Substitution, natural capital and sustainability

Lucas Reijnders

IBED, University of Amsterdam, Amsterdam, The Netherlands

ABSTRACT
Substitutability of natural capital by human-made capital would seem to be limited. When human-made capital substitutes natural capital, there are currently commonly long-lasting negative impacts of such substitutions on constituents of natural capital. Long-lasting negative impacts on natural capital can be considered at variance with justice between the generations. In view thereof, there is a case to define (environmental) sustainability as keeping natural capital intact for transferral to future generations. A major problem for such conservation regards natural resources generated by geological processes (virtually non-renewable resources), especially regarding geochemically scarce elements. Substitution of virtually non-renewable resources by generating equal amounts of renewables has been proposed as a way to conserve natural capital. However, renewables substituting for fossil carbon compounds are currently associated with negative impacts on constituents of natural capital to be transferred to future generations. The same holds for the substitution of widely used geochemically scarce virtually non-renewable copper by abundant resources generated by geological processes. Though current negative impacts of substitutions on natural capital can be substantially reduced, their elimination seems beyond the scope of what can be achieved in the near future. The less strict “safe operating space for humanity”, which has been used in “absolute sustainability assessments” is, however, not a proper alternative to keeping natural capital intact for transferral to future generations.

1. Introduction

In defining sustainability, substitution of natural capital has emerged as an important matter. It has been argued that the substitutability of natural capital by (hu)man-made capital is a crucial factor in choosing between sustainability as conserving (critical) natural capital or conserving the per capita sum of human-made capital and natural capital. E.g. Solow (1986) and Arrow et al. (2004) have argued in favour of sustainability as conserving the per capita sum of human-made capital and natural capital, whereas, in view of limitations to such substitution, Goodland and Daly...
have defended sustainability as conserving (critical) natural capital. Before going into this discussion, the concepts (critical) natural capital and human-made capital merit definitions.

Human-made and natural capital are not uniformly used in scientific literature. The uses of the concept natural capital, which is central to this paper, and its history have been discussed by Akerman (2003), Nadal (2016), Missimer (2018) and DesRoches (2019). Akerman (2003) and Nadal (2016) view natural capital as a metaphor and cover the periods of 1988–2000 (Akerman) and 1973–2013 (Nadal 2016), respectively. Missimer (2018) views natural capital as an economic concept, traces natural capital in its modern meaning back to 1908 and considers the history of this concept since then. DesRoches (2019) focuses on the history of the economic concept critical natural capital. Differently from Akerman (2003) and Nadal (2016), natural capital is not used here as a metaphor. Rather, natural capital is defined here as the stock of environmentally provided assets from which now and in the future products and services can be derived that are useful to humanity. It comprises ecosystems, providing services that benefit humans (ecosystem services), natural resources (e.g. ores) and the physical environment providing services such as insolation. Critical natural capital has been defined as natural capital for which there is no human-made capital as substitute (DesRoches 2019). (Hu)man-made capital, as defined here, includes manufactured capital (the physical human-made stock) and human capital (knowledge, information, skills, health) (Arrow et al. 2004). Social capital, that is norms, trust and networks facilitating collective action (e.g. Lethonen 2004; Gannon and Roberts 2020), has also been included in human-made capital (e.g. Costanza et al. 2021), but here social capital has not been included. The definition of sustainability as impacted by the substitutability of natural capital by human-made capital will be discussed in section 1. The conclusion of this section will be that a definition of sustainability in terms of keeping natural capital intact for transferral to future generations is preferable.

The generation, functioning and maintenance of human-made capital are impossible without the use of natural capital (Costanza and Daly 1992). Using natural capital may keep natural capital intact, for instance, by extracting not more freshwater than is rapidly replenished (Bierkens and Wada 2019). It may increase natural capital, for instance, by restorative land use to reverse soil degradation (Lal 2015). It may also negatively impact natural capital, for instance, by fish catches that cannot be restored by natural reproduction (Kantoussan et al. 2018). Furthermore, manufactured capital can give rise to mixed positive and negative impacts on constituents of natural capital, as for instance in the case of offshore wind-power facilities (Hooper et al. 2017).

If (environmental) sustainability is defined as keeping (critical) natural capital intact for transferral to future generations, it is important how the current provision of food, without which the generation, functioning and maintenance of human-made capital would be impossible, impacts natural capital. This will be discussed in section 2. Also, beyond the provision of food, manufactured capital life cycles are linked to impacts on natural capital. These will be considered in section 3. The conclusion drawn from sections 2 and 3 will be that when human-made capital substitutes
natural capital, there are currently commonly long-lasting negative impacts of such substitutions on constituents of natural capital. Consumption of mineral resources generated by geological processes contributes much to this negative impact.

Mineral resources generated by geological processes include fossil carbon compounds, ores and salt deposits. These resources have been called non-renewable, but geological formation processes may continue in the case of fossil fuels (e.g. Didyk and Simoneit 1989; Patzek 2008), ores (e.g. Hedenquist and Lowenstern 1994) and salt deposits (e.g. Melchiorre et al. 2018), be it that for geochemically unabundant substances current consumption may well be very large if compared with current formation (e.g. Patzek 2008). In view thereof, here the term virtually non-renewables is used.

As pointed out by the UN International Resource Panel (2011) and Baninla et al. (2019), virtually non-renewable mineral resources are very important for current economies. Twenty-seven methods for measuring depletion of virtually non-renewable mineral resources have been proposed, but no consensus about the best among these methods has emerged (Sonderegger et al. 2020; Berger et al. 2020). However, there appears to be no doubt that for practical purposes stocks of virtually non-renewable minerals are finite and that the sums of many of these stocks and their derivatives in current economic use are currently subject to reduction. This is shown in studies regarding fossil carbon compounds (e.g. Patzek 2008; Höök et al. 2010), potassium salts (Drillon et al. 2019), 50 ore-derived elements (Ciacci et al. 2016; Helbig et al. 2020) and 47 mineral commodities (Calvo et al. 2017).

A potential way out of problems regarding the conservation of natural resources that are generated by geological processes has been suggested by Daly (1990) and Ekins et al. (2003). They have proposed that keeping natural capital intact allows for the depletion of non-renewable natural resources to the extent that the rate of depletion equals the creation of renewable substitutes. The current emergence of renewables as substitutes for virtually non-renewable fossil carbon compounds allows for an evaluation of this proposal. This evaluation will be presented in section 4. Another option for dealing with problems regarding the conservation of natural resources that are generated by geological processes might be sought in exploiting the variation in their abundance. The deposits of the abundant elements aluminium (Al), iron (Fe) and silicium (Si) generated by geological processes might be considered for practical purposes inexhaustible, whereas this is not the case for deposits of geochemically scarce elements. Thus, the substitution of geochemically scarce elements by geochemically abundant elements and the impacts thereof on natural capital merits consideration. This will be done in section 4 for the geochemically scarce element copper. Worldwide copper production ranks currently third, after Fe and Al, and relatively much work has been done regarding the substitution of copper by Al, Fe and Si. Section 4 concludes that the substitution of virtually non-renewable fossil carbon compounds by renewables and the substitution of geochemically scarce copper by abundant elements is currently associated with long-lasting negative impacts on constituents of natural capital.

In section 5 it will be pointed out that there is technical scope for a substantial reduction of the current long-lasting negative impacts on constituents of natural capital by the substitutions considered in this paper, but their elimination seems beyond the scope of what can be achieved in the near future. For this reason, section 5 will discuss whether the less strict concept of a safe operating space for humanity is a proper alternative to keeping natural capital intact in defining (environmental) sustainability. Section 6 will present the conclusions of this paper.
2. Substitution of natural capital by human-made capital and its impact on definitions of sustainability

As pointed out in the introduction, there are divergent points of view regarding the degree to which (hu)man-made capital can substitute natural capital. Many economists hold the view that (hu)man-made capital, especially manufactured capital, can to a large extent substitute natural capital (e.g. Mäler 1986; Solow 1986, 1993; Arrow et al. 2004; Cohen et al. 2019). In line with this view, it has been argued that per capita the sum of (hu)man-made capital and natural capital should remain intact, a requirement that has been equated with sustainability (e.g. Solow 1986, 1993; Arrow et al. 2004). The assumption that there is a high degree of substitutability of natural capital by human-made capital has been contested. E.g. Ekins et al. (2003) and Ayres (2007) argued that substitutability of natural capital by human-made capital is limited. Drupp (2018) found that actual substitution of ecosystem services by manufactured goods is limited. Cohen et al. (2019) reviewed available empirical studies regarding the substitutability of energy by other forms of capital. They found major deficiencies in these studies. Cohen et al. (2019) concluded from surveying the available evidence that substitutability of energy in heavy industry and of land (soil) in agriculture by other forms of capital can only be plausibly low to moderate, here equated with limited.

Substantial substitutability of natural capital by manufactured capital currently regards resource-efficiency, such as energy- and material efficiency. This has been shown for manufacturing and heavy industry (e.g. Gutowski et al. 2013; Camilleri 2018), electronics and vehicles (Hertwich et al. 2019) and buildings (Kedir and Hall 2020; Saade et al. 2020). Improving such efficiencies by manufactured capital leads to the substitution of only a part of the resource-, energy- or material input. In the case of, for instance, fossil fuels this implies that natural capital embodied in the stock of fossil carbon compounds is still negatively impacted. A similar negative impact is currently also highly likely in the case of improved efficiency regarding other virtually non-renewables, such as ores and ore-derived substances (e.g. Reijnders 2014; Ciacci et al. 2016). In the case that there is sharing, the natural capital embodied in the object that is shared gets more users but is not fully substituted.

Substitution of natural capital by manufactured capital does not necessarily mean that the pressure on natural capital linked to the resource involved is reduced to the extent of substitution. Firstly, the opposite, substitution of manufactured capital by natural capital, can also occur. For instance, an analysis regarding manufacturing sectors in 10 OECD countries during the 1980–2007 period suggests that the substitution of manufactured capital by energy was actually larger than the substitution of energy by manufactured capital (Kim and Heo 2013). Secondly, Jevons (1866) found that more efficient coal consumption by using improved manufactured capital in the United Kingdom led to an economy-wide increase in coal consumption. This phenomenon, known as Jevons’ paradox, is now often referred to as an economy-wide rebound effect. Brockway et al. (2021) reviewed the evidence regarding current improvements in energy efficiency and concluded that economy-wide rebound effects may erode more than half of the expected energy savings by using human-
made capital for energy efficiency. Skelton et al. (2020) reviewed economy-wide rebound effects of improved material efficiency on resource demand and found values ranging between 3%, which they viewed as an underestimate, and 68%. Lu and Schandl (2021) studied economy-wide impacts of improved material efficiency in the Australian iron- and steel, non-ferrous metals and non-metal construction mineral sectors on well-mixed greenhouse gas emissions. They concluded that due to rebound effects in other sectors and other processes there was not necessarily a decrease of well-mixed greenhouse gas emissions and that there even might be an increase. In a study of improved water efficiency in irrigation regarding water-stressed Kansas (USA), Pfeiffer and Lin (2014) found a rebound effect >100%. Drip irrigation has been described as the most water-efficient irrigation technology (e.g. Megersa and Abdulahi 2015). But studies regarding drip irrigation in water-stressed parts of India and Morocco concluded that, due to associated shifts in cropping patterns, water consumption was actually increased when drip irrigation was applied (Birkholz 2017; Molle and Tanouti 2017). In the case of sharing rebound effects can occur too. Warwington-Lundström and Laurenti (2020) found an average 46.5% direct (not economy wide) rebound effect for platform-based boat sharing. These findings suggest that in the case of improved resource efficiency actual net substitution of the resource(s) involved may be much reduced by rebound effects.

The position that substitutability of natural capital by human-made capital is limited has led to the point of view that natural capital that cannot be substituted by human-made capital should remain intact, a requirement that has been equated with (environmental) sustainability (Desroches 2019). In sections 2–4 it will emerge that commonly current substitutions of natural capital do not keep natural capital intact. For this reason, the conservation of natural capital rather than the conservation of critical natural capital will be considered in this paper. In such conservation, the time-scale of negative impacts on natural capital is important. This follows from considerations of intergenerational justice: the just distribution of resources and environmental burdens between present and future generations. One may assume that there may be many future generations of Homo sapiens, as primate species frequently exist in the order of $10^6$ years (Springer et al. 2012). Under this assumption, keeping natural capital intact for transferral to future generations is in line with the expected outcome of applying the decision rule that judgment about intergenerational justice as to the use of natural capital should be “behind the veil of ignorance” regarding the generation to which one belongs (Rawls 2001). Against this background, in the next sections the focus will be on the conservation of natural capital that is to be transferred to future generations. Long-lasting (>20 years) human impacts on natural capital relevant to transferral of natural capital from generation to generation, will be prominent in the next sections. Examples of such impacts are in Table 1.

3. The impact of the current provision of food on natural capital

There are many things that humans may do without, but humans cannot do without food. Thus, as noted in the introduction, without food the generation, functioning and maintenance of human-made capital would be impossible. From its inception, the provision of
Table 1. Examples of long-lasting (>20 years) human impacts on natural capital.

| Long-lasting impact of human activities on natural capital | References |
|-----------------------------------------------------------|------------|
| Climate change by well-mixed greenhouse gases             | Myrhe et al. 2013; Steffen et al. 2015 |
| Ozone layer depletion by halogenated compounds with long atmospheric lifetimes | Fang et al. 2019 |
| Ecosystem destruction (e.g. deforestation)                | Steffen et al. 2015 |
| Reduction of ecosystem integrity and extinction of species | Steffen et al. 2015; Di Marco et al. 2018 |
| Burdening ecosystems beyond their carrying capacity        | Steffen et al. 2015 |
| Acidification and nitrification of soils                  | Tian and Niu 2015; Li et al. 2018 |
| Acidification of lakes                                    | Keller et al. 2019 |
| Ocean acidification                                       | Penman and Zachos 2018; Doney et al. 2020 |
| Eutrophication (by phosphates and fixed nitrogen compounds) of inland and coastal waters | Le Moal et al. 2019 |
| Groundwater pollution by persistent substances            | Burri et al. 2019; Schulze et al. 2019 |
| Soil deterioration (e.g. desertification, large losses of soil organic carbon, pollution by persistent chemicals and radioactive substances) | Karlen and Rice 2015 |
| Depletion mineral natural resources generated by geological processes (virtually non-renewables) | Sverdrup et al. 2014; Helbig et al. 2020 |
| Depletion of fossil water stocks and large reductions of groundwater stocks with slow recharge rates | Mekonnen and Hoekstra 2016; Bierkens and Wada 2019 |
| Severe overfishing leading to fish population collapse or extinction | Le Pape et al. 2017; Sguotti et al. 2019 |

food for humans has been based on combinations of human-made capital (e.g. knowledge about the use of fire) and natural capital (e.g. Thompson et al. 2021). Changes in the amount of food provided can be linked to changes in the combinations of human-made and natural capital used (e.g. Slicher van Bath 1966; Bocquet- Appel 2011). So, as to the current impact of human-made capital for substituting natural capital, it is an important question whether the current use of human-made capital and natural capital in providing food is compatible with the conservation of natural capital for transferral to future generations.

Farming dominates the current provision of food. In current farming, human-made capital underpins increased inputs of plant nutrients (phosphate, fixed nitrogen and potassium salts) and energy, increased use of machinery (mechanization), processing and conservation technologies and long-distance transport. Pest control based on human-made capital has much expanded (Burri et al. 2019; Van Lenteren et al. 2020).

Constituents of natural capital used in the current provision of food by farming are in part traditional ones, such as freshwater, insolation, climate conducive to food production and the ecosystem services pollination and pest control. To a large extent, the current provision of food relies on virtually non-renewable mineral constituents of natural capital, such as fossil carbon compounds (Pimentel 2018), phosphate ores (Reijnders 2014), potassium salt deposits (Dhillon et al. 2019) and ores providing metals used in food life cycles (Reijnders 2016). The rise of virtually non-renewable minerals has reduced the contribution of renewables to the provision of food. For instance, in agriculture, the use of synthetic fertilizers has decreased the application of clover and of human excrements (Kjaergaard 2003; Jewitt 2011).

The current impact of current food provision practices on natural capital can be summarized as follows:

Food production is the main consumer of freshwater and responsible for about 70% of worldwide freshwater withdrawals (Campbell et al. 2017; Bierkens and Wada 2019). These frequently cause reductions of freshwater stocks, including long-lasting negative effects
such as desertification and vanishing surface waters, which have been documented by Du et al. (2014), Marston et al. (2015) Rosa et al. (2019) for a variety of geographical settings. The depletion of fossil groundwater (dating from before 12,000 before present), and of groundwater stocks with long recharge times (Bierkens and Wada 2019) reduce natural capital to be transferred to future generations.

The provision of food currently contributes an estimated 19–29% to worldwide well-mixed greenhouse gas emissions (Vermeulen et al. 2012). These emissions originate in the reduction of soil- and aboveground organic carbon stocks, the conversion of nitrogen compounds to dinitrogen oxide (N$_2$O), the use of fluorinated refrigeration fluids and the input of fossil fuels (Myrhe et al. 2013; Clune et al. 2017). This corresponds with a reduction of natural capital to be transferred to future generations linked to reduced stocks of fossil carbon compounds (Pimentel 2018), ocean acidification (Steffen et al. 2015) reduced ecosystem services due to climate change and ecosystem destruction (Maseyk et al. 2016; Campbell et al. 2017) and soil degradation (Lal 2015; Stavi et al. 2016). Also, climate change is likely to have negative impacts on future food production (Agarwala et al. 2014; Ray et al. 2019) and habitability (Davis et al. 2018; Liang et al. 2020).

Current agricultural practices in addition lead to widespread degradation of agricultural soils by accelerated erosion, acidification, loss of fertility and salinization, thus negatively affecting natural capital to be transferred to future generations (Pimentel and Burgess 2013; Lal 2015). Accelerated erosion causes increased deposition of sediment which negatively affects aquatic ecosystem services (Owens 2020).

Major current trends in food production, such as expansion of food production in deforested areas (Carter et al. 2018; Wagner 2020), and intensification (Cumming et al. 2014; Rasmussen et al. 2017) can decrease ecosystem services and can increase ecosystem dis-services (e.g. Glibert et al. 2014; Rasmussen et al. 2017; Le Clec’h et al. 2018). Agricultural production furthermore presently leads to widespread long-lasting contamination of groundwater and small streams fed by groundwater by fixed nitrogen compounds (Erisman et al. 2008) pesticides and hazardous pesticide-metabolites (Lapworth et al. 2012; Burri et al. 2019). These substances have negative effect on aquatic ecosystems and ecosystem services (Glibert et al. 2014; Campbell et al. 2017; Mahler et al. 2021). The current use of metals for manufactured capital serving the provision of food is associated with a negative impact on natural capital to be transferred to future generations (cf. Table 2).

In agricultural soils, the presence of the plant nutrient phosphate traditionally originated primarily in rock weathering, volcanism and the deposition of air and flooding, and secondarily in residues of organisms and excrements (Vitousek et al. 2010; Doughty et al. 2016). By now, large amounts of phosphate derived from ores are widely applied in agriculture (Reijnders 2014). This causes reductions in constituents of natural capital to be transferred to future generations linked to a substantial depletion of phosphate ore stocks (Reijnders 2014), eutrophication of ecosystems (Campbell et al. 2017) and to persistent pollution by heavy metals such as cadmium and radionuclides such as uranium linked to primary processing of phosphate ores and their presence in commercial ore-derived phosphate fertilizers
Table 2. Long-lasting (>20 years) impacts of important inputs in manufactured capital lifecycles on natural capital.

| Category of inputs                                      | Examples                                                                 | Negative impacts (>20 years) on natural capital                                                                 | References                                                                                                                                 |
|--------------------------------------------------------|--------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|
| Fossil fuels and fossil carbon-based substances        | Coal, mineral oil, natural gas, asphalt, bitumen, carbon fibres, synthetic polymers, lubricants, paints, surfactants & solvents | Depleting stocks of fossil carbon compounds; reduced provision of ecosystem services; reduced habitability and food production due to climate change; persistent soil pollution; ocean acidification | Capello et al. 2009; Raimondi et al. 2012; Agarwala et al. 2014; Steffen et al. 2015; Davis et al. 2018; Penman and Zachos 2018; Schowanek et al. 2018; Ray et al. 2019; Doney et al. 2020; Liang et al. 2020; Paiano et al. 2021 |
| Metals applied as building materials (including piping) | Aluminium alloys, copper, lead, steel, zinc                             | Reduced stocks of metal resources due to dissipation; persistent soil- and sediment pollution linked to primary production; reduced provision of ecosystem services; degradation of fresh water stocks can occur & impacts fossil fuels used in production and transport (see above) | Niemeyer et al. 2012; Pokhrel and Dubey 2013; Li et al. 2014; Resongles et al. 2014; Ciacci et al. 2016; Reijnders et al. 2016; Reijnders et al. 2018; Farjana et al. 2019; Rehman et al. 2019; Fry et al. 2020; Schneider-Marin and Long 2020; Tost et al. 2020; Bai et al. 2021; Tiwari et al. 2021 |
| Minerals-based building and construction materials     | Sand & bricks, tiles, concrete, glass, mineral insulation based on (a. o.) raw materials clay, sand, limestone and rock | Reduced provision of ecosystem services due to mining; cement from limestone linked to relatively large emissions of CO₂; & impacts fossil fuels used in production and transport (see above) | Jiang and Wu 2019; Pedersen Zari 2019; Schneider-Marin and Long 2020; Sacchi and Bauer 2020 |
| Wood applied as building material                      | Aluminium alloys, beryllium, bismuth, cobalt, copper, gallium, gold, indium, lithium, nickel, palladium, rare earths, synthetic polymers, silver, tin | Impacts fossil fuels used in harvesting, processing and transport (see above); dependent on forest composition and harvesting practices: reduction in the provision of ecosystem services; impact on carbon stocks dependent on harvesting practices and wood life cycle | Verkerk et al. 2014; Brunet-Navarro et al. 2016; Chaudary et al. 2017; Liu et al. 2018 |
| Metals and fossil carbon-based materials for ICT hardware | Aluminium alloys, beryllium, bismuth, cobalt, copper, gallium, gold, indium, lithium, nickel, palladium, rare earths, synthetic polymers, silver, tin | Persistent pollution & reduced provision of ecosystem services linked to primary production; depletion of stocks of especially geochemically scarce elements due to dissipation; degradation of fresh water stocks due to mining can occur & impacts fossil carbon compounds for synthetic polymers and fuels used in production and transport (see above) | Pokhrel and Dubey 2013; Li et al. 2014; Resongles et al. 2014; Wäger et al. 2015; Cancarel et al. 2015; Ciacci et al. 2016; Belkhir and Elmegi 2018; Blanco et al. 2018; Marra et al. 2018; Reijnders 2018; Farjana et al. 2019; Liu et al. 2019; Buechler et al. 2020; Fry et al. 2020; Hällström et al. 2020; Tost et al. 2020; US Geological Survey 2020; Wang et al. 2020; Orosun 2021; Tiwari et al. 2021 |
| Category of inputs                                                                 | Examples                                                                 | Negative impacts (>20 years) on natural capital                                                                 | References                                                                 |
|----------------------------------------------------------------------------------|--------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------|
| Materials for machinery, turbines, reactors, storage tanks, smelters, (excluding ICT hardware and building materials) | Aluminium alloys, ceramics, chromium, cobalt, copper, molybdenum, nickel, niobium, refractories, rhenium, steel, synthetic polymers, titanium alloys, tantalum, tungsten, vanadium, wolfram, zinc | Reduced provision of ecosystem services linked to primary production; persistent pollution due to metal ore mining and smelting; depletion of stocks of virtually non-renewables due to dissipation; degradation of fresh water stocks due to mining can occur & impacts fossil carbon compounds used for synthetic polymers and used in production and transport (see above) | Kasah 2014; Pokhrel and Dubey 2013; Li et al. 2014; Resongles et al. 2014; Ciaci et al. 2016; Reijnders 2016, Reijnders 2018; Aihemaiti et al. 2018; Ceniceros-Gómez et al. 2018; Gao et al. 2018; Darolia 2019; Farjana et al. 2019; Horckmans et al. 2019; Lu et al. 2019; Pedersen Zari 2019; Ebrahim et al. 2020; Fry et al. 2020; Simic et al. 2020; Tost et al. 2020; US Geological Survey 2020 |
| Materials for means of transport                                                  | Aluminium alloys, carbon fibre, copper lead, magnesium alloys, steel, synthetic polymers, titanium alloys, zinc | persistent pollution and reduced provision of ecosystem services linked to primary production; depletion of stocks of virtually non-renewables due to dissipation; degradation of fresh water stocks due to mining can occur & impacts fossil carbon compounds used for synthetic polymers and carbon fibre and used in production and transport (see above) | Niemeyer et al. 2012; Pokhrel and Dubey 2013; Resongles et al. 2014; Ciaci et al. 2016; Reijnders 2016, Reijnders 2018; Vieira et al. 2018; Ceniceros-Gómez et al. 2018; Yi and Tang 2018; Simic et al. 2020; Tost et al. 2020; US Geological Survey 2020 |
(Bigalke et al. 2017; Saadaoui et al. 2017). Sverdrup and Ragnarsdottir (2012) modelled the impact of fully depleting phosphate ores, assuming varying levels of P recycling. Their exercise suggests that at a 90% level of phosphate (re)cycling (well above the 60% currently thought achievable in municipal waste water treatment (Reijnders 2014)), traditional phosphate resources would allow for a human world population \(<3 \times 10^9\), much below the current world population of about \(7.8 \times 10^9\) (Population Reference Bureau 2020).

In conclusion: the provision of food for humanity presently negatively impacts a range of the constituents of natural capital to be transferred to future generations. These negative impacts are also implicated in the generation, functioning and maintenance of human-made capital, as these would be impossible without food. Though the negative impacts outlined in this section are not necessarily linked to the diet of each current member of the species, it would appear that such negative impacts are commonly linked to the diets of the present human population.

4. The impact of manufactural capital lifecycles on natural capital

Manufactured capital is defined here as including building stock, including built infrastructure for transport (Weisz et al. 2015; Dombi 2018), industrial plants and factories (Frischknecht et al. 2007; Weisz et al. 2015), machinery (Dombi 2018), equipment (Eaton and Kortum 2001), hardware for information and communication technology (ICT) (Weisz et al. 2015; Dombi 2018), utilities and infrastructure for handling inputs in the economy such as water and energy (Frischknecht et al. 2007), infrastructure and facilities for handling non-product outputs of production, “wastes” and end-of-life products (Weisz et al. 2015; Dombi 2018), and means of transport (Weisz et al. 2015). The life cycles of manufactured capital are “from cradle to grave”, from the extraction of resources to disposal. Current end-of-life recycling can often partially offset the environmental burdens linked to the inputs of materials into producing manufactured capital. This has been shown in the studies regarding metal products (Reuter and van Schaik 2012), ships (Gilbert et al. 2017), cable networks (Unger et al. 2017) aircraft (Vieira et al. 2018), buildings (Di Maria et al. 2018), solar power systems (Lunardi et al. 2018; Muteri et al. 2020), wind turbines (Jensen 2019) concerning wind turbines, synthetic polymers used in manufactured capital (Geyer 2020) and electric vehicles (Zeng et al. 2021). Table 2 summarizes important inputs in manufactured capital lifecycles and the long-lasting impacts of those inputs on natural capital.

Manufactured capital can substitute natural capital, as exemplified by the following examples. The long-lasting impacts on natural capital linked to the associated requirements are in Table 2. In growing crops, insolation is substituted by greenhouses with lighting and heating (Katzin et al. 2021). The natural hydrological cycle is substituted by desalination plants producing freshwater from seawater (Gao et al. 2017). Both substitutes require building materials, equipment, dedicated infrastructure (piping, cables) and large inputs of energy, currently often fossil fuels (Ahamed et al. 2019; Elsaid et al. 2020a,b; Katzin et al. 2021). When snow-tourism is problematic due to climate change, there is currently artificial snow production, likely to be powered by fossil fuels, as documented for a variety of geographical settings by
Pintaldi et al. (2017), Masotti et al. (2018) and Steiger et al. (2019). Artificial snow requires infrastructure for the supply of water, manufactured capital for the production of refrigerants, and equipment for the production and delivery of artificial snow and the grooming thereof (Pintaldi et al. 2017; Masotti et al. 2018). Reared natural enemies of agricultural pests such as parasitoid species (Parra 2010; Hill et al. 2019) and nematode species (Kagimu et al. 2017; Cortés-Martinez and Chevarria-Hernández 2020) are mass produced in facilities resembling factories (needing building materials, equipment and infrastructure for supply of energy and water) and the delivery of natural enemies of pests can require dedicated equipment.

Improving energy and material efficiency commonly requires dedicated inputs in manufactured capital, as illustrated by the following examples. Improvement in energy efficiency in the use stage of buildings are commonly linked to increased inputs of building materials (e.g. Pacheco et al. 2012; Saade et al. 2020). Heat recovery systems in industry that serve the improvement of energy efficiency require substantial inputs in metals such as steel and copper for additional equipment and the distribution of heat (Chowdhury et al. 2018). Machinery for additive manufacturing of metals that can be conducive to energy- and material efficiency (Wippermann et al. 2020) depends strongly on ICT hardware (Yang et al. 2017). Platform-based sharing also depends on ICT hardware (e.g. Amatuni et al. 2020; Warmington-Lundström and Laurenti 2020). The long-lasting impacts of these dedicated inputs on natural capital can be found in Table 2.

Land use changes to accommodate manufactured capital may well decrease ecosystem services. This has e.g. been shown for facilities of the oil and gas industry (Allred et al. 2015), roads (Kleinschroth and Healy 2017), buildings (Wang et al. 2018), hydropower (Briones-Hidrovo et al. 2019) and desert-based concentrated solar power systems (Grodsky and Hernandez 2020). But there are also examples (e.g. regarding photovoltaic solar parks and offshore wind energy) where positive or mixed positive and negative impacts on ecosystem services have been found (Hooper et al. 2017; Randle-Boggis et al. 2020).

Table 2 shows that the inputs of metals and of fossil carbon compounds (both derived from natural resources generated by geological processes) during the life cycles of manufactured capital are an important contributor to the long-lasting negative impacts of manufactured capital on constituents of natural capital. The input of fossil carbon compounds consists mainly of fossil fuels and tends to be dominated by the use stage, as e.g. shown for welding lines in car production (Heinemann et al. 2014), newsprint paper production (Kasah 2014), construction machinery (Ebrahimi et al. 2020; Saade et al. 2020) and electric vehicles (Zeng et al. 2021). For some kinds of manufactured capital, for instance, roads (Huang et al. 2018), the production stage dominates life cycle of fossil carbon inputs. For several types of manufactured capital, there is a trend that the relative importance of the fossil fuel input in the production stage increases, if compared with the use stage. Cases in point are buildings with improved energy efficiency (Saade et al. 2020), automotive capital goods with electric traction, sensors and computing sub-systems (e.g. Gawron et al. 2018; Zeng et al. 2021) and examples of ICT hardware (Arushanyan et al. 2014; Hischier et al. 2015; Belkhir and Elmeligi 2018).
In conclusion, though the coverage of the long-lasting impacts of manufactured capital lifecycles on natural capital presented here is not comprehensive, it would seem that long-lasting negative impacts of manufactured capital lifecycles on constituents of natural capital are common. The consumption of natural resources generated in geological processes is an important contributor to these long-lasting negative impacts.

5. Substitution of natural resources by other natural resources

Substituting constituents of natural capital by other constituents is limited by functionality of the products and services they supply. The ecosystem service pollination cannot be substituted by carbon sequestration. The limitation to substitutability holds for natural resources too (also: Babbitt et al. 2021). The plant nutrient phosphate generated from phosphate ores cannot be substituted by plant nutrients based on other elements than phosphorus. And iron cannot substitute for copper in the electricity grid. Still, within limitations following from functionality, there can be scope for substitution of natural resources by other natural resources. Here, the focus will be on substitutions of natural resources that may be conducive to conserving natural capital.

5.1. Substitution of virtually non-renewable resources by renewables

Daly (1990) and Ekins et al. (2003) have stated that keeping natural capital intact allows for the depletion of non-renewable natural resources to the extent that the rate of depletion equals the creation of renewable substitutes. The current emergence of renewable energy and of bioplastics as substitutes for energy and plastics based on fossil carbon compounds provides data for an evaluation of what Daly (1990) and Ekins et al. (2003) proposed.

As suggested by the contents of the scientific journal Renewable Energy, renewable energy includes wind- and solar power and biofuels. Substitution of renewable energy is mediated by manufactured capital (e.g. Luo et al. 2018; Alsaleh and Sattler 2019). Such manufactured capital is currently commonly characterized by life cycle inputs of materials that, as indicated in Table 2, have long-lasting negative impacts on constituents of natural capital. Wind- and solar power can substitute power production based on fossil fuels, but there currently tend to be significant inputs of fossil fuels and emissions of well-mixed greenhouse gas linked to the life cycles of photovoltaic and wind turbine systems (e.g. Nugent and Sovacool 2014). If it is assumed that wind and solar power are used as energy input in lifecycles of products supplying wind and solar power, there still will be reductions of constituents of natural capital linked to virtually non-renewable ore-derived elements used in the current expansion of solar and wind power such as copper (Bradshaw and Hamacher 2012; Seck et al. 2020), lithium (Bradshaw and Hamacher 2012) and rare earths (Bradshaw and Hamacher 2012; Balaram 2019). These reductions are mainly due to mining and processing (persistent pollution of soils and sediments, reduced provision of ecosystem services, deterioration of freshwater stocks) (cf. Table 2) and to the reduction of stocks in ores and their derivatives in the current economic use.
Current commercial liquid biofuels can substitute fossil petrol and diesel (Jeswani et al. 2020). The life cycles of these biofuels are commonly associated with environmental interventions that have long-lasting negative impacts on natural capital, such as the consumption of virtually non-renewable mineral resources (e.g. fossil fuels and phosphate ore), eutrophication, a substantial contribution to climate change, reduced provision of ecosystem services and reduced freshwater stocks in water-stressed areas (Reijnders 2019, 2020; Jeswani et al. 2020). Thus, the kinds of renewable energy considered here commonly negatively impact constituents of natural capital to be transferred to future generations.

Conventional plastics based on fossil fuels are currently substituted by bioplastics based on renewables, mainly polylactic acid and polyhydroxyalkanoate (e.g. Masutani and Kimura 2018; Esposti et al. 2021). Manufactured capital is instrumental in this substitution (e.g. Chen 2010; Masutani and Kimura 2018). Such manufactured capital is commonly characterized by life cycle inputs of materials that have long-lasting negative impacts on constituents of natural capital. Tabone et al. (2010) found that the conventional plastics polyethylene and polypropylene were associated with a smaller environmental life cycle burden regarding (long-lasting) eutrophication, acidification and ozone layer depletion than the bioplastics polylactic acid and polyhydroxyalkanoate based on agricultural production. A review by Walker and Rothman (2020) concluded that published LCAs of fossil-based plastics and bio-based plastics did show similar ranges of well-mixed greenhouse gas emissions (in CO₂-equivalents) and did not prove a climate benefit for bio-based plastics. Bioplastics based on agricultural produce are furthermore likely to be linked to reduced freshwater stocks in water-stressed areas, consumption of rock phosphate and negative impacts on the provision of ecosystem services (cf. section 2). Thus, bioplastics currently commonly negatively impact constituents of natural capital to be transferred to future generations.

Summing up: the statement that keeping natural capital intact allows for the substitution of (virtually) non-renewable resources by an equal amount of renewables cannot be accepted without restrictions regarding the impact of renewables on natural capital to be transferred to future generations.

5.2 Substitution of geochemically scarce copper by abundant natural resources formed by geological processes

Elements vary much in abundance. Geochemically scarce elements may be defined as elements with an average abundance in the upper continental crust of <0.025 weight% (e.g. Reijnders 2016). There are also elements which are on average abundant in the upper continental crust, such as silicium (Si) (29.5 weight %), aluminium (Al) (8 weight %) and iron (Fe) (4.6 weight%) (Yaroshevsky 2006). There might be a case to consider the deposits of these abundant elements formed by geological processes for practical purposes inexhaustible when Homo sapiens is to exist for the order of 10⁶ years.

Copper (Cu) is a geochemically scarce element with an average abundance of about 0.005 weight%, but worldwide copper production ranks currently third, after Fe and Al (Henckens and Worrell 2020; US Geological Survey 2020). Current use of Cu gives rise to substantial losses from the economy. The worldwide collection rate of end-of-life copper
as functional Cu input for materials recycling is estimated at about 45%, whereas copper loss in primary production is about 16–20% and dissipation of copper during use about 2% (Glöser et al. 2013; Sverdrup et al. 2014). Persistent pollution (Duester et al. 2017; Rehman et al. 2019), reduced provision of ecosystem services (Tost et al. 2020) and deterioration of freshwater stocks (Tiwari et al. 2021) are linked to the primary production of Cu and current fossil energy inputs in copper production are high (Mansilha et al. 2019). This corresponds with a substantial decline of natural capital to be transferred to future generations. In view thereof, there is a case for considering substitution of copper. What is the scope for replacing copper by the abundant elements Al, Fe and Si?

When the Iron Age superseded the Bronze Age (or Copper Age), iron and carbonized iron (carbon steel) substituted copper and copper alloys such as bronze (Maddin Mulhy and Wheeler 1977). In the Iron Age, steel also found applications beyond the scope of copper and its alloys (e.g. Baddoo 2008). Copper found new applications in transporting electricity and in telecommunication (Henckens and Worrell 2020). Fe is currently the most widely applied metal. A problem with its use as iron or carbon steel is the negative impact on its functionality by processes such as oxidation (rust formation) and corrosion. The negative impact of oxidation and corrosion can be much reduced by the use of coatings and alloying elements (Reijnders 2016). The coatings often contain geochemically scarce elements, such as cerium (Ce), cobalt (Co), chromium (Cr), nickel (Ni) and zinc (Zn) (Reijnders 2016). High-quality (“stainless”) steel can contain geochemically scarce alloying elements, such as Cr, molybdenum (Mo), niobium (Nb), Ni and vanadium (V) (Reijnders 2016). The current cradle-to-smelter/gate production of steel is characterized by loss of natural capital due to long-lasting reductions in the provision of ecosystem services (Tost et al. 2020), persistent soil and sediment pollution (Yi et al. 2013) and large inputs of fossil fuels (e.g. Yellishetti et al. 2011). In current recycling, the geochemically scarce elements present in steel and its coatings rapidly lose functionality (Reijnders 2016) leading to a loss of natural capital to be transferred to future generations. The dissipative loss for iron is about one-third of the amount of Fe extracted (Helbig et al. 2020).

Apart from Fe, abundant elements Si and Al can also have a role in the substitution of the geochemically scarce element copper. Cables of optic fibres based on Si are widely used to substitute copper cables for data transport (Chagnon 2019; Chen et al. 2019). The current input of fossil fuels in the production of glass fibre is large (Pinto et al. 2017), though somewhat lower than in Cu, servicing the same transport of data (Unger and Googh 2008). Processes for recycling silicium from optical fibres have been developed (e.g. Ogura et al. 2004), but substantial recycling of Si-based optical fibres has not been reported (e.g. Chen et al. 2017). This lack of recycling negatively impacts natural capital. Dopants in silicium-based optic fibres commonly are the geochemically scarce elements erbium (Er) and germanium (Ge) (Licht et al. 2015; Chraplyvy 2016). Of the Ge input about 40% has been reported to be recycled from effluents of optical fibre production (Licht et al. 2015). Processes have been developed for the extraction of Ge from end-of-life Si-based optical fibres (e.g. Chen et al. 2017), but the actual recovery of Ge from such optical fibres has been reported to reach only 5–10% (Licht et al. 2015). Erbium-doped silica is applied to optical fibre cables as amplifier (Chraplyvy 2016). There is currently no reported recycling process for Si-based optic fibres that retains the functionality of erbium. Loss of functionality by erbium and low recoveries of Ge from end-of-life Si-based optic fibres corresponds with a reduction of natural capital.
Apart from very small-sized applications such as in chips for electronics, aluminium (Al) alloys can be commercial substitutes for copper in wiring for electricity transport (Reijnders 2021). Al mining and processing is characterized by long-lasting negative impacts on the provision of ecosystem services (Tost et al. 2020), persistent soil pollution (Pokhrel and Dubey 2013; Farjana et al. 2019) and large inputs of fossil fuels (Zhang et al. 2016; Mansilha et al. 2019), which negatively impact natural capital to be transferred to future generations. The input of fossil fuels for electricity-grade aluminium is much higher than for copper in servicing the same transport of electricity (Mansilha et al. 2019). Compositional data for electricity-grade aluminium alloys show the presence of geochemically scarce elements (e.g. borium (B), Cu, Cr, gallium (Ga), Zn) with combined concentrations in the 0.1–0.7 weight per cent range (Aluminum Association 2015). Recycling of end-of-life aluminium alloys is commonly by remelting of mixed scraps, which implies that geochemically scarce elements tend to lose functionality after remelting (Paraskevas et al. 2015; Reijnders 2018). The dissipative loss for aluminium is about one third of the amount extracted (Helbig et al. 2020).

Summing up: substituting the geochemically scarce element copper by abundant elements does not keep natural capital to be transferred to future generations intact. Though the relative depletion of resources is much lower for the abundant elements than for copper, there are currently high fossil fuel inputs in production and large life cycle losses of the copper-substitutes considered here. The geochemical scarce elements used for doping, coating and alloying copper substitutes are rapidly lost when the end-of-life substitutes are recycled and even more rapidly lost when these are disposed of. Also, the inputs of materials in life cycles of manufactured capital involved in substituting Cu commonly have long-lasting negative impacts on constituents of natural capital (cf. Table 2).

6. An alternative to conservation of natural capital?

In view of the preceding sections, it is safe to state that, commonly, current substitutions of natural capital do not keep natural capital intact. But current negative impacts of substitutions on natural capital can be reduced. The supply of energy may illustrate this. Changing economic arrangements may lessen rebound effects that currently reduce energy efficiency. Completely replacing fossil fuels by a combination of improved energy efficiency and solar, wind-based and geothermal technologies would seem possible (e.g. Loftus et al. 2015; Hansen et al. 2019). The losses from the economy of ore-derived elements linked to application of those de-carbonizing energy technologies can be substantially reduced by improvements in extraction (Pokhrel and Dubey 2013; Spooren et al. 2020), production (Reuter et al. 2015; Reijnders 2016, 2018), design and recycling (e.g. Reuter and van Schaik 2012; Babbitt et al. 2021). Such changes could substantially reduce the long-lasting negative impacts of substitutions on natural capital. But in view of the extent of current losses, eliminating the negative impact linked to losses of ore-derived elements on natural capital would seem beyond the scope of what can be technically achieved in the near future (e.g. Reuter et al. 2015). Also, problematic is reducing the long-lasting negative impacts on constituents of natural capital by the provision of food, summarized in section 2. All the more, because the world population
is expected to grow substantially (e.g. Tian et al. 2021). Reducing the contribution to diets of animal husbandry in favour of plant-based foods may e.g. limit the long-lasting negative impact of providing food on natural capital (e.g. Thaler et al. 2015; Aleksandrowicz et al. 2016). But in view of the heavy dependence of agriculture on phosphate ores (cf. section 2) keeping natural capital intact for transferral to future generations in the provision of food would seem impossible in the near future.

In view thereof, one might ask whether there is not a less strict alternative to equating (environmental) sustainability with keeping natural capital intact. In this context, the concept of a “safe operating space for humanity” (Steffen et al. 2015) would seem a prime candidate. This concept is linked to planetary boundaries, defined as global limits to environmental interventions to avoid risks of abrupt non-linear environmental change leading to collapses of ecosystems (Steffen et al. 2015). When humanity remains within these boundaries there is, according to Steffen et al. (2015), a safe operating space for humanity.

Recently, the safe operating space for humanity seems to have become more popular than the conservation of natural capital in the context of (environmental) sustainability. Not the conservation of natural capital, but the safe operating space for humanity is used in Raworth’s Doughnut Economics (2017) to define the ceiling for planetary pressure. I have been unable to find any recent life cycle assessment using the conservation of natural capital as a reference, but the studies of Sandin et al. (2015), Ryberg et al. (2020) illustrate the use of the safe operating space for humanity within planetary boundaries in “absolute sustainability assessments”. Thus, the question arises: can in defining (environmental) sustainability the safe operating space for humanity be considered a proper alternative to conservation of natural capital?

Steffen et al. (2015) proposed no boundary for virtually non-renewable mineral resources. In defence thereof, Steffen et al. (2020) have argued that the depletion of virtually non-renewable mineral natural resources does not threaten the stability of the Earth system. This is a curious argument in view of the term “safe operating space for humanity” used by Steffen et al. (2015) and the importance of virtually non-renewable mineral resources in current human economies, including the provision of food, pointed out above. Without the use of virtually non-renewable mineral resources, current economies and food security would collapse. Also, no planetary boundary proposed by Steffen et al. (2015) regards the deterioration of soils to be used in the provision of food for humans, though more than 99% of world food supply is soil-based (Pimentel and Burgess 2013). These characteristics preclude intergenerational justice of what Steffen et al. (2015) proposed.

On the other hand, planetary boundaries presented by Steffen et al. (2015) provide guidance for defining sufficient natural capital to prevent ecosystem collapses. Regarding the environment, Steffen et al. (2015) address climate change by well-mixed greenhouse gases, deterioration of the ozone layer, the impact of novel entities (new chemicals and genetically modified organisms) and loading of the atmosphere with aerosols. No global boundaries for novel entities and aerosols were proposed by Steffen et al. (2015). As for climate change by well-mixed greenhouse gases and deterioration of the ozone layer, Steffen et al. (2015) provide guidance for protecting humanity against severe long-lasting negative impacts. Of the renewable natural resources, freshwater consumption is considered by Steffen et al. (2015). A planetary boundary presented by Steffen et al. (2015) is the consumption of 4000 km$^3$ fresh surface- and groundwater. The actual worldwide
consumption of such freshwater is well below this level. However, there are many areas that are subject to dwindling freshwater stocks and there are long-lasting negative consequences thereof for humans and ecosystems (Du et al. 2014; Mekonnen and Hoekstra 2016; Rosa et al. 2019). All in all, the safe operating space for humanity proposed by Steffen et al. (2015) is not a proper alternative to using conservation of natural capital for defining (environmental) sustainability.

7. Conclusions

Substitutability of natural capital by human-made capital would seem to be limited. Substitution of manufactured capital by natural capital can also occur. Substitution of natural capital by improving resource efficiency mediated by human-made capital can currently be much reduced by rebound effects. When human-made capital substitutes natural capital, there are commonly long-lasting negative impacts of such substitution on constituents of natural capital. Long-lasting negative impacts on natural capital can be considered at variance with justice between the generations. In view thereof, there is a case to define (environmental) sustainability as keeping natural capital intact for transferral to future generations. A major problem for such conservation regards natural resources generated by geological processes (virtually non-renewable resources), especially geochemically scarce elements. Substitution of virtually non-renewable resources by generating equal amounts of renewables has been proposed as a way keep natural capital intact. However, the generation of renewables substituting for fossil fuels is currently commonly associated with negative impacts on constituents of natural capital to be transferred to future generations. The same holds for the substitution of geochemically scarce virtually non-renewable copper by abundant resources generated by geological processes. Though current negative impacts of substitutions on natural capital can be substantially reduced, their elimination seems beyond the scope of what can be achieved in the near future. In defining (environmental) sustainability, the less strict “safe operating space for humanity”, which has for instance been used in “absolute sustainability assessments” is, however, not a proper alternative to the conservation of natural capital for transferral to future generations. An important deficiency is that, despite their importance for humanity, virtually non-renewable mineral resources and agricultural land are not considered in establishing the “safe operating space for humanity”. This deficiency precludes inter-generational justice. There is a case for focussing on the conservation of natural capital for transferral to future generations in sustainability research.

Acknowledgments

The editorial comments and the comments of two anonymous reviewers are gratefully acknowledged.

Disclosure statement

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
ORCID

Lucas Reijnders http://orcid.org/0000-0002-2969-0661

Data availability statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

References

Agarwala M, Atkinson G, Baldock C, Gardiner R. 2014. Natural capital accounting and climate change. Nature Clim Change. 4:520–522.
Ahamed MS, Guo H, Taylor L, Tanino K. 2019. Heating demand and economic feasibility analysis for year-round vegetable production in Canadian Prairies greenhouses. Inform Process Agric. 6:81–90.
Aihemaiti A, Jiang J, Li D, Liu N, Yang M, Meng Y, Zhou Q. 2018. The interaction of metal concentration and soil properties on toxic metal accumulation of native plants in vanadium mining area. J Environ Manag. 222:216–226.
Akerman M. 2003. What does natural capital do? The role of metaphor in economic understanding of the environment. Environ Values. 12:431–448.
Aleksandrowicz L, Green R, Joy EJM, Smith P, Haines A. 2016. Impacts of dietary change on greenhouse gas emissions, land use, water use, and health: a systematic review. PLOS ONE. 11:e105797 (16).
Allred BW, Smith WK, Tidwell D, Haggerty JH, Running SW, Naugle DE, Fuhlendorf SD. 2015. Ecosystem services lost to oil and gas in North America. Science. 348:401–402.
Alsaleh A, Sattler M. 2019. Comprehensive life cycle assessment of large wind turbines in the US. Clean Technol Environ Policy. 21:887–903.
Aluminum Association. 2015. International Alloy Designations and Chemical Composition Limits for Wrought Aluminum and Wrought Aluminum Alloys. Arlington VA 22209 (USA).
Amatuni L, Ottelin J, Streubing B, Mogollon JM. 2020. Does car sharing reduce greenhouse gas emissions? Assessing the modal shift and life time shift rebound effects from a life cycle perspective. J Clean Prod. 266:121869 (10).
Arrow K, Dasgupta P, Goulder L, Daily G, Ehrlich P, Heal G, Levin S, Mäler K, Schneider S, Starrett D, et al. 2004. Are we consuming too much? J Econ Persp. 18:147–172.
Arushanyan Y, Ekener-Petersen E, Finnveden G. 2014. Lessons learned: review of LCAs for ICT products and services. Comput Ind. 65:211–234.
Ayers RU. 2007. On the practical limits to substitution. Ecol Econ. 61:115–128.
Babbitt CW, Althaf S, Rios FC, Bilec MM, Graedel TE. 2021. The role of design in circular economy solutions for critical material. One Earth. 4:353–362.
Baddoo NR. 2008. Stainless steel in construction: a review of research, applications, challenges and opportunities. J Constr Steel Res. 64:1199–1206.
Bai X, Wang J, Dong H, Chen KJ, Ge Y. 2021. Relative importance of soil properties and heavy metals/metalloids to modulate microbial community and activity at a smelting site. J Sol Sedim. 21:1–12.
Balaram N. 2019. Rare earths elements. A review of applications, occurrence, exploration, analysis, recycling and environmental impact. Geosci Front. 10:1285–1303.
Baninla Y, Zhang M, Lu Y, Liang R, Zhang Q, Zhou Y, Khan K. 2019. A transitional perspective of global and regional mineral flows. Resour Conserv Recycl. 140:91–101.
Belkhir L, Elmarghi A. 2018. Assessing ICT global footprints: trends to 2040 & recommendations. J Clean Prod. 177:448–463.
Berger M, Sonderegger T, Alvarenga R, Bach V, Cimprich A, Dewulf J, Frischknecht R, Guinée J, Helbig C, Huppertz T, et al. 2020. Mineral resources in life cycle assessment: part II Recommendations on application-dependent use of existing methods and future method development needs. Int J Life Cycle Assess. 25:798–813.

Bierkens MFJ, Wada Y. 2019. Non-renewable groundwater use and groundwater depletion: a review. Environ Res Lett. 14:063002 (43).

Bigalke M, Ulrich A, Rehms A, Keller A. 2017. Accumulation of cadmium and uranium in arable soils in Switzerland. Environ Pollut. 221:85–93.

Birkenholz T. 2017. Assessing India’s drip-irrigation boom: efficiency, climate change and groundwater policy. Water Int. 42:623–667.

Blanco CF, Marques A, van Bodegom PJ. 2018. An integrated framework to assess impacts on ecosystem services in LCA demonstrated by a case study. Ecosyst Services. 30:211–218.

Bocquet-Appel J. 2011. When the world’s population took off: the springboard of the Neolithic demographic transition. Science. 333:560–561.

Bradshaw AM, Hamacher T. 2012. Non-regenerative natural resources in a sustainable system of energy supply. ChemSusChem. 5:550–562.

Briones-Hidrovo A, Uche J, Martinez-Garcia A. 2019. Estimating the hidden cost of hydropower through an ecosystem services balance: a case study from Ecuador. J Clean Prod. 233:33–42.

Brockway P, Sorrell P, Semieniuk G, Heun HK, Court V. 2021. Energy efficiency and economy-wide rebound effects: a review of the evidence and its implications. Renew Sustain Energy Rev. 141:110781 (20).

Brunet-Navarro R, Jochheim H, Muys B. 2016. Modelling carbon stocks and fluxes in the wood product sector: a comparative review. Glob Change Biol. 22:2555–2569.

Buechler DT, Zyaykina NN, Spencer CA, Lawson E, Ploss NM, Hua I. 2020. Comprehensive element analysis of consumer electronic devices: rare earths, precious and critical elements. Waste Manag. 103:67–75.

Burri NM, Weather R, Moeck C, Schirmer M. 2019. A review of threats to groundwater quality in the Anthropocene. Sci Total Environ. 684:136–154.

Calvo G, Valero A, Valero A. 2017. Assessing maximum production peak and resource availability if non-fuel mineral resources: analyzing the influence of extractable global resources. Resour Conserv Recycl. 125:208–217.

Camilleri MA. 2018. Closing the loop for resource efficiency, sustainable production and consumption: a critical review of the circular economy. Int J Sustainable Developm. 21:1–17.

Campbell BM, Beare DJ, Bennett EM, Hall-Spencer JM, Ingram JSI, Jaramillo F, Ortiz R, Ramakutty N, Sayer JA, Shindell D. 2017. Agricultural production as a driver of Earth System exceeding planetary boundaries. Ecol Soc. 22(4):8 (10).

Cancerel P, Marwede M, Nissen NF, Lang K. 2015. Estimating the quantities of critical metals in ICT and consumer equipment. Resour Conserv Recycl. 98:9–18.

Capello C, Wernet G, Sutter J, Hellweg S, Hungerbühler K. 2009. A comprehensive assessment of petroleum solvent products. Int J Life Cycle Assess. 14:467–479.

Carter S, Herold M, Avitabile V, de Bruin S, De Sy V, Kooistra L, Rufino MC. 2018. Agriculture driven deforestation in the tropics from 1990-2015: emissions, trends and uncertainties. Environ Res Lett. 13:014002 (13).

Ceniceros-Gómez AI, Macías-Macias KY, de La Cruz-moreno JE, Guitiérrez-Ruiz ME, Martínez-Jordanes LG. 2018. Characterization of mine tailings in Mexico for the possible recovery of strategic elements. J South Amer Earth Sci. 88:72–79.

Chagnon M. 2019. Optical communications for short reach. J Lightwave Technol. 37:1779–1797.

Chaudary A, Carrasco LR, Kastner T. 2017. Linking national wood consumption with biodiversity and ecosystem service loss. Sci Total Environ. 586:985–994.

Chen GQ. 2010. Industrial production of PHA. Microbiol Monographs. 14:121–132.

Chen WS, Chang BK, Chiu KL. 2017. Recovery of germanium from waste optical fibers by hydrometallurgical method. J Environ Chem Engin. 5:5215–5221.

Chen X, Himmeldreich JE, Hurley JE, Zhou C, Jiang Q, Qin Y, Li J, Wu C, Chen H, Coleman D, et al. 2019. Universal fiber for short-distance optical communications. J Lightwave Technol. 37:389–395.
Chowdhury JI, Hu Y, Haltas I, Balta-Ozkan N, Matthew G Jr., Varga L. 2018. Reducing industrial energy demand in the UK: a review of energy efficient technologies and energy saving potential in selected sectors. Renew Sustain Energy Rev. 94:1153–1178.

Chraplyvy AR. 2016. Roadmap of optical communications: history. J Opt. 18:063002, 5–6.

Ciacci L, Harper EM, Nassar NT, Reck BK, Graedel TE. 2016. Mineral dissipation and inefficient recycling intensify climate forcing. Environ Sci Technol. 50:1394–1402.

Clune S, Crossin E, Verghese K. 2017. Systematic review of greenhouse gas emissions for different fresh food categories. J Clean Prod. 140:766–783.

Cohen F, Hepburn CJ, Teytelboym A. 2019. Is natural capital really substitutable? Ann Rev Environ Resour. 44:425–449.

Cortés-Martinez CI, Chevarria-Hernández N. 2020. Production of entomopathogenic nematodes in submerged monoxenic culture: a review. Biotechnol Bioeng. 117:3968–3985.

Costanza R, Daly HE. 1992. Natural capital and sustainable development. Conserv Biol. 6:37–46.

Costanza R, Kubiszewski I, Stoekl N, Kompa T. 2021. Plurality discounting recognizing different capital contributions: an example estimating the net present value of global ecosystem service. Ecol Econ. 183:106961 (8).

Cumming GS, Buerkert A, Hoffmann EM, Slecht E, van Cramon-taubadel S, Tscharntke T. 2014. Implications of agricultural transitions and urbanization for ecosystem services. Nature. 515:50–57.

Daly HE. 1990. Towards some operational principles of sustainable development. Ecol Econ. 2:1–6.

Darolia R. 2019. Development of strong, oxidation and corrosion resistant nickel-based super alloys: critical review of challenges, progress and prospects. Intern Mater Rev. 64:355–380.

Davis KE, Bhattachan A, D’Odorico PD, Suweis S. 2018. A universal model for predicting human migration under climate change: examining future sea level rise in Bangladesh. Environ Res Lett. 13:064030 (10).

DesRoches CT. 2019. On the concept and conservation of critical natural capital. Int Stud Philosophy Sci. 32:207–228.

Dhillon JS, Eckhoff EM, Mullen RW, Raun WR. 2019. World potassium use efficiency in cereal crops. Agron J. 111:889–896.

Di Marco M, Venter O, Possingham HP, Watson JEM. 2018. Changes in human footprint drive change in species extinction rate. Nature Commun. doi:10.1038/s41467-018-07049-5(9).

Di Maria A, Eyckmans J, van Acker K. 2018. Downcycling versus recycling of construction and demolition waste: combining LCA and LCC to support sustainable policy making. Waste Manag. 75:3–21.

Didyk BM, Simonet BRT. 1989. Hydrothermal oil of Guaymas Basin and implications for petroleum formation mechanisms. Nature. 342:65–69.

Dombi M. 2018. Modeling the material stock of manufactured capital with production function. Resour Conserv Recycl. 138:207–214.

Doney SC, Busch DS, Cooley SR, Kroeker KJ. 2020. The impacts of ocean acidification on marine ecosystems and resilient human communities. Ann Rev Environ Resour. 45:83–1112.

Doughty CE, Roman J, Faurby S, Wolf A, Haque A, Bakker ES. 2016. Global nutrient transport in a world of giants. Proc Natl Acad Sci- USA. 113:868–873.

Drupp MA. 2018. Limits to substitution between ecosystem services and manufactured goods and implications for social discounting. Environ Resour Econ. 69:135–158.

Du T, Kang S, Zhang X, Zhang J. 2014. China’s food security is threatened by unsustainable use of water resources in North and Northwest China. Food Energy Security. 3:7–18.

Duester L, Wahrendorf DS, Brinkmann C, Fabricius A, Meermann B, Pelzer J, Ecker D, Renner M, Schmid H, Ternes TA, et al. 2017. A framework to evaluate the impact of armourstones on the chemical quality of surface water. PLOS ONE. 12:e0168926 (12).

Eaton J, Kortum S. 2001. Trade in capital goods. Eur Econ Rev. 45:1195–1235.

Ebrahimi B, Wallbaum H, Jakobsen PD, Booto GK. 2020. Regionalized environmental impacts of construction machinery. Int J Life Cycle Assess. 25:1472–1485.

Ekins P, Simon S, Deutsch L, Folke C, De Groot R. 2003. A framework for the practical applications of the concept of critical natural capital and strong sustainability. Ecol Econ. 44:165–185.
Elsaid K, Kamil M, Sayed ET, Abdelkareem MA, Wilberforce T, Olabi A. 2020a. Environmental impact of desalination technologies. Sci Total Environ. 748:1415238 (19).

Erisman JW, Sutton MA, Galloway J, Klimont Z, Winiwarter W. 2008. How a century of ammonia synthesis changed the world. Nature Geosci. 1:636–639.

Esposti MD, Morselli D, Fava F, Bertin L, Cevani F, Viaggi D, Fabbri D. 2021. The role of biotechnology in the transition from plastics to bioplastics: an opportunity to reconnect global growth with sustainability. FEBS Open Bio. 11:967–983.

Fang X, Pyle JA, Chipperfield MP, Daniel JS, Park S, Prinn RG. 2019. Challenges for the recovery of the ozone layer. Nature Geosci. 12:592–596.

Farjana SH, Huda N, Mahmud MAP. 2019. Impacts of aluminum production: a cradle to gate investigation using life-cycle assessment. Sci Total Environ. 663:958–970.

Frischknecht R, Althaus H, Bauer C, Doka G, Heck I, Jungbluth N, Kellenberger D, Nemecek I. 2007. The environmental relevance of capital goods in life cycle assessments of products and services. Int J Life Cycle Assess. 13:7–17.

Fry KL, Wheeler CA, Gillings MM, Flegal AR, Taylor MP. 2020. Anthropogenic contamination of residential environments from smelter As and Pb emissions: implications for human health. Environ Pollut. 262:114235.

Gannon B, Roberts J. 2020. Social capital: exploring theory and empirical divide. Empir Econ. 58:899–919.

Gao F, Nie Z, Yang D, Sun B, Lin Y, Gong X, Wang Z. 2018. Environmental impacts analysis of titanium sponge using Kroll process in China. J Clean Prod. 174:771–779.

Gao L, Yoshikawa S, Iseri Y, Fujimori S, Kanae S. 2017. An economic assessment of the global potential for seawater desalination. Water. 9:763 (19).

Gawron JH, Keoleian GA, De Kleine RD, Wallington D, Kim HC. 2018. Life cycle assessment of connected and automated vehicles: sensing and computing subsystem and vehicle level effects. Environ Sci Technol. 52:3249–3256.

Geyer R. 2020. Production, use, and fate of synthetic polymers. In: Letcher TM, editor. Plastic waste and recycling. Academic Press, Stratton on the Fosse (UK); p. 13–32.

Gilbert D, Walsh WP, Hodgson C. 2017. The role of material efficiency to reduce CO₂ emissions during ship manufacture: a life cycle approach. Marine Policy. 75:227–237.

Gilbert PM, Maranger R, Sobota DJ, Bouwman L. 2014. The Haber Bosch-harmful algal bloom (HB-HAB) link. Environ Res Lett. 9:105001(13).

Glöser S, Soulier M, Espinoza LAT. 2013. Dynamic analysis of global copper flows: global stocks, postconsumer material flows: recycling indicators and uncertainty evaluation. Environ Sci Technol. 47:6564–6572.

Goodland R, Daly H. 1996. Environmental sustainability: universal and non-negotiable. Ecol Applic. 6:1002–1017.

Grodskey SM, Hernandez RR. 2020. Reduced ecosystem services of desert plants from ground-mounted solar energy development. Nature Sustain. 3:1036–1043.

Gutowski TG, Allwood JM, Hermann C, Sahni S. 2013. A global assessment of manufacturing, economic development, energy use, carbon emissions and the potential for energy efficiency and materials recycling. Ann Rev Environ Resour. 38:81–106.

Hällström LPB, Salifu M, Alakangas L, Martinsson O. 2020. The geochemical behaviour of Be and F in historical mine tailings of Yxsjöberg, Sweden J Geochem Explor. 218:10661 (10).

Hansen K, Breijer C, Lund H. 2019. Status and perspectives on 100% renewable energy systems. Energy. 175:471–480.

Hedenquist JW, Lowenstern JB. 1994. The role of magmas in the formation of hydrothermal ore deposits. Nature. 370:519–525.

Heinemann T, Kaluza A, Thiede S, Ditterich D, Linzbach J, Herrmann C. 2014. Life cycle evaluation of factories: the case of a car body welding line with pneumatic actuators. Adv Inform Communicat Technol. 44:546–554.

Helbig C, Thorenz A, Tuma A. 2020. Quantitative assessment of dissipative losses of 18 metals. Resour Conserv Recycl. 153:104537 (8).
Henckens MLCM, Worrell E. 2020. Reviewing the availability of copper and nickel for future generations. The balance between production growth, sustainability and recycling rates. J Clean Prod. 264:121460 (12).

Hertwich EG, Ali S, Ciacci L, Fishman T, Heeren N, Masanet E, Asghari EN, Olivetti E, Pauliuk S, Tu Q, et al. 2019. Material efficiency strategies in reducing greenhouse gas emissions associated with buildings, vehicles and electronics - a review. Environ Res Lett. 14:043004 (20).

Hill JG, Albaraccin EL, Araoz MVC, Virla EG. 2019. Effect of host species and host age on biological control of Anagrus virilae (Hymenoptera: Mymaridae) an egg parasitoid of Balbulus maidis (Hemiptera: Cicadellidae) and Peregrinus maidis (Hemiptera: Delphacidae). Biol Control. 131:74–80.

Hischier R, Coroama VC, Schien D, Achachlouei MA. 2015. Grey energy and the environmental impacts of ICT hardware. In: Hilty L, Aebischer B, editors. ICT innovations for sustainability. Cham: Springer; p. 171–189.

Höök M, Bardi U, Feng L, Pang X. 2010. Development of oil formation theories and their importance for peak oil. Marine Petr Geol. 25:1995–2004.

Hooper T, Beaumont N, Hattam C. 2017. The implications of energy systems for ecosystem services; detailed case study for offshore wind. Renew Sustain Energy Rev. 70:230–241.

Horckmans L, Nielsen P, Dierckx P, Ducastel A. 2019. Recycling of refractory bricks used in basic steelmaking; A review. Resour Conserv Recycl. 14:297–304.

Jensen JP. 2019. Evaluating the environmental impacts of recycling wind turbines. Wind Energy. 22:316–326.

Jeswani HK, Chilvers A, Azapagic A. 2020. Environmental sustainability of biofuels: a review. Proc Soc Roy Soc A. 476:20200351 (37).

Jevons WS. 1866. The coal question. London: Macmillan.

Jewitt S. 2011. Poo gurus? Researching the threats and opportunities provided by human waste. Appl Geography. 31:761–769.

Jiang R, Wu P. 2019. Estimates of environmental impacts of roads through life cycle assessment: a critical review and future directions. Transp Res Transp Environ. 77:148–163.

Kagimu N, Ferreira T, Malan AP. 2017. The attributes of survival in the formulation of entomopathogenic nematodes utilized as insect control agents. Afr Entomol. 25:275.291.

Kantoussan J, Lae R, Tine M. 2018. Review of the fisheries indicators for monitoring the impacts of fishing on fish communities. Rev Fish Sci Aquacult. 26:460–478.

Karlen DL, Rice CW. 2015. Soil degradation: will humankind ever learn? Sustain. 7:12490–12501.

Kasah T. 2014. LCA of a newsprint paper machine: a case study of capital equipment. Int J Life Cycle Assess. 19:417–428.

Katzin D, Marcelis LFM, van Mourik S. 2021. Energy savings in greenhouse transition from high-pressure sodium to LED lighting. Appl Energy. 281:116019 (14).

Kedir F, Hall DM. 2020. Resource efficiency in industrialized housing construction- a systematic review of current performance and future opportunities. J Clean Prod. 286:125443 (15).

Keller W, Heneberry J, Edfwards BA. 2019. Recovery of acidified Sudbury, Ontario, Canada, lakes: a multi-decade synthesis and update. Environ Rev. 217:1–16.

Kim J, Heo E. 2013. Asymmetric substitutability between energy and capital: evidence from manufacturing sectors in 10 OECD countries. Energy Econ. 40:81–89.

Kjaergaard T. 2003. A plant that changed the world: the rise and fall of clover 1000-2000. Landscape Res. 28:41–49.

Kleinschroth F, Healy JR. 2017. Impacts of logging roads on tropical forests. Biotropica. 49:820–835.

Lal R. 2015. Restoring soil quality to mitigate soil degradation. Sustain. 7:5875–5895.

Lapworth DJ, Baran N, Stuart ME, Ward RS. 2012. Emerging organic contaminants in groundwater: a review of sources, fate and occurrence. Environ Pollut. 163:287–303.

Le Clec’h S, Jégou N, Decaens T, Dufour S, Grimaild M, Oszwald J. 2018. From field data to ecosystem services maps: using regressions for the case of deforested areas within the Amazon. Ecosyst. 21:216–236.
Le Moal M, Gascuill-Odeux C, Ménesguen A, Souchon Y, Étrillard C, Levain A, Moatar E, Pannard A, Souchu P, Lefebvre A, et al. 2019. Eutrophication: a new wine in an old bottle? Sci Total Environ. 651:1–11.

Le Pape O, Bohommeau S, Nieblas A, Fromentin J. 2017. Overfishing causes frequent fish population collapses but rare extinctions. Proc Natl Acad Sci USA. 114:E6274.

Lethonen M. 2004. The environmental-social interface of sustainable development: capabilities, social capital, institutions. Ecol Econ. 49:199–214.

Li Y, Chapman SJ, Nicol GW, Yao H. 2018. Nitrification and nitrifiers in acidic soils. Soil Biol Biochem. 116:290–301.

Li Z, Ma Z, van der Kuijp TG, Yuan Z, Huang L. 2014. A review of soil heavy metal pollution from mines in China: pollution and health risk assessment. Sci Total Environ. 468-469:843–853.

Liang L, Deng X, Wang P, Wang Z, Wang L. 2020. Assessment of the impact of climate change on cities livability in China. Sci Total Environ. 726:138339 (11).

Licht C, Talens Peiro L, Villalba G. 2015. Global substance flow analysis of gallium, germanium and indium. J Ind Ecol. 19:890–903.

Liu CLC, Kuchma O, Krutovsky V. 2018. Mixed-species versus monocultures in plantation forestry: development, benefits, ecosystem services and perspectives for the future. Glob Ecol Conserv. 15: e00419 (13).

Liu W, Augusdinata DB, Myint S. 2019. Spatiotemporal patterns of lithium mining and environmental degradation in the Atacama salt flat, Chile. Int J Appl Earth Observ Geoinform. 80:145–166.

Loftus PJ, Cohen AM, Long JCS, Jenkins JD. 2015. A critical review of global decarbonisation scenarios: what do they tell us about feasibility? WIRE’s Clim Change. 6:93–112.

Lu KW, Gong XZ, Sun BX, Ding Q. 2019. Life cycle assessment of tungsten production in China. In: Han Y, editor. Materials science forum. Vol. 994; p. 1137–1143.

Lu Y, Schandl H. 2021. Do sectoral material efficiency improvements add up to greenhouse gas emission reductions on an economy-wide level? J Ind Ecol. 25:523–536.

Lunardi MM, Alvarez-Gaitan JP, Bilbao JI, Corkish R. 2018. Comparative life cycle assessment of end-of-life silicon photovoltaic solar modules. Appl Sci. 8:1396 (15).

Luo W, Khoo YS, Kumar A, Low JSC, Li Y, Tan YS, Wang Y, Aberle AG, Ramakrishna S. 2018. Comparative life cycle assessment of photovoltaic electricity generation in Singapore by multi-crystalline silicon technologies. Solar Energy Mater Solar Cells. 174:157–162.

Maddin Mulhy JD, Wheeler TS. 1977. How the Iron Age began. Sci Amer. 237(4):122–131.

Mahler BJ, Nowell LH, Sandstrom MW, Bradley DM, Romanok KM, Konrad CP, van Metre PC. 2021. Inclusion of pesticide transformation products is key to understanding pesticide exposures and effects in small US streams. Environ Sci Technol. 55:4740–4752.

Mäler KG. 1986. Comment on R.M. Solow ‘On the intergenerational allocation of natural resources’. Scand J Econ. 88:151–152.

Mansilha MB, Brondani M, Farret FA, Da Rosa LC, Hoffmann R. 2019. Life cycle assessment of electrical distribution transformers: comparative study between aluminum and copper coils. Environ Egin Sci. 36:115.135.

Marra A, Cesaro A, Belgiorno V. 2018. Separation efficiency of valuable and critical metals in WEEE mechanical treatments. J Clean Prod. 186:490–498.

Marston L, Konar M, Cai X, Troy TJ. 2015. Virtual groundwater from overexploited aquifers in the United States. Proc Natl Acad Sci USA. 112:8561–8566.

Maseyk FJF, Mackay AC, Possingham HP, Dominati EJ, Buckley YM. 2016. Managing natural capital stocks for the provision of ecosystem services. Conserv Lett. 10:211–220.

Masotti P, Bogoni P, Campisi B. 2018. A preliminary LCA analysis of snow making in Fiemme Valley. Proc. 12th Italian LCA network conference, Messina pp 241–249.

Masutani K, Kimura Y. 2018. Present situation and future perspectives of poly(lactic acid). Adv Polym Sci. 279:1–26.

Megersa G, Abdulahi J. 2015. Irrigation system in Israel: a review. Int J Water Res Environ Engin. 7 (3):29–37.
Mekonnen M, Hoekstra A. 2016. Four billion people facing severe water scarcity. Sci Adv. 2:e1500323 (6).
Melchiotte EB, Sickman JD, Talyn BC, Noblet J. 2018. Isotope stratigraphy: insight in paleoclimate and formation of nitrate deposits in the Atacama desert. J Arid Environ. 148:45–80.
Missimer A. 2018. Natural capital as an economic concept. History and contemporary use. Ecol Econ. 143:90–96.
Molle F, Tanouti O. 2017. Squaring the circle: agricultural intensification vs. water conservation in Morocco. Agric Water Manag. 192:170–179.
Muteri V, Cellura M, Curto D, Franzitta V, Longo S, Mistretta M, Parisi ML. 2020. Review on life cycle assessment of solar photovoltaic panels. Energies. 13:252 (38).
Myrhe G, Shindell D, Bréon F, Fuglestvedt J, Huang J, Koch D, Lamarque J, Lee D, Mendoza B, Nakajima T, et al. 2013. Anthropogenic and natural radiative forcing. In: Climate change 2013: the physical science basis. Contribution of Working Group I to the fifth assessment report on the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge (United Kingdom and New York)
Nadal A. 2016. The natural capital metaphor and economic theory. Real World Econ Rev. 74:64–84.
Niemen YC, Nogueira MA, Carvalho GM, Cohn-De-Pinto SJ, Outeiro US, Rodrigues GG, Da Silva EM, Sousa JP. 2012. Functional and structural parameters to assess the ecological status of a metal contaminated area in the tropics. Ecotoxicol Environ Saf. 86:188–197.
Nugent D, Sovacool BF. 2014. Assessing the life cycle greenhouse gas emissions for solar PV and wind energy: a critical meta-survey. Energy Policy. 65:229–244.
Ogura M, Astuti I, Yoshikawa T, Morita K, Takahashi M. 2004. Development of a technology for silicon production by recycling waste optical fiber. Ind Engn Chem Res. 43:1890–1893.
Orosun MM. 2021. Assessment of arsenic and its associated health risks due to mining activities in part of North-central Nigeria: probabilistic approach using Monte Carlo. J Hazard Mater. 412:125262 (14).
Owens PN. 2020. Soil erosion and sediment dynamics in the Anthropocene: a review of human impacts during a period of rapid global environmental change. J Soil Sedim. 20:4115–4143.
Pacheco R, Ordóñez J, Martínez G. 2012. Energy efficient design of buildings: a review. Renew Sustain Energy Rev. 16:3559–3573.
Paiano A, Gullucci T, Pontrandolfo A, Lagioia G, Piccinno P, Lacalamita A. 2021. Sustainable options for paints through a life cycle assessment method. J Clean Prod. 295:126464 (15).
Paraskevas D, Kelkens K, Dewulf W, Duflou J. 2015. Environmental modelling of aluminum recycling: a life cycle assessment tool for sustainable metal management. J Clean Prod. 105:357–370.
Parra JRP. 2010. Mass rearing of egg parasitoids for biological control programs. Progr Biol Control. 9:267–292.
Patzek TW. 2008. Exponential growth, energetic Hubbert cycles, and the advancement of technology. Arch Min Sci. 53:131–159.
Pearce D. 1997. Substitution and sustainability: some reflections of Georgescu-Roegen. Ecol Econ. 22:295–297.
Pedersen Zari M. 2019. Ecosystem services impacts as part of building materials selection. Mater Today Sustain. 3:4:10010 (10).
Penman DE, Zachos JC. 2018. New constraints to the massive carbon release and recovery processes during the Paleocene-Eocene thermal maximum. Environ Res Lett. 13:105008 (14).
Pfeiffer L, Lin CC. 2014. Does efficient irrigation technology lead to reduced groundwater extraction? Empirical evidence. J Environ Econ Manag. 67:184–205.
Pimentel D, editor. 2018. Handbook of energy utilization in agriculture. Boca Raton (New York, London): CRC Press.
Pimentel D, Burgess M. 2013. Soil erosion threatens food production. Agric. 3:443–463.
Pintaldi E, Hudek C, Stanchi S, Spiegelberger T, Rivella E, Freppaz M. 2017. Sustainable soil management in ski areas: threats and challenges. Sustain. 9:2150 (17).
Pinto JTM, Amaral KJ, Hartard S, Janissek PR, Helling K. 2017. Reducing the environmental impacts of vitreous optical fiber production - a life cycle impact assessment. J Clean Prod. 165:762–776.
Pokhrel LC, Dubey B. 2013. Global scenarios of metal mining, environmental repercussions, public policies and sustainability: a review. Crit Rev Environ Sci Technol. 43:2352–2388.

Population Reference Bureau. 2020. World population data sheet. www.prb.org, accessed 2021 Jan 28.

Raimondi A, Girotti G, Blengini GA, Fino D. 2012. LCA of petroleum-bases lubricants: state of art and inclusion of additives. Int J Life Cycle Assess. 17:987–996.

Randle-Boggis RJ, White PCL, Cruz J, Parker G, Montag H, Scurlock JMO, Armstrong A. 2020. Realising co-benefits for natural capital and ecosystem services from solar parks: a co-developed evidence-based approach. Renew Sustain Energy Rev. 125:109775 (10).

Rasmussen LV, Christensen AE, Danielsen F, Dawson N, Martin A, Mertz O, Sikor T, Thongmanivong S, Xaydouvang P. 2017. From food to pest: conversion factors determine switches between ecosystem services and dissipers. Ambio. 46:173–183.

Rawls J. 2001. Justice as fairness. Oxford (UK: Basil Blackwell).

Raworth K. 2017. Doughnut Economics. In: Seven ways to think like a 21st century economist. White River Junction VT (USA): Chelsea Green Publishing.

Ray DK, West PC, Clark M, Gerber JS, Prishchepov AV, Chatterjee S. 2019. Climate change has likely already affected global food production. PLOS ONE. 14:e0217148 (18).

Rehman H, Liu L, Wang Q, Saleem MH, Sahir S, Ullah S, Pang D. 2019. Copper environmental toxicity, recent advances, and future outlook: a review. Environ Sci Pollut Res. 26:18003–18016.

Reijnders L. 2014. Phosphorus resources, their depletion and conservation. Resour Conserv Recycl. 93:32–49.

Reijnders L. 2016. Conserving the functionality of relatively rare metals associated with steel life cycles: a review. J Clean Prod. 131:76–96.

Reijnders L. 2018. Quality of recycling: conserving functionality of geochemically scarce elements associated with aluminum life cycles. In: Recycling and reuse of materials. New York: Nova Science Publishers; p. 115–180.

Reijnders L. 2020. Is the production of biofuels environmentally sustainable? In: Handbook of renewable and sustainable materials. Vol. 3. Elsevier, Amsterdam; p. 545–550.

Reijnders L. 2021. Copper substitutability may be about 60% or more of current use. J Clean Prod. 284:124774 (3).

Reijnders L. 2019. Biofuels and green perspectives. In: Maurice P, editor. Encyclopedia of water: Science, technology, and society. Wiley; p. 2391–2400.

Resongles E, Casiot C, Freydier R, Dezileau L, Viets J, Elbaz-Paulet F. 2014. Persisting impact of historical mining activity to metal (Pb, Zn, Cd, Tl, Hg) and metalloid (As, Sb) enrichment in sediment of the Gardon river, Southern France. Sci Total Environ. 481:509–521.

Reuter MA, van Schaik A, Gediga J. 2015. Simulation-based design for resource efficiency of metal production and recycling systems: cases - copper production and recycling, e-waste (LED lamps) and nickel pig iron. Int J Life Cycle Assess. 20:671–692.

Reuter M, van Schaik A. 2012. Opportunities and limits of recycling: a dynamic model-based analysis. MRS Bull. 37:339–347.

Rosa L, Chiavelli DP, Tu C, Rulli MC, D’Oдорicico P. 2019. Global unsustainable water flows in agricultural trade. Environ Res Lett. 14:114001 (11).

Ryberg MW, Andersen MM, Owsianik M, Hauschild MZ. 2020. Downscaling the planetary boundaries in absolute environmental sustainability assessments: a review. J Clean Prod. 276:123278 (12).

Saadaoui E, Ghazel N, Romdhane CB, Massoudi N. 2017. Phosphogypsum: potential uses and problems - a review. Int J Environ Stud. 74:558–567.

Saade MRM, Guest G, Amor B. 2020. Comparative whole building LCAs: how far are our expectations from the documented evidence? Build Environ. 167:106449 (12).

Sacchi R, Bauer C. 2020. Should we neglect carbonation in life cycle inventory databases? Int J Life Cycle Assess. 25:1532–1544.

Sandin G, Peters GM, Svanström M. 2015. Using planetary boundaries framework in setting impact-reduction targets in LCA contexts. Int J Life Cycle Assess. 20:1684–1700.
Schneider-Marin P, Long W. 2020. Environmental costs of buildings: monetary evaluation of ecological indicators for the building industry. Int J Life Cycle Assess. 25:1637–16549.
Schowanek D, Bosboom-Patel T, Bouvy A, Colling J, de Ferrer JA, Eggers D, Groenke K, Gruenenwald T, Martinsson J, Mckeown P, et al. 2018. New and updated life cycle inventory for surfactants used in European detergents: summary of the ERASM surfactant life cycle and ecofootprinting project. Int J Life Cycle Assess. 23:867–886.
Schulze S, Zahn D, Montes R, Rodil R, Quintana J-B, Knepper TP, Reemtsma T, Berger U. 2019. Occurrence of emerging persistent and mobile organic contaminants in European water samples. Water Res. 153:80–90.
Seck GS, Hache E, Bonnet C, Simoen M, Carcanaque S. 2020. Copper at the cross-roads: assessment of the interactions between low-carbon energy transition and supply limitations. Resour Conserv Recycl. 163:10572 (21).
Sguotti C, Otto SA, Frelat R, Langbehn TJ, Ryberg MP, Lindgren M, Durant JM, Stenseth NC, Möllmann C. 2019. Catastrophic dynamics limit Atlantic cod recovery. Proc Roy Soc Biol Sci. 286:20182877 (10).
Simic M, Alli A, Nartinovic S, Vlahovic M, Sivic A, Husovic TV. 2020. High temperature materials: properties, demands and applications. Hum Ind. 74:273–284.
Skelton ACM, Paroussos L, Allwood JM. 2020. Comparing energy and material efficiency rebound effects: an exploration of scenarios in the GEM-E3 macroeconomic model. Ecol Econ. 173:106544 (14).
Slicher van Bath BH. 1966. The agrarian history of Western Europe, AD 500-1850. London: E. Arnold.
Solow RM. 1986. On the intergenerational allocation of natural resources. Scand J Econ. 88:141–149.
Solow RM. 1993. Sustainability: an economist’s perspective. In: Dorfman R, Dorfman NS, editors. Economics and the environment: selected readings. New York: W. & W. Norton & Co; p 179–187.
Sonderegger T, Berger M, Alvarenga R, Bach V, Cimprich A, Dewulf J, Frischknecht R, Guinée J, Helbig C, Huppertz T, et al. 2020. Mineral resources in life cycle impact assessment part II: a review. Int J Life Cycle Assess. 25:784–797.
Spoooren J, Binnemans K, Björkmalm J, Breeemersch K, Dams Y, Folens K, Gozález-Moya M, Horckmans L, Komitas K, Kurylak V, et al. 2020. Near-zero waste processing of low grade, complex primary ores and secondary raw materials in Europe: technology development trends. Resour Conserv Recycl. 160:104919 (18).
Springer MR, Meredith RW, Gatesy J, Emerling CR, Park J, Rabosky DL, Stadler F, Steiner C, Ryder GA, Janecka JE, et al. 2012. Macroevolutionary dynamics and historical biogeography of primate diversification inferred from a species super matrix. PLOS ONE. 7:e49521 (23).
Stavi M, Bel G, Zaaad E. 2016. Soil functions and ecosystem services in conventional, conservation and integrated agricultural systems. A review. Agron Sustain Dev. 36:32 (12).
Steffen W, Richardson K, Rockstrom J, Cornell SE, Fetzer I, Bennett EM, Biggs R, Carpenter SR, de Vries W, de Wit CA, et al. 2015. Planetary boundaries guiding human development on a changing planet. Science. 347:1259855. doi:10.1126/science.1259855.
Steffen W, Richardson K, Rockstrom J, Schellnhuber HJ, Dube OP, Dutreuil S, Lenton TM, Lubchenko J. 2020. The emergence and evolution of Earth system science. Nature Rev Earth Environ. 1:54–63.
Steiger R, Scott D, Abegg B, Pons M, Aall C. 2019. A critical review of climate change risk for ski tourism. Curr Issues Tourism. 22:1343–1379.
Sverdrup HU, Ragnarsdottir KV. 2012. Challenging the planetary boundaries. II Assessing the sustainable global population and phosphate supply, using a system dynamics assessment model. Appl Geochem. 26:307–310.
Sverdrup HU, Ragnarsdottir KV, Koca D. 2014. On modelling the copper mining rates, market supply, copper price and the end of copper reserves. Resour Conserv Recycl. 87:158–174.
Tabone MD, Gregg JJ, Beckman EJ, Landis AE. 2010. Sustainability metrics: life cycle assessment and green design in polymers. Environ Sci Technol. 44:8264–8269.
Thaler S, Zessner M, Weigl M, Rechberger H, Schilling K, Kroiss H. 2015. Possible implications of dietary changes on nutrient fluxes, environment and land use in Austria. Agric Syst. 136:14–29.

Thompson JC, Wright DK, Ivory SJ. 2021. The emergence and intensification of early hunter-gatherers in niche construction. Evolut Anthropol. 30:17–27.

Tian D, Niu S. 2015. A global analysis of soil acidification caused by nitrogen addition. Environ Res Lett. 10:024019 (9).

Tian X, Engel BA, Qian H, Hua E, Sun S, Wang Y. 2021. Will reaching the maximum achievable yield potential meet future food demand? J Clean Prod. 294:126285 (12).

Tiwari AK, Suozzi E, Silva C, De Maio M, Zanetti M. 2021. Role of integrated approaches in water resource management: Antofagasta Region, Chile. Sustain. 13:1297 (13).

Tost M, Murguia D, Hitch M, Lutter S, Luckeneder S, Feiel S, Moser P. 2020. Ecosystem services costs of metal mining and pressure on biomes. Extract Ind Soc. 7:79–86.

UN International Resource Panel. 2011. Decoupling natural resource use and environmental impact from economic growth. UNEP, Nairobi. p. 152

Unger N, Beigi P, Salhofer HG. 2017. The greenhouse gas benefit of recycling waste electrical and electronic equipment above the legal minimum requirement: an Austrian LCA case study. J Clean Prod. 164:1635–1644.

Unger N, Googh O. 2008. Life cycle considerations about optic fibre cable and copper cable systems: a case study. J Clean Prod. 16:1517–1525.

US Geological Survey. 2020. Mineral commodity summaries. Reston Virginia. accessed 2021 Apr 24

Van Lenteren J, Alomar O, Ravensberg WJ, Urbaneja A. 2020. Biological control agents for control of pests in greenhouses. In: Albajes GM, Nicot R, editors. Integrated pest and disease management in greenhouse crops. Cham: Springer; p. 409–439.

Verkerk PJ, Mavsar R, Giergiczny M, Lindner M, Edwards D, Schelhaas MJ. 2014. Assessing impacts of intensified biomass production on ecosystem services provided by European forests. Ecosyst Services. 9:155–165.

Vermeulen SJ, Campbell B-M, Ingram JSI. 2012. Climate warming and food systems. Ann Rev Environ Resour. 37:195–222.

Vieira DR, Vieira RK, Chain MC. 2018. Strategy and management for the recycling of carbon fiber-reinforced polymers (CFRPs) in the aircraft industry: a critical review. Int J Sustain Dev World Ecol. 24:213–223.

Vitousek PM, Porder S, Houlton BZ, Chadwick A. 2010. Terrestrial phosphorus limitation: mechanisms, implications and nitrogen-phosphorus interactions. Ecol Appl. 20:5–15.

Wächter PA, Hischier R, Widmer R. 2015. The material basis of ICT. In: Hilty LM, Aebischer B, editors. ICT innovations for sustainability. Cham: Springer; p. 209–221.

Wagner DL. 2020. Insect declines in the Anthropocene. Ann Rev Entomol. 65:457–480.

Walker S, Rothman R. 2020. Life cycle assessment of bio-based and fossil-based plastic: a review. J Clean Prod. 261:121158 (15).

Wang K, Wan J, Xiang Y, Zhu J, Leng Q, Wang M, Xu L, Yang Y. 2020. Recent advance and historical developments of high voltage lithium cobalt oxide materials for rechargeable lithium-ion batteries. J Power Sources. 460:228062 (16).

Wang Y, Li X, Zang Q, Li J, Zhou X. 2018. Projections for future land use changes: multiple scenario-based analysis on ecosystem services for Wuhan City, China. Ecol Indic. 84:430–445.

Warmingtom-Lundström J, Laurenti R. 2020. Reviewing circular economy rebound effects: the case of on-line-peer to peer boat sharing. Resour Conserv Recycl. 5:100028 (9).

Weisz M, Suh S, Graedel TE. 2015. Industrial ecology: the role of manufactured capital in sustainability. Proc Natl Acad Sci USA. 112:6260–6264.

Wippermann A, Gutowski TG, Denkena B, Dittrich MA, Wessarges Y. 2020. Electrical energy and material efficiency analysis of machining, additive and hybrid manufacturing. J Clean Prod. 251:119731.

Yang L, Heu K, Baughman B, Godfrey D, Medina F, Menon M, Wiener S. 2017. Additive manufacturing of metals: the technology, materials, design and production. Cham: Springer.

Yaroshevsky AA. 2006. Abundance of elements in the Earth crust. Geochem Int. 1:54–62.
Yellishetti M, Mudd GM, Ranjith PG, Tarumarajah A. 2011. Environmental life-cycle comparisons of steel production and recycling: sustainability issues, Problems and prospects. Environ Sci Policy. 14:650–663.

Yi G, Tang C. 2018. Environmental impact of magnesium alloy automobile hub based on life cycle assessment. J Centr South Univ. 25:1870–1878.

Yi X, YanXiao S, Chen H, Yang L. 2013. Impact of long-term heavy metal pollution on microbial community in iron mine soil. Res Environ Sci. 226:1201–1211.

Zeng D, Dong Y, Cao H, Li Y, Wang J, Li. Z, Hauschild MZ. 2021. Are the electric vehicles more sustainable than the conventional ones? Influences of the assumptions and modelling approaches in the case of typical cars in China. Resour Conserv Recycl. 167:105210 (9).

Zhang Y, Sun M, Hong J, Han X, He J, Shi W, Li X. 2016. Environmental footprint of aluminum production in China. J Clean Prod. 133:1242–1251.