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Reflections on the Role of Natural Capital for Economic Activity

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Abstract

The discussion of the role of natural capital in economic activity is not new; increasing evidence of environmental pressures, climate deregulation and biodiversity loss have however increased the interest in the role of natural capital in the production process. This paper reviews approaches to conceptualising the contribution of natural capital to economic processes. It covers the neoclassical tradition of production functions with natural resources as well as damage functions, but also considers a more heterodox approach to reflecting the vulnerability of natural assets. Different ways of modelling natural capital lead to divergent conclusions about the sustainability of economic growth on a finite planet. By focusing on efforts to integrate nature's contribution to economic production in economic modelling and standard economic metrics, this paper differs from 'beyond GDP' scoreboards that complement GDP with additional statistics. The applied part of the paper discusses selected approaches for quantifying the contribution of natural capital including production functions at different levels of aggregation, environmental-economic accounting and damage functions and highlights insights to be gained as well as difficulties. On this basis, we outline next steps for modelling natural capital in the production process.

JEL Classification: Q57, E01, E23.

Keywords: natural capital, resources, ecosystems, ecosystem accounting, production factors, production function, damage function, macroeconomic models.

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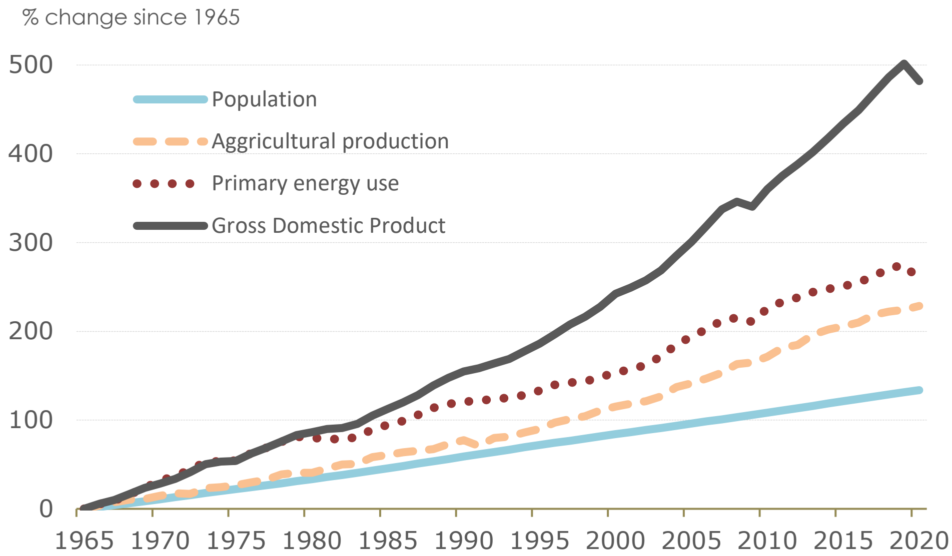
1. INTRODUCTION

"The things of nature do not really belong to us, …we should leave them to our children as we have received them." – Oscar Wilde

How important is nature for economic activity? The idea that environmental and climate conditions may substantially affect economic performance could be traced back at least to ancient Greek philosophers (Hippocrates, 400 B.C). To the extent that environmental factors play a role in economic outcomes - whether via labour productivity (human health), agricultural output, or damages related to natural disasters - acquiring better information and understanding of the causal effects of changes in natural conditions on economic output is important for better designing contemporary economic policies and institutions. This is all the more important given the expected increases in average global surface temperatures in the coming years and decades and rapid biodiversity loss.

Economic growth was uneven, unsteady and, in the aggregate, very slow prior to the Industrial Revolution. Historical records suggest that in the 2,000 years prior to the Industrial Revolution, world population grew slowly from about 200 million to 1 billion. Average incomes changed even less during this period, from the equivalent of about $500 per person annually to about $700 (Maddison 2003). Ecological pressures did occasionally contribute to the fall of a settlement or even a civilisation (cf. Butzer and Endfield, 2012), but was not generalised and global. By contrast, over the past 150 to 200 years, the sustainability of the use of natural resources has increasingly come into focus as economic output and energy use rose sharply (see Figure 1).

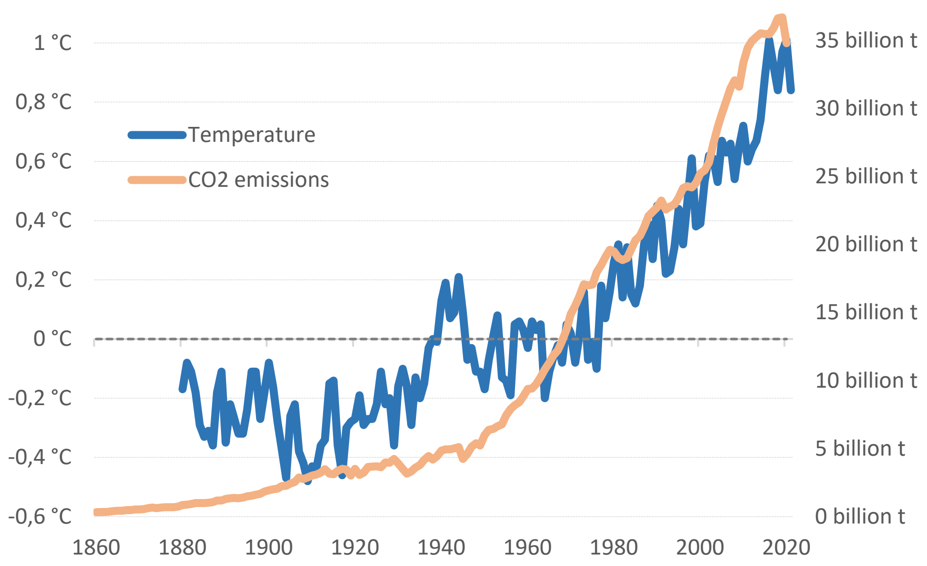
Figure 1: **Change in World Population, Agricultural Production, Energy Use and Output**



Note: World population and gross world output, measured in constant 2015 US dollars, from the World Bank (World Development Indicators database). Agricultural production, measured in constant 2014-2016 international dollars, from FAO (FAOSTAT). Primary energy use, measured in exajoules, from BP (BP Statistical Review of World Energy 70th edition).

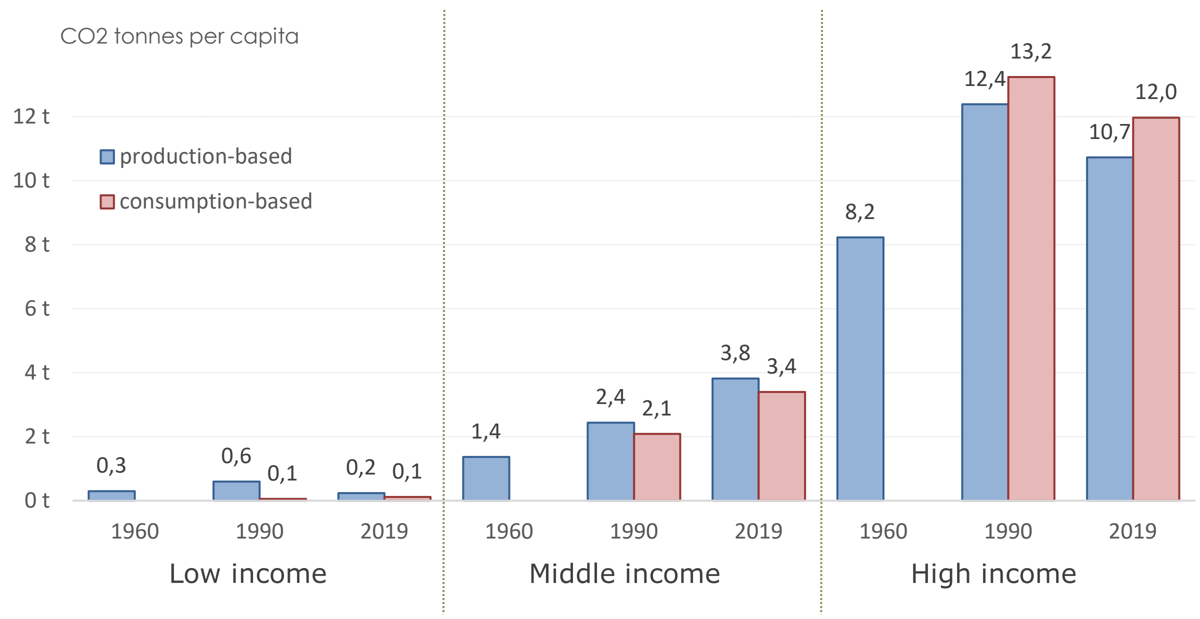
To a great extent, economic growth in both agriculture and industry has been a process of substituting fossil-fuel energy for human and animal labour. Europe's economic growth in the eighteenth and nineteenth centuries depended heavily on coal as an energy source. In the twentieth century, oil displaced coal as the prime energy source for industry and transportation. Currently, fossil fuels continue to provide about 80 percent of energy globally (BP 2021). Increasing emissions of greenhouse gases since the Industrial Revolution are the main cause of anthropogenic climate change (Figures 2 and 3; IPCC 2021). Figure 3 shows moreover that consumption-based CO_2 emissions are considerable, in particular in high-income countries such as most EU Member States. Human economic activity is also increasingly affecting biodiversity through emissions and waste as well as pressure on habitats (Figure 4).

Figure 2: **Global Carbon Dioxide (CO2) Emissions and Temperature Anomaly**



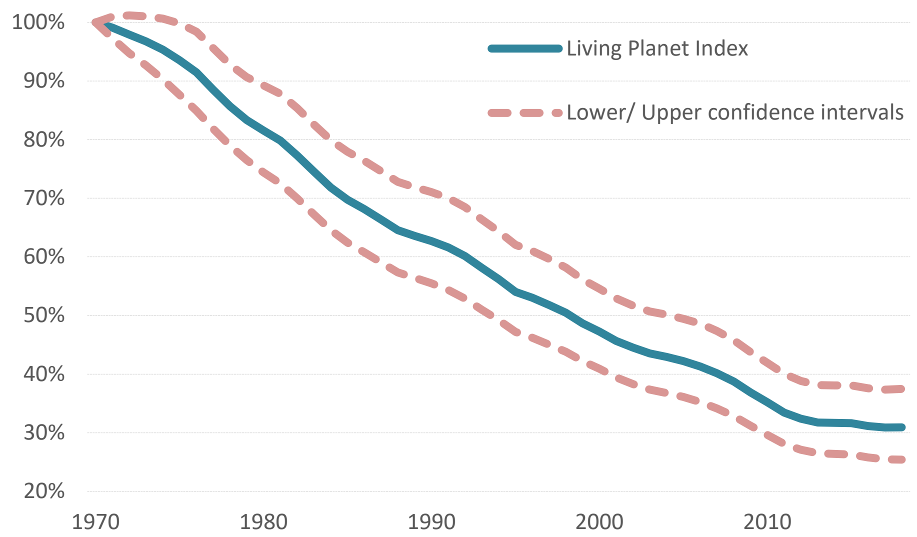
Note: The average of land air- and sea-water surface temperature anomaly is given as the deviation from the 1951–1980 mean. The source is National Aeronautics and Space Administration (NASA), Goddard Institute for Space Studies (GISS). Annual production-based emissions of carbon dioxide, measured in billion tonnes, from The Global Carbon Budget.

Figure 3: **Production- and Consumption-Based Carbon Dioxide (CO2) Emissions by Country Groups**



Notes: Annual production- and consumption-based emissions of carbon dioxide (CO2) per capita, measured in tonnes, from The Global Carbon Budget. Data has been converted from tonnes of carbon to tonnes of CO2 using a conversion factor of 3.664. In the presence of international trade, consumption- and production-embodied energy use differ. Consumption-embodied (trade-adjusted) energy use measures domestic energy use minus energy utilised to produce exported goods, plus energy utilised to produce imported goods.

Figure 4: **Living Planet Index, 1970-2016**



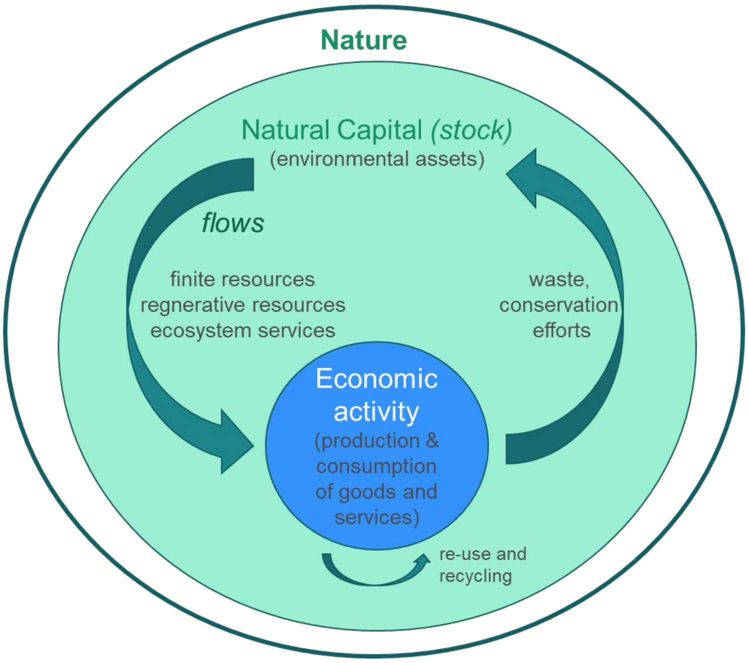
Notes: Living Planet Index, an aggregate indicator produced by the environmental organisation World Wildlife Fund (WWF), from 1970 to 2018. The Living Planet Index is based on the populations of over 4,000 vertebrate species, including mammals, birds, reptiles, and fish. *Source:* Zoological Society of London and WWF, http://stats.livingplanetindex.org/. The index value is measured relative to species' population in 1970.

Oil, gas but also biodiversity constitute assets for the economy – often referred to as natural capital. A simple definition of natural capital as we will understand it in this paper can be found in United Nations (2020): "Natural capital refers to the stocks of environmental assets (including natural resources, ecosystems and a stable climate) that generate flows of goods and services into the economy." The physical flows can go in both directions, depending on whether nature is used as a resource (e.g., mining, agriculture) or a sink (e.g. pollution – for simplicity considered as a negative 'good', here). The stock of natural capital assets is reduced where these flows are taken from non-renewable resources or exceed its regenerative capacity (e.g. deforestation, overfishing). Efforts to reuse or recycle resources[1] reduce the draw on natural capital (Figure 5).

All economic activities require some natural capital to provide raw materials, whether it is the wood to make furniture, the land to grow crops, or the fish to make a meal. Classical economists routinely included land in their production functions, and early debates on the sustainability of population growth focussed on the limited supply and productivity growth of agricultural land (Malthus 1798). 50 years ago, Meadows et al (1972) triggered a heated debate on natural limits to economic activity. Since then, economists' focus on the environment has gradually shifted from the depletion of exhaustible and renewable resources to the destruction of ecosystems and the overstepping of planetary boundaries (Barbier 2020).

[1] Amid the large literature on the circular economy, Korhonen., Honkasalo and Seppälä (2018) provides a useful overview.

Figure 5: **Stylised interactions between Natural Capital and economic activity**



The literature on natural capital is so large that it cannot be covered exhaustively in this paper. A fairly comprehensive conceptualisation of the way natural capital enters into the production process and wellbeing can be found in Bastien-Olvera and Moore (2021). They distinguish three channels: By providing raw materials, natural capital enters the economic production function for marketed goods and services. The stock of natural capital also enters the production of ecosystem services to humans (e.g. mangroves protect human settlements from flooding). Finally, humans benefit from the existence of natural capital directly, e.g. by enjoying the beauty of an unspoiled landscape.

Our approach in this paper is narrower and focuses on the contribution of natural capital to the production of market goods and services. In line with e.g. Barbier (2019), Daily et al (2020), Dasgupta (2021) and La Notte et al (2022), we also consider ecosystem services that enter the economic production process (e.g. natural water purification or pollination are crucial for agricultural output). Moreover, we are interested in the feedback loop between economic activity that affects natural capital, and the depleted natural capital that affects production possibilities

Our contribution to the already large literature on natural capital consists of:

(i) reviewing the most prominent approaches conceptualising the contribution of natural capital to economic processes in production functions at different levels of aggregation and what view of nature and sustainability these different approaches reflect; and
(ii) providing practical considerations for the empirical integration of natural capital in models of production processes including also by reviewing efforts to measure and value natural capital.

On this basis, we outline possible next steps for modelling natural capital in the production process. Our focus is on taking into account nature's contribution to economic production in a way that can be *fully integrated* in economic modelling and standard economic metrics (i.e. national accounts). It thereby differs from 'beyond GDP' indicators and scoreboards[2] that aim at *complementing* GDP with additional statistics.

The remainder of the paper is organised as follows: In section 2, we discuss key features of natural capital. Section 3 discusses different approaches to integrating natural capital into models of production. Section 4 provides some examples on how to integrate natural capital into production models in practice, and section 5 outlines possible next steps for integrating natural capital in macroeconomic models and concludes.

[2] The 'beyond GDP' approach (see for example Stiglitz, Fitoussi and Durand 2018, Terzi 2021) advocates an approach centred on welfare rather than only output. This approach proposes to take into account a broad set of indicators to measure welfare which include but go beyond GDP, such as clean air or health. The aim of the scholars working in this area is to propose a dashboard with a comprehensive set of indicators to be used for policymaking. A key challenge is the quality and harmonisation of measurement across countries as well as the choice of indicators.

2. NATURAL CAPITAL: KEY FEATURES AND SOME STYLISED FACTS

Natural capital consists of environmental assets (as mentioned above) and may refer to simple materials such as iron ore or living and complex ecosystems such as rainforests or coral reefs (with manifold interactions amid many living species and physical framework conditions). Ecosystems consist of a biological community of interacting organisms (biotic) and their physical (abiotic) environment. The same ecosystem may provide a variety of goods and services, e.g. a forest provides timber, fruits, mushrooms, climate regulation and recreational services, and some ecosystems may produce services to other ecosystems. Similarly, the same economic activity may benefit from services provided by a variety of natural capital assets, e.g. for humans to be able to produce sunflower oil, sunflowers need to receive rain, solar radiation, nutrients from the soil and pollination from insects, all of which are essential for their growth and hence for the ultimate economic output. Some of these ecosystem services are used in production processes, others go directly to consumers (recreation, health). The size of ecosystems can differ a lot. We also understand as ecosystem services some global dynamic processes such as the water cycle or the carbon cycle.

In this paper, we will distinguish the following forms of natural capital (see Table 1; note that the notation used in the text and in the table links to Section 3) [3]:

- *Finite*[4] *resources* (R_f): Goods such as minerals and metals as well as fossil fuels. Their main characteristic is that the respective stock (S) they are taken from (such as an iron ore) diminishes as they are extracted from nature (notwithstanding the discovery of deposits and recycling).[5]
- *Renewable resources (R_r)*: This category consists of goods such as crops, animal feed, fish and timber. The flow of these goods diminishes the stock from which they are provided, but that stock has the capacity to regenerate - unless the resource flows are persistently too large (overuse).
- *Ecosystem services* (S^{β}): These are regulating and maintenance services (such as climate regulation or pollination services). In contrast to renewable resources, they will not directly weaken as a function of the service provided. The stock of natural assets (S) from which they flow may however be impacted indirectly through pollution or the extraction of goods from the same ecosystem stock.[6]
- *The absorptive capacity of the environment* (G(S)) *to assimilate and neutralise waste and pollution* (w) is similar to a renewable resource in the sense that over-dependency on the regenerative capacity of the environment diminishes the stock of natural assets (S) and the assets' capacity to continue providing ecosystem services. In contrast to R_r, the relation of absorption with economic activity stems from output rather than appearing on the input side.

This framework is sufficiently general to accommodate climate change as a special case. It involves the burning of fossil fuels, a finite resource, and the emission of greenhouse gases, a form of pollution. The result is the disturbance of a global ecosystem service, namely climate regulation.

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[3] With some adaptations, we follow the notation in Dasgupta (2021), which we start introducing here and will use more extensively in chapter 3.

[4] We will use the terms finite resources and exhaustible (or depletable) resources as synonyms.

[5] Note that these resources are eventually renewed after a very long cycle of decaying plants.

[6] Any classification implies simplification, and there are necessarily elements that are hard to assign to a category or that overlap. Moreover, there can be interdependencies between categories. For instance, 'crop provision' can be considered an ecosystem service, different from, but overlapping with, the renewable resource 'crop'. The ecosystem service 'crop provision' would correspond to the contribution of nature to the growth of crops, as opposed to the labour and (conventional) capital needed for farming.

Table 1: **Characteristics of natural capital**

Selected natural capital assets / biosphere / stock supplying regulating services (*S*)	**Flow of provisioning goods and services (R) / regulation and maintenance services (S^B)**	**Characteristics**				
		finite or regenerative (*)	***externalities***	***rival***	***excludable***	***marketed***
Mineral ore	minerals and metals (R_f)	finite	deforestation	X	X	X
Fossil fields	fossil fuels (R_f)	finite	GHG emissions	X	X	X
Agricultural land	crops, animal feed (R_r)	regenerative	deforestation	X	X	X
Fish stocks	fish (R_r)	regenerative	effects of overfishing	X	(x)	X
Forests	timber (R_r)	regenerative	GHG absorption	X	X	X
	recreation (R_r)	regenerative		(x)	(x)	(x)
Mangroves	flood protection (S^B), fish (R_r)	regenerative	benefits fishery	.	.	.
			Etc.			
Global ecosystems	Regulating and maintenance services (S^B) (climate regulation, freshwater, nitrogen cycles etc …)	regenerative	complex system of ecosystem externalities (positive or negative)	.	.	.

Note: The letters in Italics refer to the notation in Section 3; (*) regenerative may become finite if persistently overused.

Table 1 summarises some characteristics of different key examples of natural capital. The first column lists selected *stocks* of natural capital assets. In the second column the assets are related to the respective flow of goods and services. These can be flows of assets taken from nature directly or flows of "regulation and maintenance services" which correspond to services that enable life to exist (cf Dasgupta 2021).

The next columns then list the assets' respective characteristics regarding whether the asset (or the good or service flowing from it):

- is ***finite versus regenerative:*** some forms of natural capital are finite and will be gone forever once used up (e.g. fossil fuels or minerals). Others are regenerative by nature (e.g. forests or fish stocks) but may collapse and thereby become finite if they are persistently overexploited.
- creates ***externalities:*** several assets can create externalities such as greenhouse gas emissions when being burnt (e.g. fossil fuels). So-called ecosystem externalities (see for example Crocker and Tschirhart 1992) can be both positive and negative. An example is the fishery ecosystem: fishing could damage the environmental habitat and at the same time it may increase food availability (see Ryan, Holland and Herrera 2014).
- is ***rival or non-rival***: For many forms of natural capital, access is non-excludable and non-rival (public goods such as air and solar radiation), or there is some rivalry in access (common goods such as fish stocks, or recreational areas).
- is ***excludable*** i.e. can only be used by its owner (a private good) as opposed to being accessible to the public (a public good). An example is timber, which can be restricted to the exclusive use of the owner of the concession or forest.
- is ***marketed*** i.e. property rights are clearly defined. An example is crude oil.

The characteristics discussed above imply that market failure is very common for the goods and services provided by nature and needs to be taken account both in terms of modelling and in terms of policy advice. Moreover, in the light of the features briefly discussed in this section, assessing the contributions of natural capital to economic processes is a highly complex matter. In the following sections we discuss possible approaches to tackle this complexity.

3. SELECTED MODELLING APPROACHES TO CAPTURE THE ROLE OF NATURAL CAPITAL FOR ECONOMIC ACTIVITY

There are many possibilities for modelling the role of natural capital for economic output or wellbeing. Natural resources can be (intermediate) inputs in aggregate production functions with more or less granularity. Damages arising from the destruction of natural assets may affect the stock or the productivity of particular production factors (e.g. floods may destroy produced capital, or heat affect the health of workers), or they could affect a share of output directly. Taking the perspective of wellbeing, a healthy nature may increase wellbeing directly as argument of the utility function, or affect material wellbeing through consumption possibilities. This section surveys a small selection of approaches. It discusses the way natural capital is conceptualised and examines the consequences of different modelling choices. We first review approaches that consider natural capital as a production factor in aggregate production functions (section 3.1). An alternative approach consists of introducing the damages to economic activity that arise from the destruction of natural capital (section 3.2). Section 3.3 highlights key differences between these approaches and reviews criticisms discussed in the literature. Section 3.4 discusses very briefly approaches in which natural capital is related to welfare or utility directly.

3.1 NATURAL CAPITAL AS A PRODUCTION FACTOR IN AGGREGATE PRODUCTION FUNCTIONS

The application of the neoclassical toolset to the discussion of growth in the presence of exhaustible natural resources goes back to Dasgupta and Heal (1974), Solow (1974) and Stiglitz (1974). Our exploration of production functions with natural resources starts from a Cobb-Douglas framework as it is widely used in resource economics. We will then turn to the more general class of Constant-Elasticity of Substitution (CES) functions and discuss the possibilities they offer for introducing greater granularity by sector and resources use.

In the presence of technical change, the elasticity of substitution may however vary over time, and we will discuss this briefly. At the end of the section we discuss a production function proposed by Dasgupta (2021) that leaves the ground of orthodox neoclassical growth theory while providing additional insights in the embeddedness of the economy in nature.

3.1.1 A Cobb-Douglas production function with natural resources (R)

A simple and widely used way of introducing natural resource flows into a production function is given in equation 1. Natural resources are added as a production factor R in a Cobb-Douglas production function. The resources can be finite or renewable.

$$Y = AK^{a}H^{b}R_{f}^{c_f}R_{r}^{c_r} \tag{1}$$

With a, b, c_f, $c_r > 0$ and $a+b+c_f+c_r = 1$;

Where Y is output, K is produced capital, H is human capital, R_f (R_r) is a finite (renewable) extracted provisioning good or service from the overall stock of natural capital. A represents the level of technology (A > 0); a, b and c are the marginal productivities of the input factors.

Production functions akin to $Y = AK^a H^b R^c$ are common in resource economics (e.g. Solow 1974; Stiglitz 1974, Dasgupta 2021). Voosholz 2014 and Couix 2018 provide useful overviews.

As we assume that a, b and c sum to 1, (1) is a Cobb-Douglas (CD) production function, a functional form that has been popular among economists because of its good fit to macroeconomic data and ease of use (Miller 2008). Among production functions in which the elasticity of substitution between production factors is constant, the Cobb Douglas function is the special case where it is one. The combination of the input factors K, H and R has constant returns to scale. At the same time, a represents the marginal productivity of capital and, under perfect competition, the capital share of income, while b and c are the marginal productivities of human and natural capital, respectively, and their respective income shares under perfect competition.

So, how does the addition of R affect output per capita in the long run? Let's first assume no technical progress (A is constant). We also abstract from population growth, assuming a constant global population and workforce. Focussing on the very long run, this is a plausible assumption: The medium scenario in the latest World Population Prospects (United Nations, 2022) sees world population peak at about 10 billion people in the second half of this century.

With the elasticity of substitution between production factors equalling one, whether economic output can be sustained in the presence of finite natural resources hinges critically on the extent to which produced capital K can replace natural capital R. In fact, constant output can be maintained even as an exhaustible natural resource is gradually used up, provided that the marginal product of produced capital exceeds the marginal product of the natural resource i.e. a>c (Solow 1974).

If we allow technical progress back in, the path of economic output in the long run (i.e. growth, stability or decline) depends on the rate of technical progress compared to the drag from resource depletion (Nordhaus 1992).

We will come back to the critical role of the elasticity of substitution in section 3.1.3.

3.1.2 A more granular production function

Instead of modelling natural capital at the highest level of aggregation, one can turn to a somewhat more disaggregated level, e.g. using nested (multi-layered) production functions.

A first step in that direction is to nest a Cobb-Douglas function with produced capital and human capital in a CES function with resources, as it is used for instance in Hassler, Krusell and Olovsson (2021) (equation 2).

$$Y = \left[(1-\gamma)(AK^a H^{1-a})^{\frac{\sigma-1}{\sigma}} + \gamma(A_R R)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \quad (2)$$

Here, γ is a share parameter, and σ is the elasticity of substitution between the bundle of produced capital / human capital and the resource R.

Crucially, σ can now differ from the elasticity of substitution between built capital and human capital in the Cobb-Douglas part of the function. This feature has for instance been exploited in recent analyses of the near-term impact of increased energy prices and gas supply disruptions in Europe (cf. the special issue 4 in European Commission 2022). In the nested CES approach, the short-run elasticity of substitution between energy and the other production factors can then be set appropriately low (see e.g. the discussion in annex 2 to Bachmann et al 2022).

More generally, nested CES functions allow for production technology to differ across sectors. For instance, elasticities of substitution are allowed to differ at different levels of aggregation. Quantities can be taken from national accounts' input-output tables, subject to some assumptions about the correspondence to the stylised sectors in the model. The particularities of finite natural resources can thereby be modelled at the appropriate level. An example with a seven-sector structure is Varga, Roeger and In 't Veld (2022) who develop a multi-sector DSGE model with energy, with the energy input being modelled at the sector level. While the seven-sector structure retains a fairly high level of abstraction (necessary for tractability in a DSGE setting), more granularity is exploited in other models.

This allows an even closer matching of economic input-output tables. This approach is followed in large-scale CGE models such as GEM-E3, which features 13 energy-transforming sectors (Capros et al 2013; Weitzel, Saveyn and Vandyck 2019) or GTAP (Corong et al. 2017, La Notte et al 2020). Standard national-accounts data cover only the flow of marketed resources. Efforts to include non-marketed ecosystem services in CGE models are discussed in section 4.2 below.

3.1.3: The crucial role of the elasticity of substitution

Section 3.1.1 already discussed the possibilities for maintaining output in the long run when natural resources are gradually depleted, under the Cobb-Douglas assumption of an elasticity of substitution of one. In the more general CES case, σ can differ from unity, and this requires some further discussion.[7]

If the elasticity of substitution between production factors is below one, each input is essential and cannot be fully substituted by another input. If R is an essential and exhaustible resource, output will converge to zero as R is gradually depleted, and there is no way to prevent this eventual collapse of economic activity.

By contrast, if the elasticity of substitution between production factors is above one, natural capital is not essential. Any natural resource that runs out can functionally be replaced by produced capital.

As a preliminary conclusion, a simple economic growth model suggests that a small number of parameters – elasticities of substitution, the marginal product of produced capital compared to the marginal product of finite natural resources, and the rate of technical progress - are critical for discussing whether economic output (or economic growth) is possible in the long run in the presence of finite natural resources. The same simple model suggests that this is an empirical question. Box 1 reviews the long-standing and still unresolved debate about natural limits to economic activity.

[7] A formal demonstration of the dependence of the path of output on the elasticity of substitution can be found in Dasgupta and Heal (1974) p16ff.

What else can be said about substitution elasticities? Substitutability is generally lower in the short run when technology is fixed, than in the longer run when alternative technologies can be employed. Most of the current transport equipment is built to run on petroleum-based fuels. In this sense, oil has to be considered a complement in the production function, with a very low elasticity of substitution in the short run. At the same time, efforts are under way to decarbonise transport, so over the period of two decades or so, the elasticity of substitution is much higher as technology for alternative engines and fuels evolves and costs come down. (The elasticity has to be greater than 1 for decarbonisation to work.)

In Varga, Roeger and in't Veld (op cit), decarbonisation is facilitated by the assumption that it is relatively easy in the long run to substitute between fossil and renewable energy. Their sensitivity analysis shows that assumptions about technical progress and the substitution elasticity are key drivers of the simulated costs of mitigation. Hassler, Krusell and Olovsson (op cit) estimate the annual elasticity of substitution between fossil fuel and the capital-labour bundle in the US at a value as low as 0.02, i.e. with a given technology, the proportion of energy and the other production factors is almost fix. In the longer run, increases in energy prices are however shown to trigger the deployment of energy-saving technology (an argument that goes back to Acemoglu et al 2012). There are good reasons to think that the elasticity of substitution is endogenous and evolves over time. As for instance the penetration of clean inputs in the economy increases, switching to these green inputs becomes technically easier (Jo and Mitavkhova 2022).

To sum up, substitution elasticity is likely to depend on the time horizon and technical progress (though that does not imply that all is substitutable in the long run).

Box 1: **UNLIMITED ECONOMIC GROWTH IN A FINITE WORLD?**

The literature on limits to the expansion of economic activity goes back as far as Thomas Malthus (1798) who highlighted the challenges of feeding a growing population on the basis of a finite supply of land. Also other classical economists such as David Ricardo and John Stuart Mill considered land an important production factor, a tradition that was later abandoned as natural capital appeared abundant. In the 20th century, it was in particular the Club of Rome's warnings about 'Limits to Growth' (Meadows et al 1972) that sparked a fierce debate about the sustainability of economic growth in the long run. New contributions continue to be added to this literature. This box sketches the main arguments and reviews the main open issues.

Macroeconomic models in the **neoclassical tradition** have been, and continue to be, widely used to study the implications of exhaustible resources (e.g.Solow 1974; Nordhaus 1992), climate change (as part of integrated assessment models e.g. Nordhaus 2017) and climate mitigation policies (e.g. Varga, Roeger and in't Veld 2022). In these models, <u>GDP is unbounded under certain conditions</u>, namely: easy substitution between inputs ($\sigma \geq 1$), technological progress (dA/dt sufficiently large to compensate the drag from resource depletion), and produced capital contributing more strongly to output than natural resources ($a<c$ in equation 1). According to neoclassical authors, whether these conditions are satisfied is an empirical question. An implication of substitution being relatively easy is that adopting technologies that mitigate ecological damages is also not very costly, and "green growth" is possible.

A competing school of thought, **ecological economics,** highlights the embeddedness of economic activity in nature, which is itself finite. According to this interdisciplinary approach, natural sciences suggest that unlimited growth of economic activity would unescapably lead to the destruction of the natural conditions that support human life. For instance, Georgescu-Roegen (1975) argues that the laws of thermodynamics imply limits to substitution and resource productivity. Since a part of the energy used in production is dispersed and cannot be recuperated (Carnot principle), there has to be a physical upper limit to the productivity of energy resources. Concerning materials, re-use and recycling can reduce the intake of natural resources, but there are theoretical as well as practical limits to a circular economy as well (Georgescu-Roegen 1971, Ayres 2007, Henckens 2021). Fresh resources are needed to continue accumulating produced capital, and this will eventually exhaust the stock of material resources (Daly 1997). Put differently, even in an economy that would push circularity to its boundaries, some intake of 'fresh' natural resources and some residual (non-recyclable) waste is unavoidable in the production process. As output continues growing, the flow of waste will at some point overwhelm the biosphere (Dasgupta 2021). These physical limits to the efficiency of resource use and waste recycling impose limits on the substitutability between produced capital and natural capital; once technical optimisation is exhausted they are complements rather than substitutes (Lawn 2004). This implies that the conditions that would allow green growth are impossible to meet in the long run.

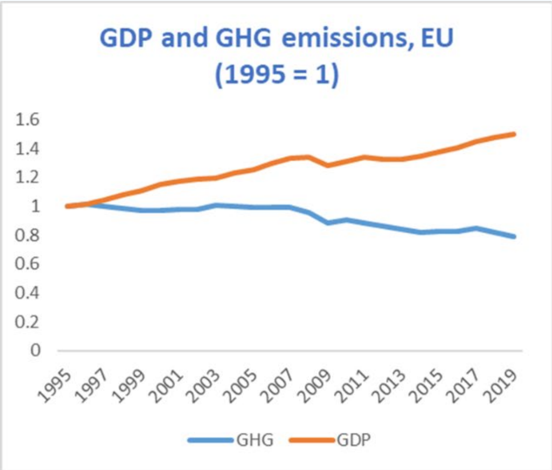
The focus of sustainability concerns has gradually shifted from energy and mineral resources in the 1970s towards environmental public goods and regenerative ecosystems that may collapse if persistently overused, e.g. fish stocks, soil or freshwater systems (for recent assessments see e.g. FAO 2022, UNCCD 2022). Most recently, increasing evidence of anthropogenic climate change and biodiversity loss has attracted attention towards Earth system processes and planetary boundaries. Rockström et al (2009) discuss nine Earth-system processes at risk of being destabilised by human activity; crossing critical thresholds would endanger the benign global conditions that have allowed human development over the past 10,000 years.

The substitutability of natural resources remains the major point of contention between the two schools of thought. The discussion on substitution possibilities in the neoclassical approach is fairly abstract (Cuix op cit). It is not easy to think of examples of substitution of a natural resource with produced capital, the mechanism highlighted by simple neoclassical growth models. Vertical indoor farming would appear an example, but it still relies on air, water and energy from outside the indoor farm. However, the focus on natural vs built capital appears to be owed to the simplicity and lack of granularity of the basic model. If the concern is to eliminate greenhouse gas emissions, various forms of substitution could be effective: from one natural resource base to another (replace protein from methane-emitting cattle with vegetal protein), from one form of capital to another (use a bicycle instead of the car) or substituting combinations of a natural resource with capital (replace petrol and combustion engines with renewable electricity and electric motors).

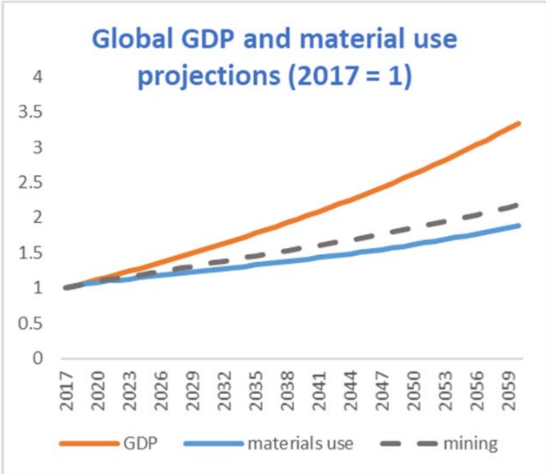
Neoclassical economists doubt that the laws of thermodynamics will impose limits on economic activity within the next few generations (though the timespan being considered as relevant is somewhat ambiguous, cf. Couix op cit). A key argument is that the second law of thermodynamics refers to a closed system, while renewable energies are ultimately reliant on the sun, i.e. a source of energy outside the Earth system. Renewable and clean energy could become sufficiently abundant to fuel growing output for a long time (e.g. Rifkin 2014), the technical limits to recycling and replacing finite materials with renewable materials are far from exhausted (Komiyama and Yamada 2018), while scarcities of specific mineral inputs could be solved by finding more abundant functional substitutes (Henckens 2021).

The initial debate on substitutability focussed on finite fossil energy and minerals. Neoclassical economists have pointed out that the pressures on exhaustible resources should ease as income and consumption levels increase. People will not accumulate more cars as they get richer, but rather buy better cars and consume more services. The demand for raw materials (used for making cars but not, or much less, for producing services) will therefore ease, contributing to a de-coupling of economic output from material resource inputs. Empirically, absolute de-coupling (i.e. rising output with falling input) is visible for fossil energy use and greenhouse gas emissions in the EU. Some Member States have also reduced domestic material consumption, but material inputs at a global scale are expected to continue increasing (see Figure B1).

Figure B1: **Decoupling of greenhouse gases and material use**



Source: AMECO and EEA



Source: OECD (2019): Global Material Resources Outlook to 2060

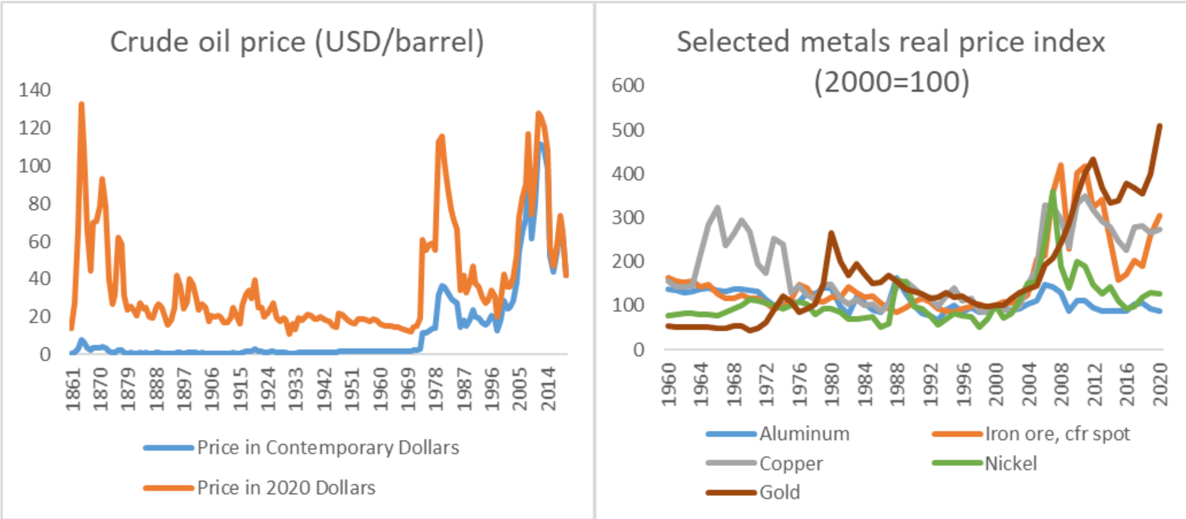
The more recent focus on the vulnerability of ecosystems highlights threats to *renewable* ecosystem services. Ayres (2007) discusses essential (i.e. non-substitutable) natural technologies embodied in the biosphere, on which humans crucially depend. Among them are photosynthesis for oxygen and nutrients, the hydrological cycle for freshwater and the phosphorous cycle.

The question of substitutability also relates to the debate between 'weak sustainability' and 'strong sustainability'. The utilitarian approach to intergenerational equity stipulates that if a particular form of natural capital is depleted it has to be replaced by another form of capital that generates the same stream of utility for future generations. By contrast, Helm (2019) calls for preserving natural capital so that future generations have the opportunity to decide for themselves how they want to use it. The current generation then is only the steward of natural capital for the next generation. This implies a stabilisation of the stock of natural capital (strong sustainability), i.e. natural capital depleted in one place has to be offset by investing in new natural capital in a different place.

Concerning the second condition for green growth in the neoclassical model, <u>technical progress has to outpace the drag from natural resources scarcity</u>. This applies both to the efficiency of resource use on the input side and to the discharge of waste into nature, respectively the efficiency of waste reduction (as pointed out by Dasgupta op. cit.) The pace of TFP growth in advanced economies has however been slowing over the past decades. In the simplest growth model, TFP growth is exogenous. By contrast, endogenous growth models highlight that a share of GDP must be devoted to R&D in order for technical progress to happen. The R&D effort required to produce new technologies has been increasing over the past several decades (Bloom et al 2020). An alternative reading of productivity developments over longer periods of time is that TFP growth is in fact linear rather than exponential as assumed in the most commonly used growth models (Philippon 2022). This would cast further doubt on the ability of productivity to outpace the drag from resources becoming scarcer.

So far however, there is little drag from exhaustible resource scarcity due to a high rate of discovery of reserves as well as new extraction technologies developed over the past decades. Where the Hotelling rule would predict a gradual increase of the scarcity rent for exhaustible resources, the evidence is in practice rather mixed (see Figure B2).

Figure B2: **Oil and metals prices**



Source: Oil prices BP (downloaded from NASDAQ) Metals prices: World Bank.
Note on oil: 1861-1944:US average. 1945-1983: Arabian Light posted at Ras Tanura. 1984-2020: Brent Dated.

Turning to the third condition, according to conventional growth accounting, produced capital contributes vastly more to economic output than natural resources. This however depends on how narrowly or broadly natural capital is defined and on the valuation method. Valuation at exchange value (see section 4.3) generally yields small estimates. However, according to the estimations in Constanza et al (2014), global ecosystem service flows would exceed GDP by far. A better understanding of, and more exhaustive accounting for, ecosystem services might thus eventually challenge the conventional view on the relative contributions of natural and produced capital to economic output.

The ecological economics school stresses that natural growth processes converge to a steady state after a phase of exponential growth (Constanza 2010). In the economic sphere, such a transition could happen if consumption demand spontaneously stabilises once households reach a satiation point above which leisure is more attractive than further consumption. This was a common view among the classical economists, and the subject of an essay by Keynes (1930). Life-satisfaction surveys indeed point out that national averages of happiness cease increasing once a certain income level is reached. However, individual happiness depends not only on absolute income (earning enough to cover all basic needs) but also on *relative* consumption compared to a peer group (Clark, Frijters and Shields, 2008, Easterlin and O'Connor 2020). Inequality and the 'rat race' of competition for social status seem to prevent the spontaneous realisation of a steady state in consumption demand.

3.1.4: Extension with regulating and maintenance services related to the biosphere (S^β)

So far, we have discussed flows of natural resources. This section turns to services flowing from the biosphere, and highlights further the embeddedness of economic activity in nature. Dasgupta (2021) modifies the Cobb-Douglas function with resources discussed above in a crucial way. He introduces a multiplicative factor S^{β}, which captures regulating and maintenance services related to the biosphere, i.e. the stock of natural capital S (op. cit p. 139).

$$Y = AS^{\beta}K^{a}H^{b}R^{c} \tag{3}$$

With β, a, b, c > 0;

S is a stock and S^{β} its services contributing to economic output (just as K is a stock from which services K^{α} flow into production). S is understood as a public good. There are boundaries to S, so that if it falls below a critical level $\underline{S}$, the ecosystem collapses[8] and economic activity with it.

In this modified production function, the Solow residual (what we commonly interpret as Total Factor Productivity) is AS^{β}. It reflects not only the state of technology and institutions (with technological progress dA allowing more efficient combinations of K, H and R) but also the state of the biosphere.

Economic activity affects the biosphere by extracting resources, finite or renewable, and producing waste. At the same time, the biosphere can regenerate itself to a certain degree. Therefore, S varies over time t[9]and its dynamics can be conceptualised in the following way (see also Dasgupta 2021):

$$dS(t)/dt = G(S(t)) – R(t) – w(t) \tag{4}$$

where G(S) is natural regeneration[10], R is resource extraction as above and w is the flow of waste that degrades the biosphere. One sees immediately that a situation in which the ecological footprint (R+w) persistently exceeds the biosphere's regenerative capacity would deplete S, and is therefore unsustainable.

This conceptual framework of equations 3 and 4 also easily applies to climate change with the use of fossil fuels (a finite resource R_f) leading to greenhouse gas emissions (a form of pollution w) that disturbs climate regulation (a global ecosystem service S^{β}).

What does the addition of S^{β} to the production function imply? First, the measurement of TFP is misleading if S is poorly understood. In fact, total factor productivity A is not directly observable, statisticians therefore estimate it as a residual in national accounts. As long as national accounts omit the services provided by the biosphere (i.e. β is assumed to be zero when it should in reality be positive), TFP is overestimated. GDP growth that is in reality attributable to the overexploitation of natural capital is then erroneously attributed to technical progress.[11]

Second, note that β, the marginal product of natural capital, cannot be inferred from market prices in the same way as it is possible to infer a and b (assuming perfect competition), as S is a public good and the services it provides are for free.

[8] An illustrative example is fish in a lake: If the number of adult individuals of a particular species falls below the number that allows effective reproduction, the species will disappear from the lake.

[9] Also produced capital K and human capital H evolve in a dynamic way, depending i.a. on investment and demographics. These are fairly standard assumptions and are therefore not further discussed here.

[10] The biosphere S regenerates at a rate that depends on the biosphere stock S. S has an upward bound, the 'carrying capacity' (e.g. the density of fish in a lake cannot increase indefinitely). But for all practical purposes dG/dS>0.

[11] Cardenas Rodriguez, HaščIč and Souchier (2018) show how the contribution of multifactor productivity to output changes when natural resource depletion and pollution are accounted.

Third, according to Dasgupta, once S is included, output becomes bounded. The production function including S is no longer an orthodox neoclassical one. Concretely, the boundaries to output hinge on the efficiency of waste treatment having an upper bound (more on this in section 3.3).

3.2 DAMAGES TO ECONOMIC ACTIVITY: DESTRUCTION OF NATURAL CAPITAL AS A DISTURBANCE TERM

An alternative way of reflecting the contribution of natural capital to economic activity is more indirectly, through damage functions. This approach focuses on the damaging impact of economic activity on nature and the negative feedback from the destruction of nature to economic activity. It has been widely used in integrated assessment models (IAM) of climate change (for a recent overview, see e.g. Dimitrijevics et al 2021, IPCC 2022 chapter 16).

The feedback loop we are interested in consists firstly of the damaging output of economic activity in the form of pollutants (e.g. waste, greenhouse gases). Secondly, the use of nature as a sink affects natural capital through bio-physical processes. In the familiar case of climate-economic models, this is the link between greenhouse gases and temperature change known as ‘climate sensitivity’. Thirdly, the disturbance to natural capital results in damages to economic output, which are reflected in the damage function.

The basic idea of the damage function is that economic losses arise from diminished ecosystem services (e.g. deregulation of the global climate), and that they drive a wedge between gross output Y and net output Q. The intuition is that part of the gross output is destroyed or has to be used to avoid or repair the damages. Only the remaining net output is available for consumption and investment. This is expressed in equation (5).

$$Q(t) = Y(t)E(t)[1-\Lambda(t)] \tag{5}$$

The multiplier E represents damages ($0<E<1$) and Λ stands for efforts (as a fraction of output) devoted to mitigating pollution.

Equation 6 explains how economic damages are linked to the accumulated stock of pollutants.

$$E(t) = \frac{1}{1+(\frac{W(t)}{W_H})^2} \tag{6}$$

Where W(t) represents the accumulated pollution that degrades the natural capital stock. Equations (5) and (6) are taken with a slight adaptation of notation from the Dynamic Integrated Climate Economy (DICE) model (Nordhaus 2008). In the DICE model, E would be the damages from climate change and W(t) the temperature increase in °C over pre-industrial times. W_H is simply the value for which E(t) equals 0.5. Damages are a quadratic function of the accumulated pollutants, so that the damage function is convex.

Hackett and Moxnes (2015) propose modelling climate-related damages and damages related to other forms of pollution in two separate feedback loops but apply the functional form of the climate damage function also to other pollutants as does our damage function.

It is important to add that there is a very large literature on the various channels through which rising global mean temperatures affects economic activity. These channels include sea-level rise, river floods, storms, damages from drought and pests, damage to fish stocks from warmer sea temperatures, the disruption or diminishing of ecosystem services and the impact of heat on human health.

Moreover, damages are likely to have repercussions through the financial system. Stern (2007) remains a good overview. Despite considerable advances in this literature, large uncertainties remain about crucial parameters and likely non-linearities.[12] The understanding of damages arising from loss of biodiversity or destruction of ecosystems providing other global regulating services is far less advanced, making the formulation of general damage functions even more challenging than in the climate case.

3.3 DAMAGE FUNCTIONS VS. PRODUCTION FUNCTIONS WITH NATURAL CAPITAL: KEY DIFFERENCES AND CRITICISMS

In sum, what are the main differences between the damage-function approach and the Dasgupta approach to covering natural capital in aggregate production functions, and what does it add to our understanding?

An illustrative feature of the damage-function approach is that net output Q can be interpreted as the output available for households' consumption or saving, hence as an approximation of material wellbeing. The effort to deal with the negative impact of environmental degradation drives a wedge between economic output and material wellbeing, which is here made explicit in the 'defensive cost' $Y(t)-Q(t)$. By contrast, approximating natural-capital degradation by reducing TFP (as with the factor S^{β} in equation 1) reduces output and material wellbeing by the same degree.

There are further important differences in modelling the way pollution is generated (or avoided) and how it affects natural capital, and in modelling nature's regenerative capacity that require a further look.

Concerning pollution, for Dasgupta the flow of waste is a function of economic output and waste-treatment technology: $w(t) = Y(t)/a_z$. The term a_z depends on technical progress A, e.g. the efficiency of recycling and the treatment of residual waste.[13]

In the damage function approach put forward by Hackett and Moxnes, the accumulation of waste depends on economic output, waste-reducing technology and the capacity of nature to decompose waste: $W_{t+1} = Y_t h_t + (1-\omega)W_t$. The intensity factor h is assumed to follow an exponentially declining path: Given enough time, economic output becomes sustainable by assumption. This is in sharp contrast with Dasgupta, where a_z is assumed to have an upper bound. If a_z cannot increase at the same rate as Y, the term Y/a_z increases as Y tends to infinity, and the burden our waste puts on the biosphere eventually causes the collapse of the economic system. Dasgupta (op. cit. p. 141) however passes rather quickly over the reasons why a_z must have an upper limit.

Another difference consists in the approach to modelling nature's regenerative capacity. In Hackett and Moxnes, a constant fraction ω of accumulated waste is neutralised in each period. There is no point at which nature becomes overwhelmed by waste. In Dasgupta, regeneration $G(S(t))$ depends on

[12] Powerful non-linearities could stem e.g. from the disappearance of the Arctic ice sheet resulting in reduced reflection of sunlight, the release of methane (a powerful GHG) from melting permafrost, a decreasing absorption capacity of natural carbon sinks, and ecosystem regime shifts (see e.g. Pistone, Eisenmann and Ramanathan 2019; Teufel and Sushama 2019, IPCC 2022). Due to important gaps in our understanding of the underlying geophysical processes, the range of climate sensitivity considered likely is quite large, and it is skewed to the upside.

[13] Note that in this formulation, all economic output produces waste. The contribution of ecosystem services to output could plausibly be excluded from this.

the stock of natural capital in a nonlinear fashion; crucially, once a tipping point (S) is passed, the biosphere collapses (Dasgupta op cit ch. 3)

More generally, the most obvious difference between production functions with natural capital and damage functions is the explicit treatment of resource flows and ecosystem services in the former. At this stage, this is however subject to limitations. We will show in the next section that covering marketed resources in an aggregate production function is relatively straightforward (though some data limitations have to be overcome). It is also already possible to calibrate the contribution of ecosystem services to the production of specific goods at a disaggregated level. By contrast, the full inclusion of natural capital in aggregate production functions is currently at the stage of conceptual reasoning - the available understanding of bio-physical mechanisms and the data situation do not yet allow a comprehensive calibration of the contribution of resources and ecosystem services to aggregate economic output.

On the other hand, the shortcomings of damage functions have led to harsh criticism in part of the literature on climate-economic modelling. While damages 'take away' some share of each period's output, they leave the production process as such intact. Many relevant channels of (climate) damages would however affect the capital stock (flood damages, for instance), the size of the available workforce (ill health, higher mortality, migration) or productivity (e.g. labour productivity declining at higher temperatures). Stern and Stiglitz (2021) point out that omitting damages to the capital stock and impacts on the growth (rather than the level) of output is likely to lead to a substantial underestimation of the economic consequences of climate change. Farmer et al (2015) point to lack of evidence about the underlying mechanisms, aggregation issues and a failure to take uncertainty explicitly into account. Pindyck (2013) describes the damage functions in standard IAMs as 'completely ad hoc'. Even the more recent damage functions may not represent the latest knowledge about climate impacts (Rose, Diaz and Blanford 2017; Dietz et al 2020).

3.4 NATURAL CAPITAL AND SOCIAL WELFARE: TAKING INTO ACCOUNT UTILITY

While our paper focuses on natural capital in production, it is important to highlight that this is only part of the story when it comes to social welfare as a whole. So far we have focussed on the production of goods and services using some form of natural capital. The consumption of these goods and services affects material wellbeing. However, nature affects wellbeing also directly, e.g. through the availability of breathable air or the aesthetic value of an unspoiled landscape. Capturing the direct contribution of nature to wellbeing requires turning to the utility function. An example of a model including natural capital both in the production function and also directly in the utility function is Bovenberg and Smulders (1995). Going one step further, Bastien-Olvera and Moore (2021) propose a utility function in which natural capital enters through three channels: firstly, through the production of consumption goods; secondly, natural capital enters into the production of ecosystem services that can in turn be an input to the production of final goods and services or can be consumed directly; and thirdly the use value of natural capital. One can easily think of more aspects to add, e.g. the utility a household is able to draw from nature may depend on their decisions about leisure time (and hence on labour market conditions). The Bovenberg and Smulders model highlights the interplay between natural capital and human capital or knowledge capital. Roseta-Palma, Ferreira-Lopes and Neves Sequeira (2010) build on this work and include also social capital in addition to natural capital and human capital in an endogenous growth model.

4. PRACTICAL AND EMPIRICAL CONSIDERATIONS FOR THE INTEGRATION OF NATURAL CAPITAL INTO ECONOMIC MODELS

For the empirical integration of natural capital in economic models, two steps are necessary. First, the *bio-physical contribution of natural capital to economic output* needs to be identified and measured with adequate metrics. For marketed resources (like crude oil or timber) that enter the production process directly, this is relatively straightforward though not without some practical issues. For some indirect-use ecosystem services such as pollination, the input is harder to trace, but the related economic output (e.g. fruit from an orchard) is easy to observe, while for other ecosystem services such as water purification or carbon absorption the service is also not directly relatable to a specific economic output. The second necessary step consists of the *monetary valuation of the resource input or ecosystem service*. When there are no market prices, this involves a number of tricky issues.

This section cannot provide definite solutions for these difficulties. It can merely illustrate with selected examples from the literature how one might go about addressing them. We follow the order in which concepts were introduced in section 3 and first discuss the simplest case of integrating marketed resources (section 4.1) before turning to the measurement of ecosystem services (section 4.2). In section 4.3., issues with the monetary valuation of non-marketed natural capital services are discussed, and we outline what their incorporation implies for the output measure. Section 4.4 discusses an example of measuring the *stock* of natural capital and its evolution over time. Finally, we discuss empirical estimates of damage functions (section 4.5) for climate damages where they have been used extensively.

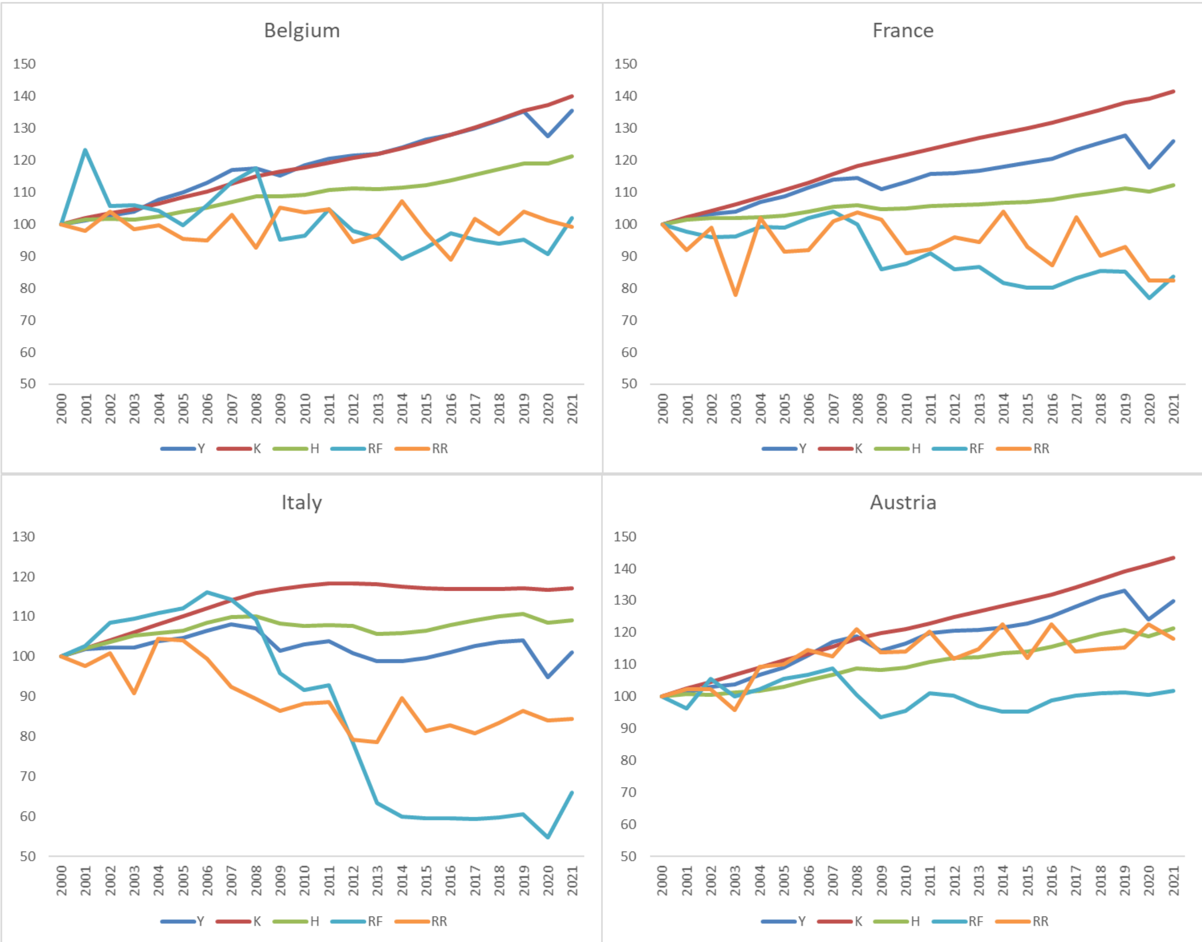
4.1 MARKETED NATURAL CAPITAL RESOURCES (R_f AND R_r)

For a conceptually simple way to incorporate resource flows into the aggregate production function, we can use the Cobb-Douglas framework of equation (1). Since in competitive markets the marginal product c of resource R corresponds to its income share, we need to compute the income share of raw materials.

Figure 6 displays the evolution over time of real GDP Y built capital K and employment H from the Commission's AMECO database and material flows data from Eurostat's material flow accounts, where R_f is the sum of metal ores, non-metallic minerals, fossil energy carriers and 'others' and R_r is biomass. The four Member States with the longest available series of material flow accounts are shown. The OECD compiles similar physical data on the natural resource base of countries and material use for a larger set of countries.

There are a few practical difficulties when it comes to measuring the value of the annual use of extracted resources. Conceptually, we want to look at commodities in a state that is as close as possible to the state in which they are extracted; in other words, they should incorporate as little labour or produced-capital inputs as possible. At the same time, we would like to cover raw materials incorporated into imported intermediate goods, which are often at a higher degree of processing. Different data sources satisfy these requirements only partly; as is illustrated by the following three examples (we focus on exhaustible resources): Eurostat's trade database COMEXT has a very detailed product breakdown but does not allow to identify the raw material content of imported goods. It thereby underestimates the material input in EU production. Eurostat's material flow accounts are closer to the definition we seek, but prices are not reported and need to be taken from other, not necessarily matching sources. The JRC's Global Energy and Climate Outlook is more aggregated, and a distinction between raw materials and processed goods is generally not possible, leading to an overestimation of raw material use. Annex 1 provides more detail. Depending on the source of the data, we find GDP-shares of fossil fuels in the EU in a range from 1.8% to 2.9%. By contrast, the GDP share for metals and minerals ranges from 0.4% to more than 9%. For illustration, if we opt for the material flow accounts, we get a GDP share of 8% for fossil fuels and metals, corresponding to a value for c_f in the order of 0.08.

Figure 6: **Output, built capital, human capital and material flows (index, 2000=100)**



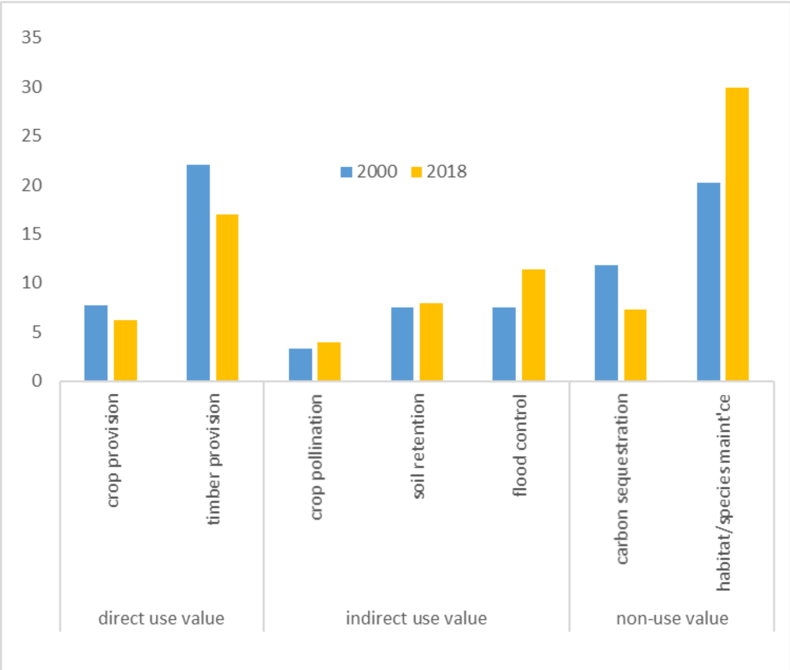
4.2 ECOSYSTEM SERVICES (S^{β})

As noted above, ecosystems are characterised by complex interactions of organisms in and with their physical environment. Ecosystems contribute to economic activities and wellbeing in various ways that are not necessarily well understood, and that are hard to measure. In this section we illustrate the valuation of the economic services provided by ecosystems with selected examples, exploring possible avenues for operationalising equation 3.

A widely noticed assessment of the value of global ecosystem services is Constanza et al (2014). The authors estimate the annual value of the services provided by 16 selected ecosystems[14] at 125 trillion USD at constant 2007 prices, a value nearly twice as large as global GDP. Compared to an earlier estimation (Constanza et al 1997), the authors find that the unit values (averages per ha) of ecosystem services have increased.[15] At the same time, the geographical extent of crucial contributors such as tropical forests and coral reefs is decreasing. The authors acknowledge that their estimations at global scale are not sufficiently precise to be used for specific policy decisions, but see them as useful for awareness-raising.

More recently, efforts to develop internationally shared methodologies and standards to link economic and environmental data have led to the adoption of the UN handbook *System of Environmental-Economic Accounting – Ecosystem Accounting* (SEEA EA) in 2021. The EU contributed to this endeavour through the *knowledge innovation project on an Integrated system of Natural Capital and ecosystem services Accounting for the European Union* (INCA) (Vysna et al 2021; Bagstad et al 2021).

Figure 7: **Total economic value of selected ecosystem service flows in the EU (bn euro)**



Source: La Notte et al (2022).
Note: The categorisation in direct and indicrect use value and non-use value is the authors'.

Figure 7 reports the valuation of selected ecosystem services for the EU taken from La Notte et al (2022). They estimate the value of the flows of seven ecosystem services at 84 bn euro in 2018. Different techniques are used for evaluating these ecosystem services: market prices for the direct use

[14] These are 5 marine ecosystems (open ocean, estuaries, seagrass/algae beds, coral reefs and shelf) as well as 11 terrestrial ones (tropical forests, temperate/boreal forests, grasslands/rangelands, tidal marsh/mangroves, swamps/floodplains, lakes/rivers, desert, tundra, ice/rock, crop land and urban land).

[15] The authors explain that changes in unit value can be due to better understanding of the services, changes in the health (functionality) of the ecosystem or changes to the human, social or built capital with which the ecosystem services are combined in production. The relative impact of these factors is not assessed.

value of crops and timber; adapted market prices, replacement cost and avoided damage for the indirect use value of pollination, soil retention and flood control respectively; and effective carbon prices compiled by the OECD as well as willingness to pay for the non-use value of carbon sequestration and habitat/species maintenance respectively.

Ecosystem service accounting involves several steps. First, the extent of different ecosystems (e.g. forests, grassland, lakes) is measured, and the development of their size over time recorded. Satellite imagery has been playing an increasing role in the development of ecosystem extent accounts, in the case of INCA the Copernicus Earth observation programme. The potential of an ecosystem to provide services depends not only on its extent but also on its quality. In a second step, the health and ecological integrity of ecosystems are examined and recorded in ecosystem conditions accounts. This involves measuring a set of relevant variables, e.g. soil characteristics or nutrients in water.

In the third step, physical flows between ecosystems and economic activity are recorded, much as if the ecosystem was an economic sector providing an input to another economic sector. This treatment of ecosystem services allows for the integration of ecosystem accounting with the input-output tables from national accounts. Note that the flow of services from a particular ecosystem to humans requires a matching of ecosystem potential and demand. Often the actual service flow depends on proximity: The coastal protection service provided by a mangrove will e.g. be evaluated more highly the closer the mangrove is to a human settlement.[16] Note further that the physical flow does not necessarily go from the ecosystem to the economy; in the case where the service consists of the use of natural sinks it is the other way round. An example is nitrogen from agricultural activity that pollutes a river, which however has the capacity to purify the water again through immobilisation, transport and biochemical denitrification.

In the fourth step, physical flows can be translated into monetary units (difficulties in this respect are discussed in section 4.3). It is also possible to go yet a step further and evaluate the stock of natural capital from the net present value of services flows (section 4.4).

La Notte et al (2020) exploit the link between the data collected as part of the INCA project and national accounts. The example of disruption to pollination services due to the Asian hornet, an invasive species and predator of pollinating insects, is particularly illustrative. The INCA project has produced supply and use tables for crop pollination. The flow of pollination services was estimated using crop pollination potential (supply) based on the location of habitats for wild pollinators (wild bees, bumblebees) and demand for pollination assessed on the basis of the location and extent of pollinator-dependent crops (mostly fruit, but also e.g. rapeseed and sunflowers). The spread of the Asian hornet in Western Europe can be modelled as a negative shock to pollination services in the concerned regions. The environmental pollination accounts are then linked ('bridged') to the national accounts data underlying the GTAP model. Due to the general-equilibrium features of GTAP, it is possible to assess the impact of the shock not only in terms of lost production, but also prices and trade flows. It is also possible to simulate the impact a further spread of the predator would have.

A criticism that is sometimes raised at the way of assessing natural capital via flows of services is that it downplays the complexity of systems. As the very name suggests, within any ecosystem various living beings and physical framework conditions interact in complex ways. The measurement of ecosystem services may not yet be able to capture these interdependencies adequately and thereby dynamics that drive system vulnerability and resilience (Daily et al 2000, De Smedt, Giovannini and

[16] Mangroves also provide other services, e.g. as nurseries for fish. For the sake of the argument, we focus here on one particular service for which geographical proximity is particularly relevant.

Radermacher 2018; Helm 2019). Further research on ecosystem vulnerability and their nonlinear response to perturbation appears warranted.

4.3 MONETARY VALUATION AND THE LINK WITH GDP

The purpose of monetary valuation of natural capital services is to compare different services or asset types using a common numéraire, in a way that is consistent with national accounts.

Estimations of physical flows in monetary units are necessary for the purpose of aggregation and comparison. One ecosystem (say a forest) produces several services (carbon sequestration, timber provision, water regulation and flood protection) that are measured in different units. Expressing each service in monetary terms provides a way to aggregate them. The same applies for aggregating or comparing the services provided by different ecosystems. Furthermore, monetary valuation allows comparing the benefits and costs of policy actions as well as highlighting the contributions of natural capital services to specific production chains, examining trends in broader concepts of wealth and wellbeing, guiding policy decisions on investment (conservation efforts) in natural capital, assessing financial risks related to environmental degradation and providing baselines for analysis and modelling (UN 2021, p. 177). Monetary valuation thus adds transparency and analytical underpinnings to economic and political decision-making.

Assigning monetary value to services derived from natural capital that are not exchanged in markets and public or common goods comes with a number of issues[17] that are briefly discussed in this section.

In line with national accounts, the SEEA favours the use of exchange value. When no market exists,[18] exchange value is approximated using various techniques such as hedonic pricing, damage avoided, replacement costs, travel costs (i.e. the cost incurred by visitors to reach a particular recreational area) or experimental/simulated exchange value (UN 2021, chapter 9; Fenichel, Abbott and Yun 2018 discuss a number of difficulties).

Constanza (2014) rejects the idea that monetary valuation of natural capital services per se leads to a 'commodification' or privatisation of nature. However, its treatment at exchange value also implies that any intrinsic value of nature is not captured. As mentioned above, the coastal-protection value of a mangrove is not independent of where it is located. Another example is that we may care about the continued existence of particular species beyond the economic benefits we receive from them. A particular objection raised to the very idea of monetary valuation is that humans may have spiritual connections to nature (Dasgupta op. cit p. 61; EEA 2018) that cannot be expressed in terms of monetary value. Though here is not the place to discuss these objections, we nonetheless take them seriously. Our focus is on the economic dimension of natural capital services, but the broader context should be kept in mind.

Finally, the use of monetary valuation for aggregating ecosystem services (or assets) and optimisation is subject to some conditions that may not always be met in practice. Aggregation and the use of

[17] The UN SEEA-EA Handbook itself lists a number of caveats and persisting areas of disagreement in the chapters on monetary valuation.

[18] Note that it is possible to estimate the monetary value of an ecosystem service indirectly if a market exists for the product to which it contributes and information is available on the production technology and the costs of the other input. Mäler (1991) describes this for different constellations of available information.

marginal reasoning requires scalability, which is not given if there are major non-linearities such as tipping points (Radermacher and Steurer 2015). The use of optimisation calculus also requires substitutability (natural capital being replaced by another form of natural or physical capital that serves the same purpose just as well). We have discussed above that what makes some forms of natural capital essential is that no substitutes exist for them.

At this stage, it is necessary to discuss how making the contribution of natural capital explicit and taking into account the various externalities involved affects the measure of aggregate output. Several cases need to be distinguished. As highlighted by Muller, Mendelsohn and Nordhaus (2011), contemporaneous externalities within the market sector are properly accounted for in measures of aggregate GDP as they stand. If the pollution emitted in one sector decreases the output in another sector, aggregate GDP reflects that damage.[19] However, many of the externalities discussed here are outside the market sector and/or do not occur contemporaneously.

Indeed, the focus of our discussion is on cases where economic activity today affects the possibilities for economic activity in the future, by reducing the stock of natural capital. Adjusting the right hand side of the production function for such temporal effects (or for externalities outside the market sector) leads to 'green' Net Domestic Product (see for example Dasgupta and Mäler 2000, Barbier 2019, Galiano Bastarrica et al 2022). (Green) Net Domestic Product takes into account the depreciation of the (natural) capital stock.[20]

Measuring the stock of natural capital S and its evolution over time is thus central. The World Bank compiles estimations of natural capital stocks for a large number of countries. This is presented in the next section.

4.4 MEASURES OF AGGREGATE NATURAL CAPITAL STOCKS (S)

In this section we briefly present the accounting of natural capital stocks, i.e. natural wealth, which has been pioneered by the World Bank (Lange, Wodon and Carey 2018, World Bank 2021). Here, the financial value of a stock of natural assets is measured based on the SEEA methodology described in section 4.2. The authors emphasise the close link between different forms of wealth (natural capital, produced capital and human capital) and the flows of GDP that result from it. The evolution of wealth thus allows assessing the sustainability of GDP over time.

Figure 8 displays the evolution of different forms of wealth according to the World Bank's most recent estimations.[21] At a global scale, human capital represents by far the largest asset, valued at more than twice the stock of produced capital. Renewable and finite natural assets are by an order of magnitude

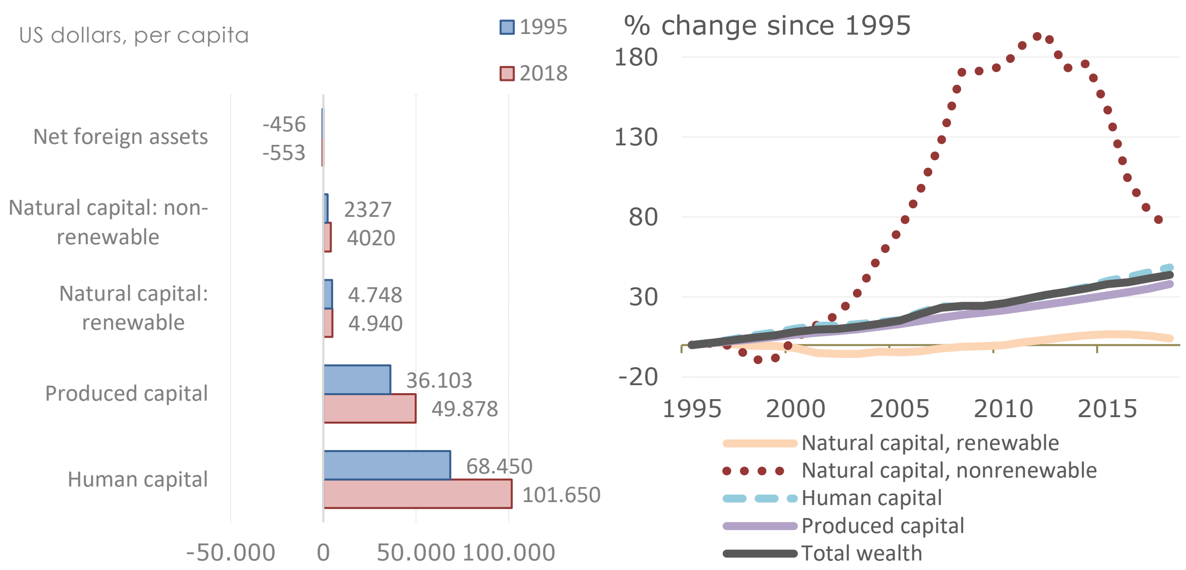
[19] The measurement of value added in the individual sectors does not capture the externality, but in this specific case the mismeasurements cancel each other out when value added is aggregated.

[20] As discussed in section 3.4, the damage-function approach also leads to a measure of net output, without however making the depreciation of the different forms of capital explicit. Also,information on the variation of the stock of natural capital can be used either to calculate net output or for adjusting TFP (while keeping GDP on the left hand side) as in Cárdenas Rodriguez, HaščIč and Souchier (2018).

[21] As mentioned above, estimations of natural assets depend a lot on the range of goods and services covered and the valuation method. An example for an ecosystem service not covered by the World Bank and with potentially large value is recreation (as contributor to tourism and real estate value).

smaller. The valuation of non-renewable natural capital has displayed the strongest growth over the 1995-2018 period accompanied by very large volatility due to large swings in market prices.

Figure 8: **Changes in per capita Natural, Physical and Human Capital**



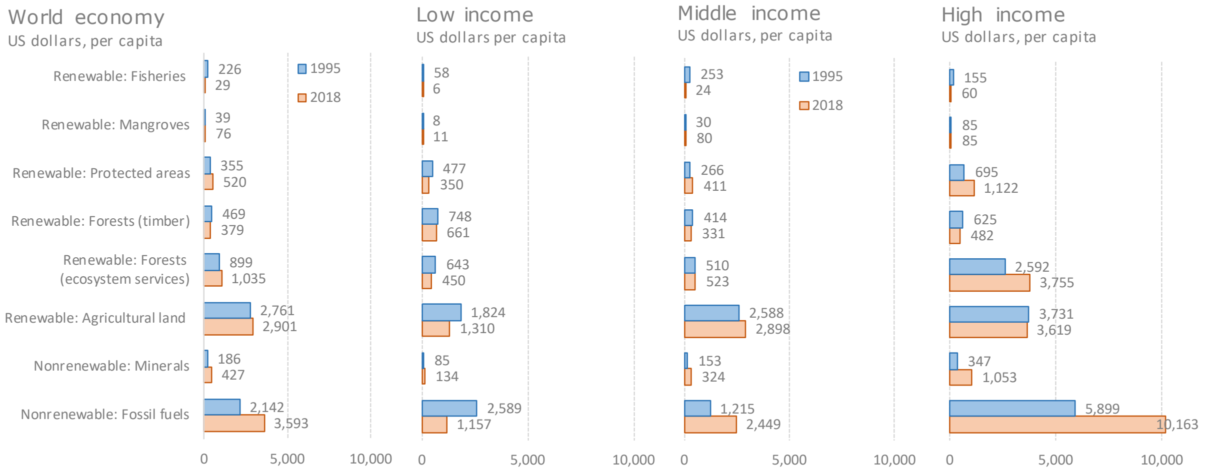
Note: World natural, physical and human capital, and net foreign assets, measured in constant 2018 US dollars and divided by population, from the World Bank (World Development Wealth Accounts).

Figure 9 zooms in on different forms of natural wealth by country-income group. Natural wealth is dominated by stocks of fossil fuels, and this dominance has increased between 1995 and 2018 with the gains in valuation of fossil fuel assets in middle-income and high-income countries, reflecting new reserves, the deployment of new extraction technologies and higher prices. Agricultural land ranks second at global scale. Its value has increased due to extension (often at the expense of forests) and changes in farming methods. In low-income countries, its value has however not kept up with population growth. Concerning marine natural assets, the value of fisheries has decreased worldwide as fish stocks have been depleted. The increase in the value of mangroves globally reflects not the growth of mangroves but rather the increase of the value of coastal constructions they protect (World Bank 2021).

Focussing on stocks, the wealth approach is designed to be used *alongside* GDP (a flow variable), by comparing the dynamics of GDP to the development over time of the natural assets that are covered. If GDP grows while natural assets decline, this points to an unsustainable over-use of resources. However, the fundamental link to GDP stems from the fact that the different assets that constitute wealth are at the same time the production factors from which GDP is derived. Moreover variation in the stocks can be used to calculate net domestic product (section 4.3).

While the coverage in terms of asset types is far from complete, and the authors acknowledge shortcomings e.g. when it comes to risks of tipping points, the World Bank asset dataset is the most comprehensive so far.

Figure 9: **Changes in per capita Natural, Physical and Human Capital**



Note: World natural, physical and human capital, and net foreign assets, measured in constant 2018 US dollars and divided by population, from the World Bank (World Development Wealth Accounts).

4.5 ESTIMATED DAMAGE FUNCTIONS IN THE CLIMATE LITERATURE

In section 3.2, we outlined the damage-function approach. While it has been used extensively in integrated assessment models of the climate, there are so far only few concrete applications of ,the integrated assessment model framework for analysing natural capital dynamics beyond climate change. The potential value of doing so has been recognised (e.g. Harfoot et al 2014). Muller, Mendelsohn and Nordhaus (op cit.) have looked at GHG and a range of non-GHG air pollutants. Hackett and Moxnes (op cit.) introduced non-climate damages in the DICE model. The IMAGE large-scale IAM uses a satellite model for ecosystem services (Stehfest et al 2014 ch 7).

But this compares to a very large literature on climate damages. For our illustration of the difficulties in estimating damage functions, we focus on climate damage functions.

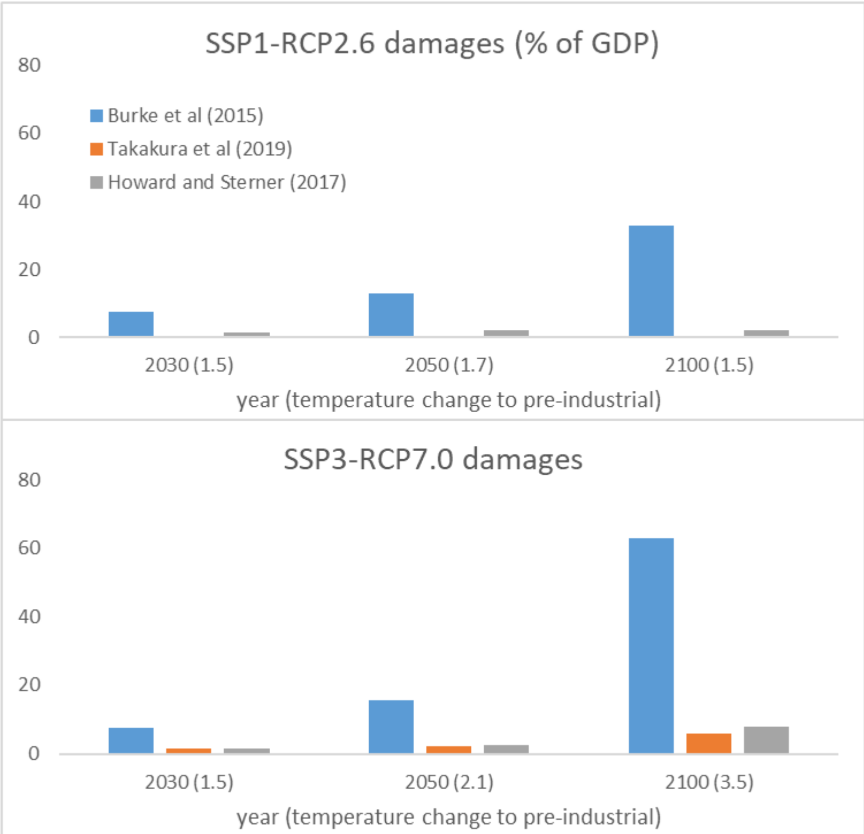
Different approaches have been used to model damages to economic output arising from climate change.

- Bottom-up approaches (e.g. COACCH 2021, Feyen et al 2020, OECD 2015) attempt to evaluate different impact channels individually, but no current model has a complete representation of the relevant mechanisms.
- Statistical approaches (e.g. Burke, Hsiang and Miguel 2015) attempt to capture the impact of climate change on the basis of the impact of observed temperature variations.
- Expert elicitation has been used to refine standard IAM damage functions (e.g. Howard and Sylvan 2020).
- Others have used literature surveys (Tol 2018, Nordhaus 2017, Howard and Sterner 2017) or plausibility considerations for large temperature changes (Weitzman 2012).

Many elements are not yet sufficiently well understood to be quantified (e.g. ecosystem dynamics and their contribution to economic output), and economists seem to have been slow to integrate the latest climate science into their damage functions (Auffhammer 2018, Dietz et al 2020).

Standard integrated assessment models incorporate economic damages caused by GHG emissions that, over the time horizon 2020 to 2100, look limited when compared to global GDP growth over the past decades. In particular, a small overall temperature increase such as the 1.5°C target of the Paris Agreement is likely to be manageable at relatively limited economic cost (see Figure 9). A common theme in the literature is the nature of the limitations of our knowledge about factors that could make damages much worse than anticipated. Most researchers however agree that economic damages increase over-proportionally as temperatures rise further.

Figure 9: **Damage ranges as a function of temperature rise**



Note: Scenarios and associated temperature changes are taken from the overview in IPCC (2022) chapter 16; values are from the three original papers. For Burke, Hsiang and Miguel, the pooled response, short-run effects are shown for 2030 and 2050, the pooled long-run for 2100.

The uncertainty surrounding climate-damage estimations is very large, even for moderate temperature increases. In the SSP1-2.6 scenario[22], global surface temperature is 1.8°C above pre-industrial level by 2050. Using a selection of the sources discussed in IPCC 2022 chapter 16, the near-term damages to GDP corresponding to a 1.8°C temperature increase would lie in the range of 0.8% (Takakura et al 2019 'RCP 2.6') to 13% (Burke, Hsiang and Miguel 2015 'pooled response, short-run').

In the SSP3-7.0 scenario, temperatures would rise to 3.5°C above pre-industrial level by 2100. The range of long-term damages from the same studies is 3% (Takakura et al, 'RCP 6.0') to 63% (Burke, Hsiang and Miguel 'pooled response, long-run'). Put differently, damages estimated for plausible temperature changes in fairly recent articles published in high-quality journals vary by an order of magnitude.

[22] The scenarios and corresponding temperature changes are taken from IPCC (2022) ch 16 p114.

We speculate that similar difficulties arise when estimating the damages related to natural capital degradation more generally.

5. CONCLUSION

This paper reviews ways to capture the contribution of natural capital to economic activity. We understand natural capital as the environmental assets that generate flows of goods and services into the economy. This contribution can be conceptualised by including resource flows and ecosystem services explicitly in production functions. Alternatively, the negative consequences arising from damages to natural assets can be added as damages into production functions, as it is common in the climate-economics literature.

There are a number of common challenges to both approaches. Firstly and most fundamentally, our understanding of the biophysical processes through which natural capital enters production is advancing but still very incomplete. This applies particularly to ecosystem services and the complex interactions that determine the regeneration or collapse of ecosystems. Limitations to our knowledge hamper the assessment of ecosystem services at small scale (e.g. soils) as well as at the scale of global regulating systems such as the climate cycle. Secondly, even where the measurement of the physical flows is feasible with sufficient precision, the monetary valuation of non-marketed environmental goods and services is challenging.

As a result, the measurement and valuation of natural assets and the related flows of goods and services remains today very partial. The (partial) omission of natural capital in national accounts and macroeconomic models is however likely to give a biased view of economic activity. For instance, national accounts may erroneously count degradation of nature as technological progress (TFP growth). Disagreements on methodology and incomplete coverage are factors behind the wide range of estimated climate damages in the literature. Failing to account for the feedbacks between economic activity and natural capital induces biases in economic surveillance and policymaking. For example, debt/GDP is a prominent metric of fiscal sustainability, but if projections of GDP over the long run do not consider damages arising from the degradation of nature, the assessment of fiscal sustainability will be biased.

Concerning the capture of the flow of environmental goods and services in a production function, we see the state of affairs as follows. The flow of marketed finite or renewable resources can be integrated into production functions, subject to some data limitations we have discussed. In the context of finite natural resource use, we have highlighted that the ease of resource substitution and the pace of technical progress are critical assumptions in neoclassical models of 'green' economic growth. In economic modelling exercises, elasticities of substitution and drivers of technical progress should therefore be assessed carefully and subjected to rigorous sensitivity checks. The recent debate on the macroeconomic impacts of gas supply disruptions has further highlighted the need to better understand substitution possibilities in the short run and the longer run. The potential of using secondary raw materials as substitute for primary resources (circular economy) also requires further empirical quantification.

Going further to quantify the dynamics of natural capital stocks, and the services flowing from natural capital, in an aggregate production function (as suggested e.g. in the Dasgupta Review) is so far at the level of conceptual development. The diversity of natural capital makes it very difficult to use it in aggregate production functions in single-sector models.

Recent advances with environmental economic accounts however make it possible to integrate flows of resources, and to some extent ecosystem services, with the input-output tables used in national accounts. This allows to capture such flows in more granular production functions, for example in CGE models. Also based on the SEEA, the World Bank is pioneering natural wealth accounting. Despite the acknowledged gaps in coverage and remaining conceptual challenges, comparing the dynamics of natural wealth to the flow of economic output (measured by GDP) already allows drawing conclusions on the sustainability of economic activity in specific circumstances, e.g. when fast GDP growth is fuelled by running down natural assets. Alternatively, combining the variation of capital stocks (depreciation of built capital and degradation of natural capital) and gross output would yield a measure of Green Net Domestic Product. We consider further work on the SEEA and its integration in national accounts as a research priority, as it will serve disaggregated assessments immediately and aggregate analysis in the longer run.

Turning to the damage-function approach, it is designed for models with a high level of aggregation. Damage functions have been used in climate IAMs for three decades, but the idea to cover damages to natural capital more broadly remains so far underdeveloped. The relative simplicity of damage functions comes with the drawback that damages are not integrated with the production function as such: Damages only apply to gross output after the production process, while the production factors and technology are unaffected. The consensus among climate-economic modellers however seems to be shifting in the direction that damages should affect growth rather than only the level of output. Moreover, available damage functions have serious limitations, and damage estimates even for temperatures that are likely to be reached by mid-century vary by an order of magnitude.

On balance, focusing further research on the full integration of the flow of environmental goods and services in a production function approach is therefore more promising in our view, even if it will require considerable time and effort.

In light of the limitations we discussed, different approaches to capturing the contribution of natural capital to economic activity are likely to coexist for some time and be applied depending on the analytical question at hand. What is then crucial for the advancement of our analytical capacities is the exchange across academic fields. In particular, tipping points in the provision of ecosystem services require further research. New insights in natural sciences should be swiftly implemented in economic modelling.

Throughout this paper, we have focussed on the integration of natural capital in the modelling of economic output rather than on the development of indicators that complement economic output indicators. We see this integrated approach as crucial for improving the macroeconomic modelling of different policies directed at economic and environmental sustainability. Moreover, it will allow to reduce inherent biases in economic surveillance and policy-making.

Beyond the scope of this paper, integrating the production function approach into a wider welfare-oriented framework is important in our view. This would require embedding a natural capital-augmented production model into a model also including the consumption side.

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ANNEX: ESTIMATING RESOURCE INPUTS

Several sources can be exploited to estimate the share of marketed exhaustible resources in GDP, but each has advantages and drawbacks.

Conceptually, we want to look at commodities in a state that is as close as possible to the state in which they are extracted; in other words, they should incorporate as little labour or capital inputs as possible. This criterion is best met by disaggregated production and trade statistics such as COMEXT.

At the same time, we would like to cover raw materials incorporated into imported intermediate goods, which are often at a higher degree of processing. This criterion would be best met by international input-output tables (e.g. GECO or FIGARO) or material flow accounts.

Below, we briefly present different sources and discuss their strengths and weaknesses.

COMEXT (EUROSTAT)

COMEXT is a very detailed database with a focus on trade in goods and services, but which also contains production data (COMEXT-PRODCOM). Its more than 4000 product classes allow zooming in on mining commodities at different stages of processing. COMEXT-PRODCOM does however not cover energy carriers. Both volumes and values are available. As discussed above, the data do not allow to identify raw materials incorporated in imported goods. The exclusion of such indirect resource flows will lead to an underestimation of the use of resources in the EU.

We construct domestic use data by adding imports and domestic sold production and subtracting exports. Table A1 is based on the latest available data, in most cases 2019.

MATERIAL FLOW ACCOUNTS (EUROSTAT)

Conceptually, domestic consumption data from Material Flow Accounts would be our favoured statistics as they follow an input-output concept and are quite detailed. However, they are subject to some severe limitations. MFA flows are recorded by mass (1000 tons per year). As we are interested in monetary values, we need to match them with price data. The most comprehensive set we could identify is world market prices for traded commodities from the World Bank. Even so, our selection of fossil energy carriers and metals is somewhat restricted by the availability of corresponding price data, and there are no prices from this source for non-metallic minerals.

Further limitations come from missing data for some resources and countries, where National Statistical Offices have pointed to confidentiality issues. Moreover, annual volumes can have strong variations due to stock building and trade, and world-market prices are volatile. We dampen these fluctuations by computing 5-year averages for 2015-2019. Nonetheless, the results for some metals, in particular copper and nickel, are implausibly large.

GECO (JRC)

The JRC's Global Energy and Climate Outlook database has input-output tables for a set of resources. It is however more aggregated than COMEXT or MFA. Notably, a distinction between raw and processed materials is generally not possible. This implies including more incorporated labour and capital in the measure and hence overestimating the raw material input. For metals and minerals the difference with COMEXT is by an order of magnitude or more. The difference with the MFA is more limited.

Table A1: **Share of exhaustible marketed resources in GDP according to different sources, EU-27**

Source	***GDP share of***		
	Fossil fuels	metals	minerals
COMEXT-PRODCOM [COMEXT for fuel]-	[2.9]	0.19	0.24
MFA	1.8	6.3	prices na
GECO	2.45	5.79	3.59
NB: GM calibration (COMEXT-based)	2.92	0.70	

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