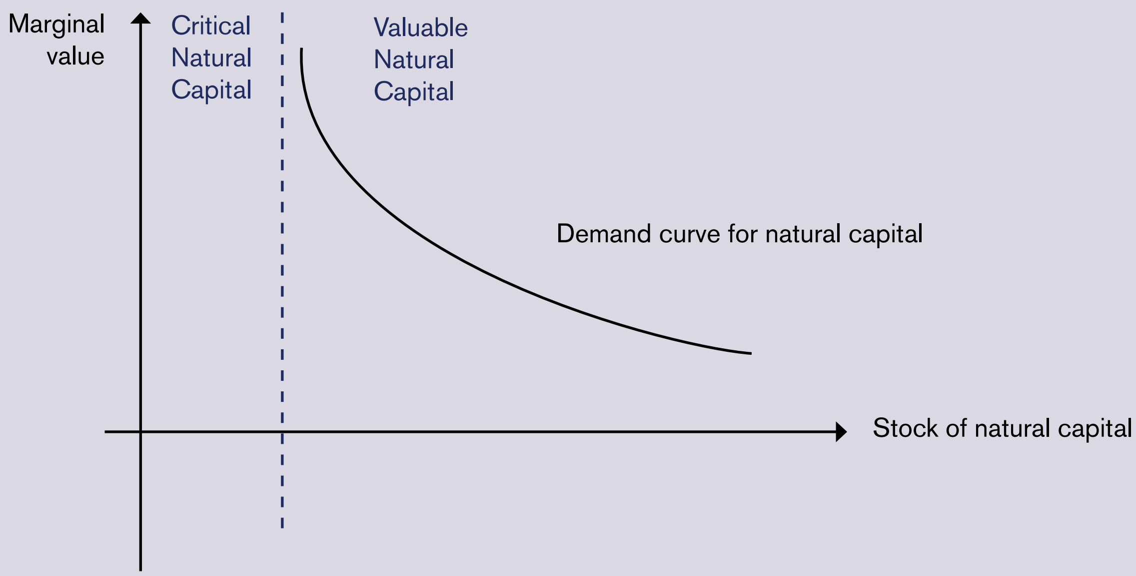
Box 3: Weak versus strong sustainability and critical natural capital

One of the key debates in the literature on sustainable development and natural capital revolves around *weak sustainability* versus *strong sustainability* (Pezzey, 1992; Ekins et al., 2003; Neumayer, 2003, 2012; Dietz and Neumayer, 2007). Proponents of weak sustainability argue that, in general, human welfare can be maintained at a constant level or increased when natural capital is destroyed as long as natural capital is replaced with sufficient quantities of physical and human capital. This view implicitly assumes that natural and human/physical capital are substitutable to some degree. The Hartwick Rule embodies this view: with enough substitutability and technological progress, even exhaustible natural capital can be replaced sufficiently quickly by human/physical capital while maintaining or increasing living standards (Hartwick, 1977; Asheim, 2013).

Strong sustainability offers an alternative view. Proponents of strong sustainability argue that other forms of capital often cannot substitute for natural capital. This might be because natural capital is *critical*, meaning that its loss will *inevitably* cause a reduction in production or welfare. There might be different reasons for criticality, including irreversibility and feedbacks that cause complete destruction of ecosystems.

The simple theoretical frameworks discussed in the Appendix (see section 6) capture both weak and strong sustainability perspectives. Both concepts may be relevant in practice. As the figure below illustrates, there may be a critical minimal level at which the value of a natural capital is so high that it must be preserved, otherwise human civilisation will no longer continue to exist.

To resolve the debate, substitutability and criticality of all capitals would need to be carefully measured and assessed at different scales, in different geographies, and across different time periods. While substitutability estimates can in principle be done with some care, estimates of criticality are extremely difficult to obtain. Unless we are in possession of a near-perfect ecological model, by the time we can observe indications of criticality (in order to estimate the threshold), it might be too late (Horan et al., 2011; Lenton, 2013).



- To address the challenges created by aggregation, analysis can proceed to a more granular level by exploring the substitutability of natural inputs at the industry or firm level. The challenges here are that granular data on natural capital inputs is frequently unavailable, at least beyond energy and materials.

We conclude that many of these estimates suffer from serious bias and estimation problems, making them an unreliable basis for policy. To the extent that tentative conclusions may be available, they are that – at present levels of natural capital – substitutability is already relatively low, implying that further reductions in natural capital are likely to harm economic output.

2.5 Conclusion

Natural capital is being eroded because of challenges in three domains: (i) measurement, (ii) accounting; and (iii) economics. While we have increasingly good data, our ability to use that to understand complex natural systems remains limited. Efforts to value and account for nature in government and business decision-making are underway[2] but are also limited. Finally, the underlying empirical economics of substitutability remains weak, meaning that any estimates of substitutability of natural capital must be treated with great caution. In particular:

- *Market prices* for different types of natural capital are either absent or incorrect, biasing estimates.
- *Data* on many relevant types of natural capital are absent.
- The estimates of substitutability apply only to *marginal* changes. The larger the agent (e.g. country), the harder it is to justify the assumption that their impact is marginal.
- Most analyses do not take into account *critical* natural capital and *tipping points*.
- Substitutability at a large (e.g. sectoral) *scale* does *not* imply substitutability on a local scale.
- Substitutability can vary dramatically over different *time* periods.

These concerns imply that we face serious risks to future prosperity if we fail to create precautionary governance regimes while strengthening our understanding of natural capital. However, recent developments provide opportunities for progress, as discussed next.

[2] For instance, 76 countries are looking to apply UN SEEA, and through the Natural Capital Coalition 35,000 copies of the business-oriented Natural Capital Protocol guidance are now in circulation.

3. Can we increase prosperity and reduce risk by managing natural capital?

3.1 Summary

Two recent developments offer potential pathways towards significant increases in prosperity, with reduced risks, through the better management of natural capital. The World Bank, UN and some national governments are leading the way in developing more comprehensive and inclusive wealth accounts. Section 3.2 discusses some of the insights that can be gained from these efforts, focusing specifically on newly-released national level data by the World Bank. Properly incorporating natural capital into national wealth accounts, and ensuring that it is appropriately priced in government decisions, will help ensure efficient management of natural capital. This is not enough, however. Section 3.3 explores how the recently agreed Sustainable Development Goals (SDGs) could help ensure that critical thresholds are not crossed. The environmental aspects of these goals – where performance has thus far been relatively weak – begin the process of codifying agreed limits to the depletion of critical natural capital.

3.2 Increasing prosperity: national wealth accounting

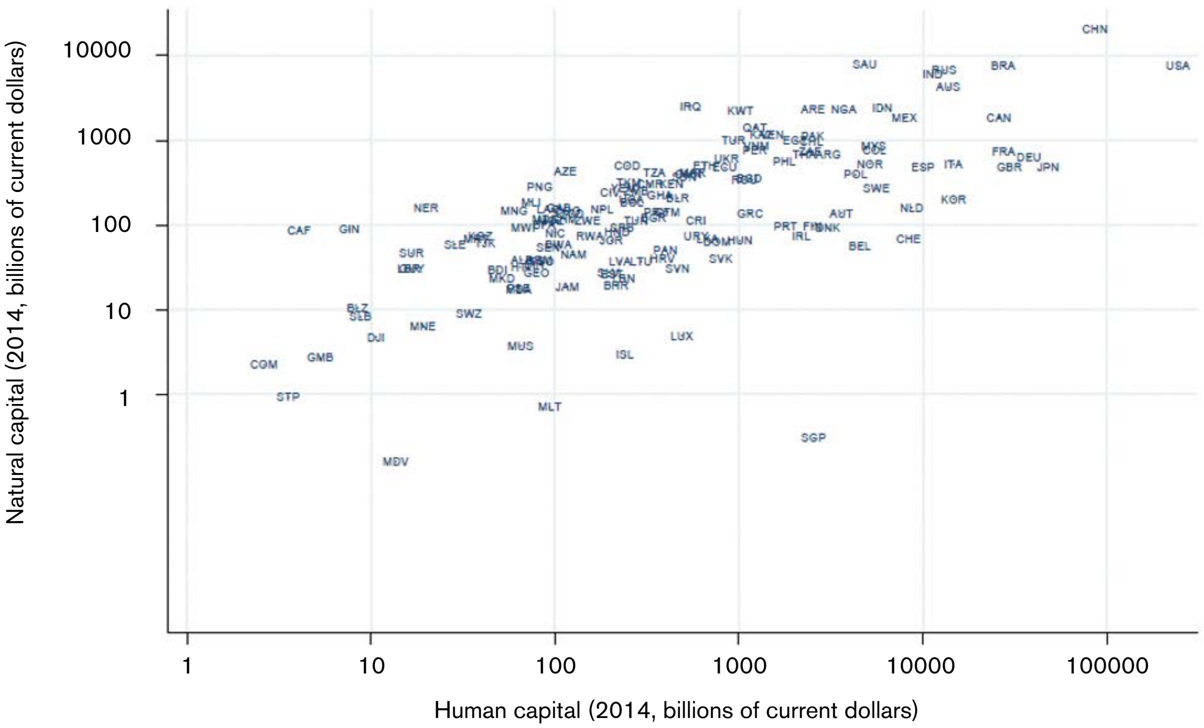
It is remarkable that until recently, and still today, many nations of the world have not had adequate balance sheets of the stock of assets that would be expected of any corporation. Flows of gross domestic product are widely reported – which is to be welcomed – but the state of the asset base that can produce annual income is frequently overlooked.

This is now changing. The World Bank and the UN are leading the way on developing more comprehensive accounts of how nations derive their wealth (e.g. World Bank, 2006, 2011; UNU-IHDP and UNEP 2012, 2014). We focus here specifically on the data set released by the World Bank in 2017, which provides time series estimates of national wealth for roughly 150 countries annually from 1970 onwards. National wealth comprises the sum of productive assets used to generate national income, namely: natural capital (both exhaustible and renewable), physical capital (e.g. roads, bridges, buildings), human capital (e.g. people and their skills), social capital (e.g. rules, institutions and norms), intellectual capital (e.g. patents) and net financial assets. These data provide new and interesting information about the state of natural capital, and the other capitals, and their role in generating national wealth.

Wealth accounting offers a coherent and systematic way to measure prosperity and therefore has the potential to steer policymaker's decisions in the future. For instance, the wealth data suggest that rich countries have grown rich by investing enormously in produced and human capital. But countries with higher human capital also have higher values of natural capital (as shown in Figure 3). Rich countries apply advanced technologies and management practices to their natural resources, boosting the value of natural capital per person. In 2014, OECD countries held natural capital assets worth around US$19,500 per capita, compared to only US$6,400 in low income countries. The share of natural capital in total wealth increased from 2.5% to 2.8% in OECD countries over the last 20 years. In other words, wealth is created not by destroying natural capital, but by investing in produced and human capital, through the application of new technologies, and the development of better institutions and management practices.

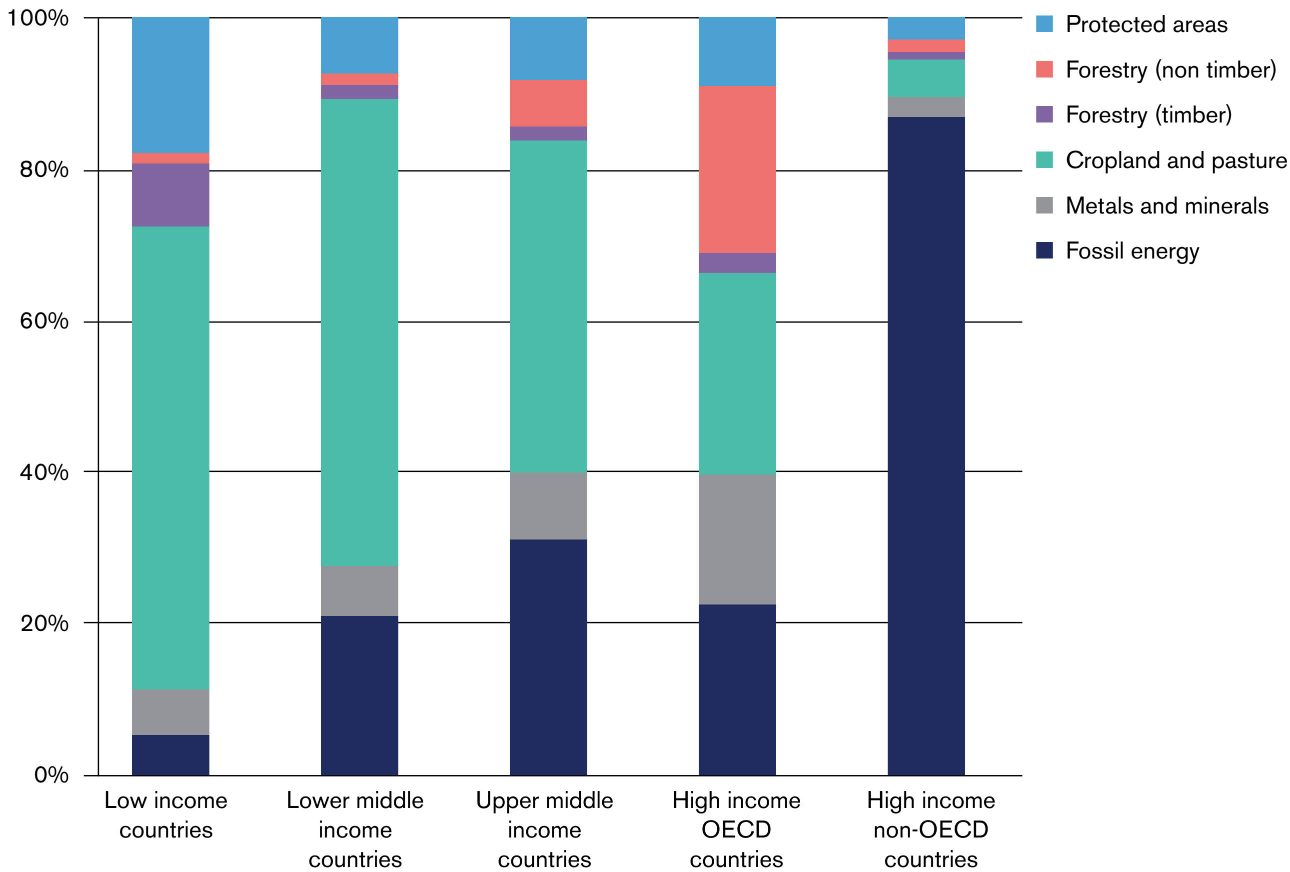
The composition of natural capital differs considerably between countries, as shown in Figure 4. For some

Figure 3. Countries with high human capital also have high natural capital



Source: World Bank Wealth of Nations Data. Logarithmic scale. World Bank country codes.

Figure 4. Composition of natural capital within income groups (2014)



countries, their natural capital is almost entirely in fossil energy (oil and gas), with relatively little in other sub-soil metal and mineral resources, or in ecosystems and land management of various kinds. In low income countries, a great deal of the natural capital is bound up in the agricultural sector – cropland and pasture amounted to roughly 30% of total wealth in low income countries. In the OECD, over one third of the value of natural capital is in protected areas and non-timber forest areas, categories which have grown in value in recent decades.

Natural resources also play a special role in development because they constitute a large proportion of wealth in low income countries – 47% of total wealth in 2014. In the short run, better management of natural resources is critical for wellbeing in these countries. In the longer run there is a clear need for these countries to diversify their economies by investing in other forms of wealth, particularly human capital.

However, there are important divergences between theory and practice in wealth accounting. The underlying theory assumes that wealth measurement, including saving, investment and depreciation, is *comprehensive*. All contributors to future wellbeing need to be measured. Natural capital is a particular problem in this respect: specific resources, such as fisheries, are often measured imperfectly, while ecosystem services are only gradually being routinely measured or modelled.

Although the World Bank has played an essential and leading role in developing national wealth accounts, the Wealth of Nations statistics are not yet comprehensive. Natural capital is computed as the sum of the capital derived from only five types of natural resources: forests, exploited land, protected areas, fossil energy and mineral resources – other natural capital is not included. Inevitably, the World Bank has had to use the data available, rather than the data that it would ideally like to use, in calculating wealth estimates.[3]

Three challenges stand out. First, more sophisticated accounting techniques should be employed to measure the value of natural capital. The traditional "net present value" approach can miss important natural capital valuation parameters, such as adjustment for the net marginal productivity and price appreciation of natural capital assets (Fenichel and Abbott, 2014; Fenichel et al., 2016). Incorporating these parameters requires careful socioeconomic and ecological modelling at a local level. Wealth accounting for natural capital should be more disaggregated and ecosystem-specific (Do et al., 2017).

Second, there are enormous data and modelling needs. If wealth accounting for natural capital is to become more precise, more and better data must be collected on ecosystem performance and function around the world. This would allow economists and ecologists to build much better models of ecosystem function and value, and prevent natural capital from degrading beyond critical thresholds.

In this direction, the UK Office for National Statistics (ONS) and the Department for Food, Environment and Rural Affairs (Defra) have been working on expanding the UK natural capital accounts to encompass a wider set of elements than the ones covered by the World Bank in the Wealth of Nations data. Their experimental accounts comprise water for public supply, hydropower and wind power production from major producers, as well as carbon sequestration and air pollution removal (particulate matter and sulphur dioxide).

Comprehensive national accounts, in which all components are valued and added up to a single figure, remain some way off. The ONS (2016) provides a long list of natural values that are not yet included, namely: (i) wild animals and plants; (ii) air pollution removal from other pollutants; (iii) waste water cleaning; (iv) heritage and aesthetic interactions with nature; (v) all other renewable energy sources; (vi) the mediation of smell, noise and visual pollution; (vii) solid wastes; (viii) water not for public water supply and water flow control; (ix) flood, erosion and landslide protection; (x) temperature regulation; (xi) the value placed on nature simply existing; (xii) lifecycle regulation; (xiii) overnight visits and visits by non-residents of natural areas; (xiv) water conditions; (xv) the physical and mental health benefits of natural assets; and (xvi) pollination and seed dispersal. Doubtless there are others missing. For most of these entries, benefits are either difficult to track (e.g. pollination) or difficult to put a value on (e.g. the value placed on nature).

Finally, accounting needs to move beyond the market-price-only approach. Market prices do not accurately reflect the scarcity of natural capital and can lead to

[3] To calculate present and future values, the accounting exercise from the World Bank uses data on production, prices and rents. Reserves are also an essential component of wealth for all the exhaustible resources considered: coal, natural gas and oil for energy resources; and bauxite, copper, gold, iron ore, lead, nickel, phosphate, silver, tin and zinc for mineral resources. For renewable resources (forests, land and protected areas), the valuation exercise is similar except that future valuation does not rely on estimates of remaining reserves, but on estimates of the areas that will be used by forests, lands and protected areas in the future.

very misleading conclusions about its societal value. Therefore, we must take into the account the lack of strong property rights over much of natural capital and its subsequent undervaluation in the data.

3.3 Reducing risk: the Sustainable Development Goals

Since economic accounts necessarily involve adding up values in order arrive at aggregate figures such as GDP, comprehensive wealth or adjusted net saving, there is an implicit assumption that the stocks or flows in question are substitutable. As we have seen in section 2.4 that this is not always correct. Therefore other complementary indicators – likely including biophysical measures relating to thresholds and limits – are helpful in designing policies to protect future prosperity.

It is arguable that a portion of natural capital should be reserved as globally *critical* natural capital, as essential to sustaining services and options that are globally relevant to current and future generations. Given uncertainties and our incomplete understanding of natural systems, such a precautionary approach is prudent.

The Sustainable Development Goals (UN, 2015b) could serve as a politically-agreed reference point. Unlike the Millennium Development Goals (MDGs), which were specifically focused on improving the situation of developing countries, the SDGs are *global* goals, applying to rich and poor countries alike. Comprised of 17 goals and 169 associated targets (UN, 2015b), the SDGs provide quantitative and qualitative specifications of the economic, social and environmental dimensions of sustainable development, seeking to strengthen the integration across multiple objectives. The development agenda for 2030 framed by the SDGs seeks to chart a path that addresses the basic human needs of people and enables prosperity, while safeguarding the life support systems of the planet (UN, 2015b).

The management of natural capital features prominently in the SDGs. Three of the global goals are directly concerned with the protection of the earth´s life support systems: SDG 13 (climate action), SDG 14 (life below water) and SDG 15 (life on land). For example, halting forest and biodiversity loss constitute specific targets for the management of terrestrial resources under SDG 15. SDG 13 by itself provides limited quantitative guidance on climate change mitigation and adaptation efforts, but is explicitly linked to the United Nations Framework Convention on Climate Change (UNFCCC) as the “primary forum for negotiating the global response to climate change” (UN, 2015b). The Paris Agreement reached by the UNFCCC has set quantitative limits on human interference with the climate system (see Box 4).

Box 4: Limiting Climate Change

The Paris Agreement on climate change commits nation states to limit global warming to well below 2°C and to pursue efforts to constrain warming to 1.5°C above the pre-industrial level (UNFCCC, 2015). These warming targets can be translated into total cumulative carbon budgets for human activities and hence be linked to iterative reviews on the effectiveness of international and national policies (Allen et al. 2009, Rogelj et al. 2015, UNEP 2016). Stabilizing climate change will ultimately require arriving at net zero CO_2 emissions, i.e. human induced emissions are balanced by the removal of greenhouse gas emissions from the atmosphere, and a phase out of other long-lived greenhouse gases (Matthews et al. 2009, Collins et al. 2013).

Recent assessment show for the first-time a decline in the growth and even a slight contraction in the annual global CO_2 emissions for 2014 and 2015, respectively, while global GDP continued to rise, but this may be a temporary phenomenon rather than a departure from the long-term trend of increasing emissions (Jackson et al. 2016, Friedlingstein et al. 2014). Stagnant emissions from industrial sources were also observed during 2016, while atmospheric CO_2 concentrations continued to set new record highs, mainly due to compounding effects of El Nino and increased emissions from land-use (Peters et al. 2017). The CO_2 level in the atmosphere reached 403 ppm in comparison to the pre-industrial level of around 280 ppm and has been increasing at a rate over the last 70 years, which is around 100 times faster than during the end of last ice age (WMO, 2017). First comprehensive estimates of the carbon budget for 2017 suggest that emissions are again on the rise (Le Quere et al. 2017). Hence, time will tell whether we are indeed making progress in decoupling global CO_2 emissions from GDP growth or whether this was merely just a brief blip in long-term trend of increasing emissions, which would be detrimental for meeting the objectives of the Paris Agreement (Jackson et al. 2017).

In short, the SDGs rely considerably on the sound management of not just human capital and physical capital, but also natural capital. Helpfully, they set out targets for the protection and maintenance of natural capital within politically-agreed global limits. These targets could serve to guide the specification of natural capital that is to be deemed critical and not further depleted.

There is another opportunity provided by the SDG agenda – to improve and harmonize data collection. The Inter-Agency Expert Group on the SDGs (IAEG-SDG) has proposed a list of indicators for tracking progress towards the SDGs and their respective targets, which could help to fill the gaps in natural capital accounting. Some of the data required for the SDGs could, to an extent, increment the evaluation of natural capital in the Wealth of Nations dataset. For instance, the SDGs aim to keep track of the proportion of fish stocks within biologically sustainable levels; the value of fish stocks is not taken into account in the World Bank accounting exercise. A few indicators used by the SDGs are close to those used to evaluate natural capital in the Wealth of Nations data. Among these indicators, the wealth accounts give a value to protected areas, and as such this relates to the SDG indicators of "coverage of protected areas in relation to marine areas" and "forest area as a proportion of total land area" (see IAEG-SDG, 2017). Likewise, some SDG indicators are normalisations of indicators used in the wealth statistics (e.g. the proportion of agricultural area under productive and sustainable agriculture; or the energy intensity measured in terms of primary energy and GDP (see IAEG-SDG, 2017)).

Other SDG indicators may help to fill the gap of natural capital accounts. For example, the World Bank does not include electricity production from renewable sources in their evaluation of natural capital, whereas coal, oil and natural gas are factored in. Such an evaluation of natural capital favours dirty energy production instead of clean energy production. "Renewable energy share in the total final energy consumption" is one of the SDG indicators proposed to capture the clean energy dimension contained in the SDG targets (see IAEG-SDG 2017). The value produced by renewable energy could be included in natural capital. Likewise, the negative impact of waste and the value added from waste treatment are not captured by the current assessment of natural capital by the World Bank. A few SDG indicators relate to this problem (e.g. national recycling rate, tons of material recycled) and could be linked to the evaluation of the remaining reserves and mineral production within a country.

More generally, pollution and environmental degradations are elements that are insufficiently factored in the natural capital valuation performed by the World Bank. The development of SDG indicators and associated data collection should allow gathering information on several sources of pollution. This could be taken advantage of to correct for environmental degradation in the evaluation of natural capital in the Wealth of Nations dataset. For example, expanding the index of coastal eutrophication and floating plastic debris density, which is a proposed indicator for the SDGs (IAEG-SDG, 2017), would help provide further information on the extent of marine pollution. The proportion of important sites for terrestrial and freshwater biodiversity that are covered by protected areas is also another indicator that could be used to include the value of biodiversity in natural capital (see IAEG-SDG, 2017). Likewise, the proportion of land that is degraded over total land area could be used to assess losses in natural capital caused by unsustainable agricultural practices.

3.4 Conclusion

Quantifying the wealth derived from natural capital can help improve natural resource management. With incomplete accounting of natural capital stocks and flows at inaccurate prices, increasing monetary values of natural capital is not necessarily an indicator of sustainability. If accounting were comprehensive and prices accurate, decreases in measured wealth would serve as reliable indicator of a lack of sustainability in a given national economy.

The existence of thresholds and system limits implies that another governance process is required to complement wealth accounting. Such a process would ideally incorporate the best science and arise through a legitimate, political consensus-building process. Happily, such a process exists and has recently delivered the SDGs, which provide initial (if incomplete) guidance on the specification of the levels of natural capital beyond which further depletion is agreed to be inadvisable.

4. Recommendations

4.1 Measurement

Scientists and scientific institutions have an important role to play in the measurement of natural capital, to ensure that it ultimately appears on corporate and national balance sheets (discussed further below). As more and more data become available, there is an outstanding opportunity to strategically improve the underlying biophysical information for wealth accounting and to track progress on the SDGs. For this to occur, more granular data and models of ecosystem functioning are required as well as the integration from multiple sources to advance the understanding of interactions between natural processes, taking place at local, regional and national scales.

Recommendation 1: Existing or new scientific institutions are clearly mandated to collect systemic and appropriately granular scientific data on the functioning of natural systems, facilitate open data access, and link to international efforts, allowing for an integration of information across scales.

Finance ministries and national statistical offices require the remit and funding to collate the underpinning scientific data and then work alongside scientists and economists to collect data on economic values on the services provided by nature. Very few if any countries are adequately resourced, leaving the World Bank and the UN to partially fill in some of the gaps. Even in countries with world-leading efforts, such as the United Kingdom, there are many missing elements.

Recommendation 2: National Statistics agencies collate the natural capital data required for tracking the SDGs and to report credible National Wealth numbers on an annual or quarterly basis.

There are some overlaps in the data required for the natural capital elements of the wealth accounts and for the SDGs. It makes sense to extract synergies, wherever they exist. For instance, as noted above, current wealth estimates omit the value of fisheries, renewable energy provided by nature, and the value added from waste treatment by nature. However, the SDGs aim to keep track of the proportion of fish stocks within biologically sustainable levels, and SDG indicator is the "Renewable energy share in the total final energy consumption", and several SDG indicators relate to waste management. Better data for the SDGs might improve wealth accounting, and vice versa.

Recommendation 3: Data collected to monitor progress on the SDGs and for the national wealth accounts is harmonised to reduce inconsistencies and duplication of effort and to increase policy relevance.

4.2 Accounting and Pricing

Good data on the physical flows of goods and services provided by nature is a vital starting point. The next step is to use such data to layer economic values and prices on top. Estimates of the *value* of the goods and services provided by nature is necessary for decision making under uncertainty by treasuries and finance ministries.

Determining appropriate values must extend beyond a market-price-only approach, given that market prices can provide very misleading conclusions about the societal value of nature. Delivering a more accurate set of societal values will involve an expanded application of economic tools – including survey and econometric methods – and going beyond rough and ready "benefits transfer" approaches.

Recommendation 4: Non-market valuation techniques are used more widely to enlarge the set of natural assets incorporated into national wealth accounts.

Businesses manage much of the natural capital of the nation. Greater data collection, data transparency, and proactive management from businesses could help scientists and government to have a more complete picture of the stock of natural capital of the nation, and allow its enhancement at ground level.

Recommendation 5: Civil society and government encourage corporate natural capital accounting and management, while firms make their natural capital accounts and data publicly available.

Finally, without increased demand for the valuation of natural capital, the supply of physical and economic data on natural capital is unlikely to be sustainable. Organisations in finance, business and civil society have roles to play in holding public bodies accountable for the provision and quality of natural capital valuations. For instance, suppose ratings agencies were to find it useful to use national wealth measures – including the breakdown into physical, human, social, natural, intellectual and financial capital – in rating countries. The countries themselves would then have a stronger incentive to ensure that such data was accurate, knowing that it would be internationally scrutinised and that the data would have consequences (as the release of GDP data does today).

Recommendation 6: Financial organisations, corporates and civil society demand that government provides wealth accounts and progress updates on SDGs, and hold them accountable if they do not.

4.3 Economics of substitutability

Our review of the literature on the substitutability of nature revealed much to be desired. Empirical estimates are often biased and provide an unsound basis for public policy. Without a more granular understanding of the irreplaceability (or otherwise) of nature at different scales, it is difficult to know what aspects of natural systems can be depleted or traded in return for increases in other forms of capital. For instance, the nine planetary boundaries provides guardrails at the global level, but they do not all translate well into region or national specific guidance. They also have relatively little, if anything, to say about economic activity, trade-offs and substitutability. If approaching one boundary can generate vast increases in human welfare for modest increases in risk, how is that trade off to be evaluated?

Recommendation 7: Scientists and economists jointly conduct more rigorous empirical and theoretical work to understand substitutability, boundaries and thresholds in natural systems at local, regional and global scales.

What does emerge from our analysis, however, is that greater substitutability of natural capital in production processes is required to continue economic development, decoupling economic output from the depletion of natural capital and environmental impacts. Elasticities of substitutability are not fixed in time and space and can be changed. Support should be provided for environmentally-friendly innovation, rather than environmentally-harmful innovation. Examples might include the development of artificial meat, and products that substitute for human demands on nature. An international initiative akin to the "Mission Innovation" effort on clean energy R&D is worth considering.

Recommendation 8: Governments actively support R&D in technologies that reduce pressure on nature. A well-funded global initiative on natural capital innovation is underway.

4.4 Governance

Second, natural systems, like financial systems, can be complex adaptive systems with non-linearities and thresholds. Just as economists discovered that it was unsafe to assume that the financial system can regulate itself – and thus left it out of models of the economy – so too is it unwise to assume that natural systems will simply work without careful market design. This report has highlighted the fact that if economic analysis assumes natural capital losses to be reversible, when they are not, or linear, when in fact they are subject to thresholds and tipping points, biased estimates of the substitutability of natural capital will result. To avoid these risks, an explicit register of *critical capital* should be drawn up on a country by country basis. An international agency should take responsibility for ensuring that globally-relevant natural assets are not omitted when the decision-making unit is the relevant national government.

Finance ministries need to be apprised of major risks to economic performance in the short and long run. After the 2008 financial crisis, they now recognise the need to keep a close watch on risks in financial systems. Some countries are now recognising that similar or greater risks exist in natural systems upon which economic production depends. This is often particularly applicable for developing countries, where natural capital comprises a much larger share of the productive capital assets.

For instance, bank regulators must trade off resilience and efficiency when setting capital reserve ratios – too high and the economy suffers, too low and dangerous risks can build. Electricity regulators face a similar trade off when supervising system capacity margins; too high and money is wasted on unnecessary power plants, too low and the lights risk going out. Natural systems are complex systems, as is the financial system, and natural infrastructure is similar to physical infrastructure, in that a great deal of other productive activity rests upon it. Just as a precautionary approach is considered wise in the financial and power systems, so too it is wise for natural systems.

We therefore recommend that quantity and quality of natural infrastructure be maintained with an appropriate reserve margin. If ignored, or over exploited without maintenance, these infrastructures will decay, reducing overall economic productivity and increasing risks of unhelpful shocks.

Recommendation 9: Informed by the SDGs, countries draw up a register of *critical capitals*, including critical natural capital. This may include the establishment of metrics and precautionary thresholds, below which such capital assets are not permitted to decline. Natural infrastructure is maintained with an appropriate reserve margin.

Finally, given the relatively poor performance at measuring and managing natural capital to date, there may be benefit in establishing new institutions to supervise, examine and report on natural systems and their implications for economic and financial decisions. The United Kingdom has established such a committee, and other countries may wish to consider establishing a body with a similar remit suitable to their own economic and political context. This could complement and support a broader dialogue of public, private and civil actors on the establishment of values for natural capital and their incorporation into national balance sheets.

Recommendation 10: Countries establish Natural Capital Committees responsible for national natural capital infrastructure reporting directly to Finance Ministries.

4.5 Future directions

The research conducted for this report has raised a number of further questions for discussion. They give rise to a research agenda beyond the scope of the current project. Questions for further exploration include the following:

1. How can the alignment between the SDG and national wealth agendas be improved?
2. How should the missing datasets be prioritised? What tools and mechanisms are most suitable to deploy to collect the necessary data and economic valuations?
3. How can demand (political, popular) for market and non-market valuations of natural capital be increased?
4. What is the role of private sector interests and initiatives in bringing together the wealth and SDG agendas to ensure that natural capital is better managed?

5. Glossary

Critical natural capital: “Part of the natural environment, which performs important and irreplaceable functions” (Chiesura and de Groot, 2003). Its “maintenance…is essential for environmental sustainability” (Ekins et al., 2003).

Elasticity of substitution: a measure of the curvature of the isoquant that indicates how substitutable different inputs are.

Isoquant: a locus of input combinations that deliver the same level of output.

Marginal analysis: an approach that studies effects of (infinitesimal) incremental additions or changes to an economic system.

Planetary boundaries: “a concept that presents a set of nine planetary boundaries within which humanity can continue to develop and thrive for generations to come. Crossing these boundaries could generate abrupt or irreversible environmental changes. Respecting the boundaries reduces the risks to human society of crossing these thresholds.” (Stockholm Resilience Centre)

Precautionary principle: “An approach to risk management whereby if there is the possibility that a given policy or action might cause harm to the public or the environment and if there is still no scientific consensus on the issue, the policy or action in question should not be pursued. Once more scientific information becomes available, the situation should be reviewed. The precautionary principle may only be invoked in the event of a potential risk and can never justify arbitrary decisions.” (European Commission, EUR-Lex)

Resilience: “The ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions.” (IPCC, 2012)

Sustainable development: “Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” (WCED, 1987).

The Anthropocene: “Earth’s most recent geologic time period as being human-influenced, or anthropogenic, based on overwhelming global evidence that atmospheric, geologic, hydrologic, biospheric and other earth system processes are now altered by humans.” (www.anthropocene.info)

Tipping Point: “A level of change in system properties beyond which a system reorganizes, often abruptly, and does not return to the initial state even if the drivers of the change are abated.” (IPCC 2014)

Transformation: “A change in the fundamental attributes of natural and human systems.” (IPCC 2014)

Hartwick Rule: “Invest *all* profits or rents from exhaustible resources in physical [or human] capital.” (Asheim, 2013).

Weak sustainability: a view of sustainable development that views most natural capital as substitutable with physical or human capital.

Strong sustainability: a view of sustainable development that explicitly recognises the presence of critical natural capital.

6. Appendix: Substitutability

6.1 Overview

This appendix sets out the basic concepts and theory of substitutability (section 6.2), outlining its importance (section 6.3) and some of the caveats on using elasticities of substitution (section 6.4).

6.2 Substitutability in production functions

Substitutability and complementarity are fundamental concepts in economic analysis. They help us understand how our *use* of one resource changes when the *availability* of another resource changes. Substitutability and complementarity appear in many areas of theoretical economics, including consumer theory (Slutsky, 1915; Hicks and Allen, 1934; Samuelson, 1974), auctions (Ausubel and Milgrom, 2002), and matching markets (Kelso and Crawford, 1982), but here we will focus on their importance in *production theory* in order to build a foundation for the understanding of substitutability of natural capital.

Production theory is concerned with how firms make production decisions. Consider a firm that produces an output or a product with a combination of inputs. The firm's operations can be described by *production function* that assigns a level of output to any combination of inputs. Exactly how much the firm chooses to produce depends on the prices and availability of the inputs, the price at which it can sell its output, and the nature of the market it operates in (for example, whether it is competitive or not). Here, we will make some simplifying assumptions that will closely tie the firm's production decision to the production function.

Let us suppose a firm requires physical capital (e.g. machines) and natural capital (e.g. land, water, trees, or fish) to produce an output. An isoquant (Figure 5) describes combinations of inputs that are consistent with a particular level of output. Pick a point on an isoquant. The slope of the isoquant at that point describes the *marginal rate of technical substitution (MTRS)*: how many units of natural capital need to be added to maintain the same level of output when the physical capital available to the firm is reduced.

For simplicity, consider the standard case in which isoquants are convex to the origin (as in Figure 5). Here, the MTRS is always decreasing in the availability of inputs. This means that if a resource becomes scarcer, it becomes harder to substitute. If, in addition, the isoquants never touch the axes, this means that in order to produce any (positive) amount of output, the firm will require some amount of *both* inputs. Note that even though the MTRS varies along the isoquant, isoquants are *always* downward sloping (if all the inputs of the firm increase, it shouldn't be producing less than before since it can throw these inputs away), so the marginal rate of technical substitution is always negative. In this sense, when there are two inputs are (almost) always (*net*) substitutes.

When firms face relative prices for different inputs, we can represent a constant cost level by an isocost line (Figure 6). Then, given a particular cost level, the firm can choose how much of each input to use according to its production function. In the data, we typically observe firms' production decisions and relative prices of inputs and under the assumptions that firms take the prices as given we can make inference about the shape of their isoquants. MTRS therefore plays a very important role in the analysis of firm decisions in competitive markets: if a firm takes input prices as given, then the firm will choose to produce at the point where MTRS is equal to the ratio of input prices (Figure 6).

Isoquants can capture our intuition about the notions of complementarity and substitutability. If an isoquant is a straight line (Figure 7), then the firm can always substitute any unit of labour for a fixed number of units of capital. In this case, labour and capital are clearly *perfect* substitutes. On the other hand, an L-shaped isoquant captures the fact that without a minimum level of both inputs, a given level of production is not possible. In this case, labour and capital are clearly

Figure 5: Production of a fixed quantity of a good using physical and natural capital

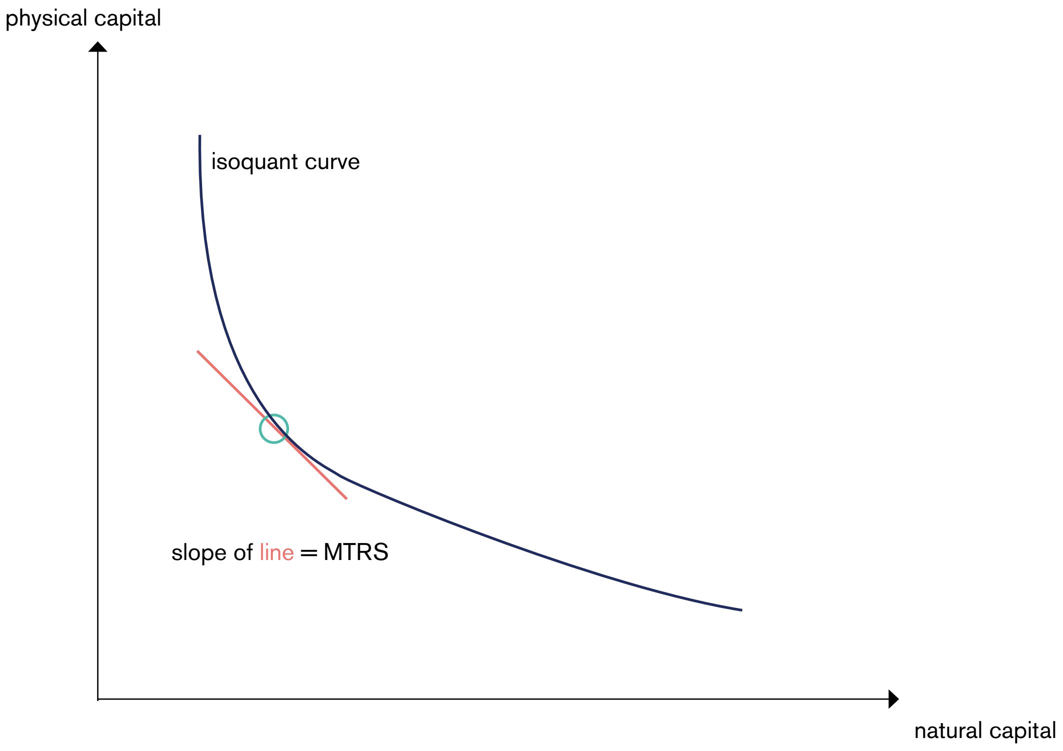


Figure 6: Firms substitutes different inputs depending on their relative price

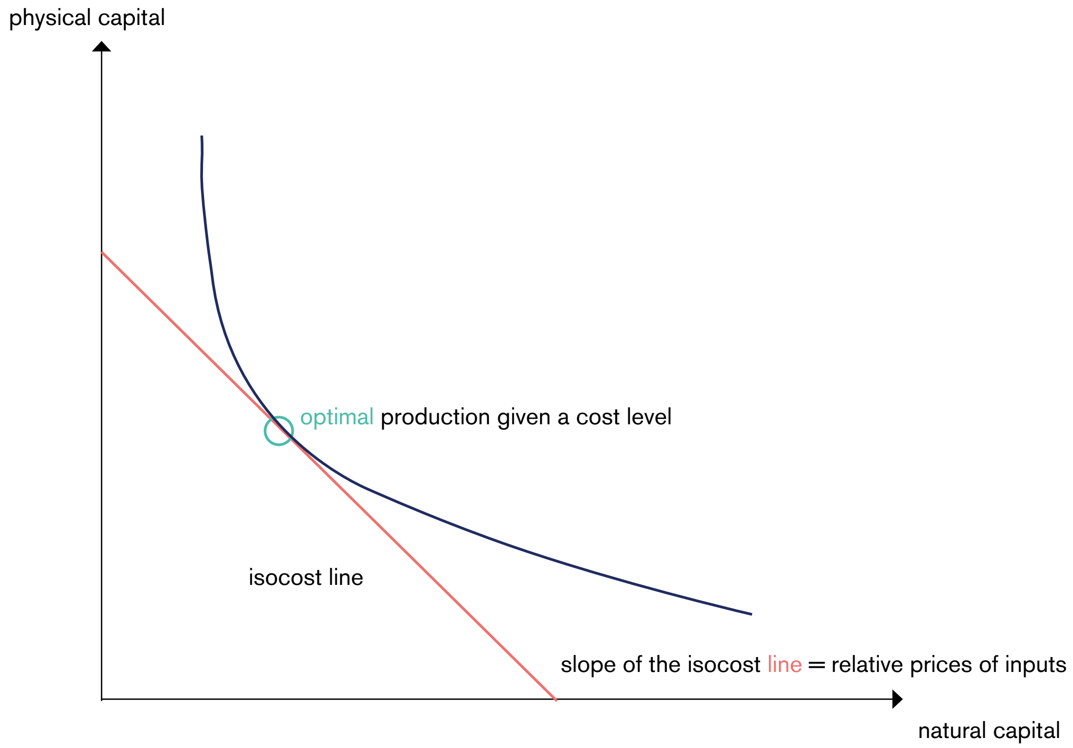
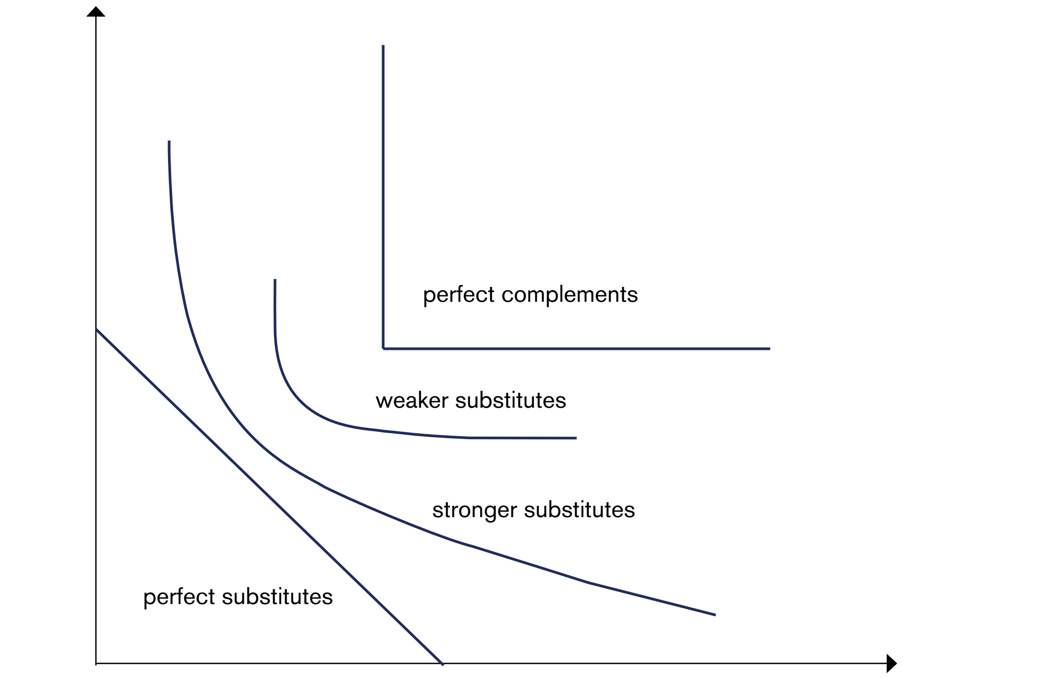


Figure 7: Perfect complements, perfect substitutes and intermediate isoquants



perfectly complementary. The intermediate cases are less clear, though that the *greater* the *curvature* of the isoquant is, the *more complementary* inputs are.

One way to measure the curvature of the production function is by *elasticity of substitution.* The elasticity of substitution measures the percentage change in the ratio of inputs *used* in response to a percentage change in the MTRS i.e. the relative *availability* of inputs. If the two inputs are perfectly complementary, then the elasticity of substitution is zero: a change in the MTRS has no effect on the ratio of inputs used. If the two inputs are perfectly substitutable, then the elasticity of substitution is infinite: any small change in the MTRS would mean that that firm wants to use *only one* of the inputs. These are both extreme cases and empirically we expect the elasticity of substitution to be somewhere in between.

Nothing in our discussion above would change if we considered welfare (or utility level) of a person instead of a production function and consumption decisions instead of choices of inputs. Different types of elasticity of substitution between goods are defined analogously for a consumer. However, since welfare and utility levels, unlike production, are unobservable the link between our theoretical foundation and empirical methods would be different. The substitution model with utility (rather than production) starkly highlights the trade-offs between alleviating poverty or increasing consumption and depleting natural capital. The only way to avoid the trade-off between consumption and natural capital is by expanding by moving to a higher utility level i.e. expanding the utility frontier with technological change or economic growth.

6.3 Importance of substitutability

Why is the elasticity of substitution so crucial? The main reason is that elasticity of substitutability is a key parameter in understanding whether a particular level of consumption and investment in the economy is "sustainable" i.e. whether the future generations will be able to enjoy the same level of consumption (see also our discussion of wealth accounting and natural capital above). Suppose, for simplicity, that consumption goods are produced with two inputs (factors of production): physical capital and exhaustible and irreplaceable natural capital e.g. oil (exhaustibility and irreplaceability are not crucial, as we discuss below, but they make our key point clearer). The planner (the firm or the government – there is only one agent in our framework) has to decide how much oil to extract, how much output to consume and how much output to save. The planner can reinvest proceeds from savings (output that was not consumed) into accumulating more physical capital (e.g. building more roads) that would increase the ability to produce more output in the future.

What are the optimal rates of consumption, saving and oil extraction in this simple economy? Is it possible to sustain a constant level of consumption/production/welfare over time?

Clearly, in order to sustain a constant level of production (or consumption or welfare) forever, it should not be possible to extract all the oil since in the production function both inputs are needed to produce a positive amount. But as the oil runs out, the planner will find it harder and harder to substitute the oil for the physical capital while remaining on the same isoquant.

It turns out that if the elasticity of substitution is high, then the planner will be able to compensate for the loss of the *exhaustible* natural capital (e.g. oil) by investing the proceeds into physical capital (e.g. solar panels that take advantage of *renewable* natural capital) and maintaining the same level of production forever (Dasgupta and Heal, 1974, 1979). In the extreme case of perfect substitutes, the planner does not need to extract *any oil* at all and only use physical capital to produce output.

This observation was the basis for the famous *Hartwick Rule*: "Invest *all* profits or rents from exhaustible resources in other capital." If there is sufficient *substitutability*, the optimal level of constant production is obtained if and only if the Hartwick Rule is followed (Hartwick, 1977; Asheim, 2013).

However, if natural capital and physical capital are sufficiently *complementary*, even the Hartwick Rule might fail to sustain constant production. It might simply be impossible to sustain a constant level of production.

This analysis, while instructive, is not comprehensive. We described a very simple model to illustrate concepts from our discussion including elasticity of substitution and production functions. Of course, our "toy model" excluded a number of key elements: technological change, increasing population, multiple inputs, renewability of some forms of natural capital (e.g. forests, fish) etc. If advances in technology make natural capital more substitutable over time, then the Hartwick Rule might still ensure constant consumption. On the other hand, if population grows very fast, then the Hartwick Rule might fail again. With multiple inputs, it really matters which are renewable, which are exhaustible and what the elasticities of substitutability between different pairs are. Finally, we have assumed that the best-case scenario: that the Hartwick Rule can actually be committed to over a long period of time. It is very tempting for every government to spend and "consume" the proceeds from an extracted mineral resource. Some countries around the world follow it much closer (Norway) than others (the UK).

In conclusion, substitutability (and, in particular, the elasticity of substitution measure) between natural capital and other inputs is a key parameter that indicates whether there is even a possibility that future generations could inherit an opportunity to enjoy the same level of consumption, production or welfare as the present one.

6.4 Empirical estimates and caveats

There are several other reasons to be very cautious about estimates of the substitutability of natural capital. In paper prepared to support this report, Cohen, Hepburn and Teytelboym (2017) review the literature on the substitutability of natural capital with other forms of capital. Their review finds that most estimates of substitutability of natural capital are potentially unreliable. Recent statistical methods that deal with several econometric problems pervasive in the literature have not been applied yet to look at energy or resource substitutability. For the other types of natural capital, prices are often unavailable or do not reflect scarcity of resources.

Due to the lack of robust estimate, Cohen, Hepburn and Teytelboym (2017) focus on relevant studies that do not directly assess the degree of substitutability, but are still informative on the technical feasibility of using less natural capital in production. They opt for analysing two cases: energy use in industry and land use in agriculture. The conclusions from these analyses are that substitutability between natural capital and other capitals must be "low to moderate", a long way from the assumption of perfect substitutability that is implicit in much natural capital accounting.

7. Appendix: Wealth Accounting

It is sometimes assumed that rich countries became rich by consuming their natural capital or converting it to other uses. This assumption appears to be confirmed by examining the *shares* of natural capital in total wealth for OECD countries and low income countries (Figure 8). In 2014, natural capital (shown in light green) constituted less than 3% of the wealth of OECD countries versus over 47% of low income countries.

Description: This figure describes the proportion of capital that is either human, physical or natural within an income group. Source: World Bank Wealth of Nations Data. Income categories are as defined by the World Bank.

However, looking only at shares of wealth can deceive, as Figure 9 shows. In per capita terms, natural wealth in OECD was roughly three times the value in low income countries in 2014 and roughly two times the value in 1995. Rich countries have grown rich not by destroying nature, but by investing enormously in produced and human capital, respectively 28% and 70% of total wealth in 2014. Moreover, rich countries apply advanced technologies and management practices to their natural resources, further boosting the value of natural capital per person.

Figure 10 continues the process of deconstructing the differences between rich and poor countries by excluding the values of subsoil assets and non-timber

Figure 8. Composition of capital within income groups (2014)

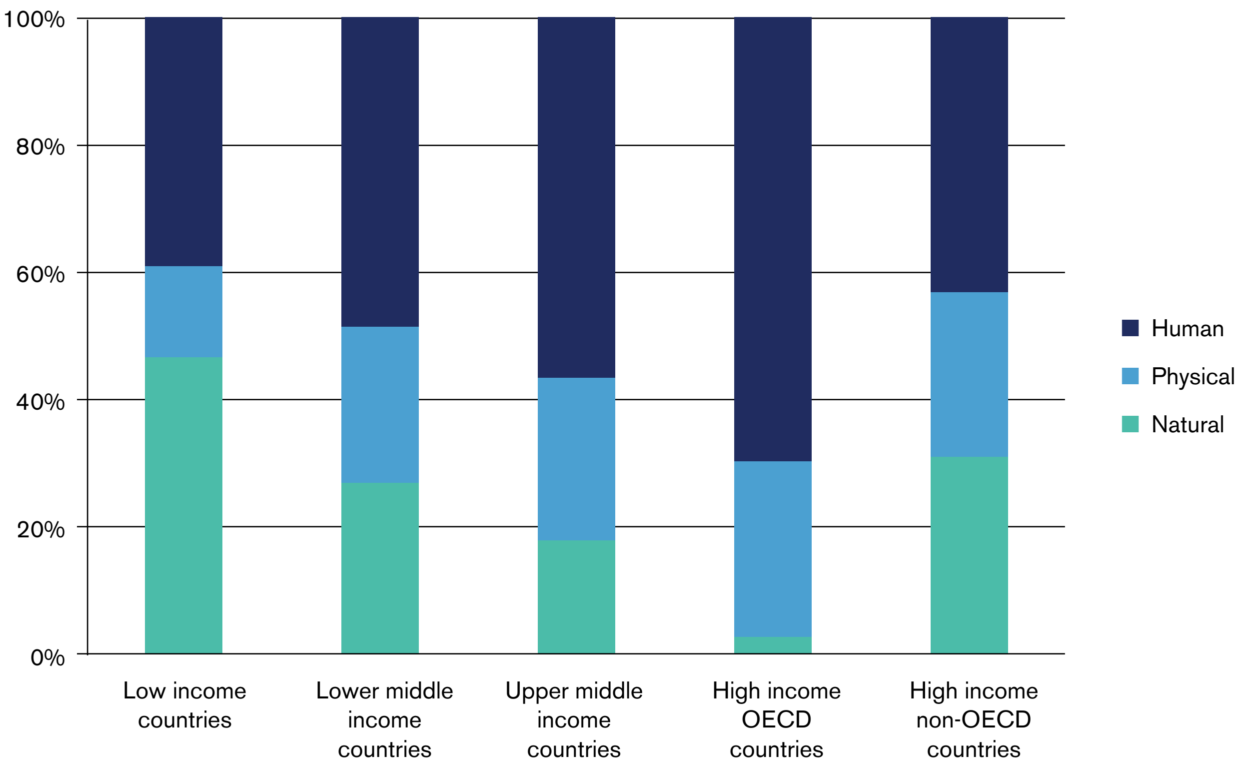


Figure 9. The value of natural capital (US$) per capita

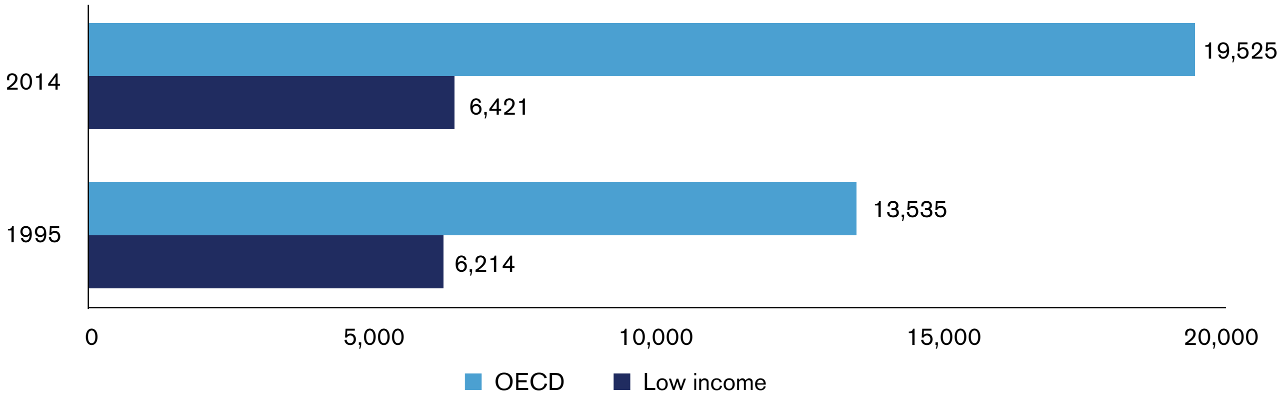
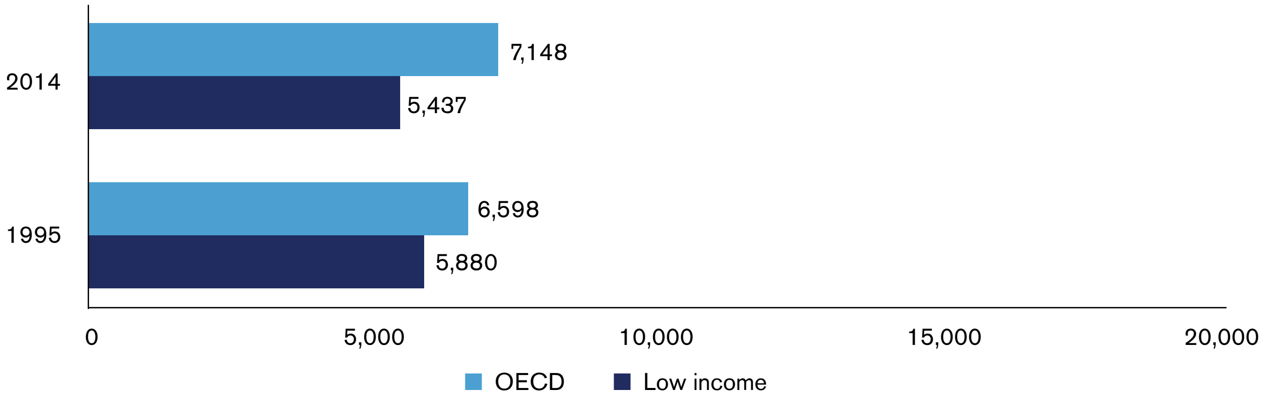


Figure 10. Natural capital per capita excluding subsoil and non-timber forest resources



Source: World Bank (2017)

forest resources from natural capital. By this measure rich countries still enjoy slightly more natural wealth per person than poor countries, but the gap is narrowed.

The reasons for a comparison excluding these two components are as follows. First, OECD countries had nearly $7,500 more mineral and fossil fuel wealth per capita than low income countries in 2014, and nearly $4,500 more non-timber forest resources. It can be argued that the difference in subsoil wealth per capita between rich and poor countries is an endowment effect, the result of a roll of the geological dice, rather than a result of national decisions. That said, Paul Collier has argued persuasively that Africa in particular (where the majority of low income countries are found) is 'under-explored' by resource firms, largely owing to weak governance in these countries (Collier, 2011). While some African countries do attract foreign investment, for many firms it is simply too risky to invest when governments may expropriate assets, revoke licenses or impose punitive taxation after investments have been made.

Second, the higher values of non-timber forest resources – largely recreation and water service values – in OECD countries are driven by valuation of these services using measures of willingness to pay. Willingness to pay is constrained by ability to pay, and therefore reflects the roughly 100-fold gap in per capita income between rich and poor countries (at market exchange rates), rather than any superior management of natural capital in OECD countries.

Irrespective of these debates, it is clear that natural capital is more valuable and better managed in wealthier countries. The World Bank wealth data shed important light on the linkages between natural resources and development. In contrast with the standard assumption, that rich countries consumed their natural wealth in order to develop, the picture that emerges highlights the importance of diversifying development through produced and especially human capital, the application of new technologies, and the development of better institutions and management practices.

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