The macroeconomic money-nature nexus: Are growing money supplies a relevant obstacle on the way to an ecologically sustainable global economy?

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Abstract

Production, consumption and nature depletion have been growing rapidly for more than 300 years, even faster than exponential population growth. A comprehensive understanding of the causes behind this great acceleration is necessary if we are to achieve a sustainability transformation. This paper is intended to draw the attention in the sustainability debate to the amounts of money that have been growing rapidly all over the world. The money supply has not been a main focus so far, since for the economic mainstream it is not a growth driver, as according to the neoclassical view, money growth is largely neutralized by inflation, while for Keynesians it merely follows economic growth. However, the growing money supply means greater liquidity for consumption as well as for investments in production, assets and resource exploitation. An expansion of the money supply is even a prerequisite for a simultaneous increase in investment and consumer spending. At the same time, the expansion in the supply of raw materials, goods and services keeps inflation rates behind money growth globally. The paper aims to identify and illustrate the causalities of how the money supply and the use of natural resources are interconnected by means of economic activities. This money-nature nexus would explain why, due to high money growth rates, both the real economy and the depletion of natural resources and ecosystems continue to increase despite all efficiency improvements and sustainability efforts to date. It should therefore be a realistic fear that without a global limitation of exponential money growth, ecological sustainability cannot be achieved.

Author summary

The money supply and the use of natural resources are interconnected by means of economic activities. This money-nature nexus explains why, due to high money growth rates, both the real economy and the depletion of natural resources and ecosystems continue to increase despite all efficiency improvements and sustainable transformation efforts to
date. It is therefore to be feared that without a global limitation of exponential money growth, environmental sustainability of the global economy cannot be achieved.

1. Introduction

“Rapid growth of output is the distinguishing feature of modern times and contrasts sharply with human history going back to its origins millions of years ago. This is perhaps the central economic fact of the century.”

[1p. 501]

Over the past 300 years, humanity, and to an even greater extent the volume of goods and services produced as well as the use of natural resources as a source of raw materials and as a sink for waste has grown exponentially [2–7]. This development, also known as the Great Acceleration, is unique in human history [8,9]. The global output growth per person rose from a level of 0.016%/a before the 18th century to an average of 2.1%/a in the period from 1700 until 2012 [5], which is an increase in the economic output per person by over 1100%. Due to the simultaneous population growth of over 1000% (from 0.6 to 7.05 trillion), the total output of mankind grew by more than 14000% (from 495 to 71,169 trillion in constant EUR 2012) over the last 300 years.

Since 1950, global production output \( O \) has grown over 3%/a in real terms [5]. Between 1971 and 2016 the global real GDP (cf. OECD definition [10]), which measures national income \( Y \) and the total production output of goods and services produced in a given year in monetary terms \( Y = P_{GDP} \times O \), increased inflation-adjusted annually by 3.06%/a (see Fig 1 and Table B in S1 Appendix). By contrast, the population grew only 1.53%/a. Over this time span, natural resource consumption also increased faster than the population. The global land use for settlements and transport (built-up land) has been the fastest growing environmental factor with rates of 2.88%/a highly correlated with real GDP and the consumption expenditures of households and governments (3.03%/a). Global material consumption and material extraction have increased by 2.65%/a and 2.64%/a in correlation with GDP, whereby CO\(_2\) emissions have increased by 1.89%/a. Even if a relative decoupling of GDP growth from energy, material resources and greenhouse gas emissions can be observed during this time period (cf. [11]), further economic growth in combination with population dynamics brings mankind even closer to the ecological limits of planet Earth [6,11–14].

Although technological progress has enhanced energy and resource efficiency since the beginning of the industrial revolution, a faster growing demand has further increased overall natural resource consumption [15–19]. Up to date, there is no sign of an absolute decoupling of resource consumption from economic growth at the global level as efficiency improvement or recycling rates lag behind the growing demand and regional decoupling effects are mainly based on spatial displacements [2,3,14–16,20]. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and the OECD therefore concluded in 2019:

“Yet, existing evidence shows that current strategies and practices have not accomplished a decoupling of economic growth from energy and materials consumption over an extended
time span. Without an adjustment of orientations and priorities, including an effective instrumentation of such policies, a sustainable economy is not going to be achieved.”

[4, Ch. 6, p. 141]

“This Outlook projects that, in the absence of new policies, global materials use would rise from 89 Gt in 2017 to 167 Gt in 2060. This growth is reflected in all major categories of materials: metallic ores (9 to 20 Gt), non-metallic minerals (44 to 86 Gt), biomass (22 to 37 Gt) and fossil fuels (15 to 24 Gt). In addition, the extraction, processing and disposal of materials brings significant environmental consequences, which will be magnified as materials use increases. These include a doubling of greenhouse gas emissions, pollution to the soil, water and air, and toxic effects on humans and aquatic and terrestrial ecosystems.”

[2, p. 3]

Currently, there is a vibrant debate about the causes of the Great Acceleration. A correct and comprehensive understanding of the factors and drivers is crucial for finding ways towards an ecologically sustainable development that ends the exponential increase in the use of natural resources and enables a primarily qualitative development within the planetary boundaries. So far, the most important causes of the great acceleration have been regarded as: scientific and technological progress, the development of free citizenship and free enterprise,
the discovery of fossil fuels, as well as the expanding human population and rising levels of education [1,22–25].

What is striking about the Great Acceleration is that the forerunners are the volumes of money as well as debt on a global scale (see Fig 1 and Table B in S1 Appendix) and in particular in the USA and China (see S2 Appendix). Between 1971 and 2016 the global amount of money increased nominally by 8.94%/a whilst debt increased by 8.68%/a (see Fig A and Table A in S1 Appendix). This was faster than nominal GDP (7.24%/a) and much faster than inflation (4.05%/a), representing the rates of change in consumer price indexes (CPI) and also referred to as the GDP deflator. After 45 years, those differences have increased even further, so that global GDP is now barely half the size of the money supply and the credit volume. In 2017, worldwide public and private debt exceeded US$184 trillion [26], which is more than 225% of the global Gross Domestic Product (GDP). Between 1971 and 2016, money growth in nominal terms was more than 9 times higher than the US Consumer Price Index or the implicit GDP Deflator and more than 47 times higher than world population growth (see Table A in S1 Appendix). This is an important finding as even small differences in annual growth rates lead to large and exponentially growing differences in absolute terms in the long run (see Fig B in S3 Appendix). The exponential expansion of the amount of money is possible because today’s money predominantly exists as immaterial deposit money, which is created by central and private banks out of nothing when granting loans or buying bonds (see section 2).

The paper examines, if and how this globally growing amount of money increases the human use of natural resources. Because if the exponentially growing money supply has been a major driver or at least an enabler of global economic growth, and if economic growth is accompanied by growing resource use in spite of all those advances in efficiency, then rising money supplies are a critical barrier to a global economy that can function within the planet’s boundaries. Therefore, this is a central topic to humanity’s future sustainable transformation policy. It should be noted that for a sustainable global economy, the total money supply and not the per capita money stock is decisive. The latter comes into play in the distribution of wealth and natural resources, which is currently highly unequal due to the very different individual liquidity conditions [27–29].

Since the introduction of paper money there has been a discussion [30–33] about the consequences of money growth for the economy, society and nature [34,35]. With recent financial crises and the impending climate crisis, the discussion has resurfaced, although the debate in ecological macroeconomics focuses primarily on pricing mechanisms, promoting green investments and possible monetary growth imperative [36–43], the ecological impact of growing money supplies receives attention only from few authors [34,44–49].

Generally, it is recognized that money, as freely available capital (liquidity), and the lending thereof are of fundamental importance in modern capitalist economies, since money enables maintenance and growth investments in physical capital and production as well as matches the demand and supply for goods, labor and assets [1,23,24,35,50–53]. Money circulates through the entire economy in exchange for labor, goods, services and assets (see the standard model of economic flows in Fig 2), which is why the growth in credit and liquidity is generally seen as a sign of economic prosperity, but doubts are starting to grow [26,34,54–57].

However, the standard model does not reflect the growth in money and credit volumes (see section 2). The reason for this is that, in spite of its acknowledged importance and general economic presence, money is not a driver of economic growth according to mainstream economic opinion (see section 3). The paper points out how both the orthodox assumption of a neutralization of the money supply from inflation within 2–3 years and the heterodox assumption of a merely temporary monetary expansion initiated by economic growth do not stand up
to empirical verification, since on the global scale inflation rates lag behind money growth by an average of around 5%/a and debt alone increased by over 8.5%/a between 1971 and 2016. It is rather the case that there are strong interactions between monetary expansions, economic growth, and increasing resource use, whereby:

- an increase in the use of natural resources (>2% per annum since 1971) is essential for the growth in production and consumption in spite of all the progress made in resource efficiency and recycling (see section 4.1);
- the expansion of the money supply is essential for both the demand and supply of goods, services and assets by enabling more investment in production, R&D as well as resource extraction (see section 4.2);
- both of the above result in a self-reinforcing money-nature nexus between money growth and increasing resource consumption (see section 4.3), which is also empirically visible (see section 4.4).

States and international institutions should therefore not only focus on the availability and distribution of liquidity in their economic policies, but also include the money supply in their sustainability transformation policies and align their monetary policies with planet boundaries (see the conclusion in section 5).

2. Money and modern money creation

Money has always been a social construct whose institutional purpose is to facilitate trade as an artificial universal medium of exchange with inherent asset value, which is at the same time also a measurement unit for the value of other assets [56,58]. Since the establishment of states, they issued money as currency, in order to contain private credit money systems, pay state
employees (e.g. soldiers) and levy monetary taxes [56,59]. Thereby, general acceptance and official recognition as a means of payment distinguishes money from other assets (e.g. gold, bonds, stocks, derivatives, Bitcoins, bonus points) or other IOUs [1,35,58]. If some representatives of the concept of endogenous money regard nearly every credit, monetary claim and transferable asset as money [60], this goes too far [35] as it equates money as a means of payment with the monetary value of assets, which would make the entire economy identical to the money supply. For this reason the narrower concept of money will be used in the following. Money in this sense has experienced two decisive changes and a partial privatization of money creation over the last 300 years.

From the 17th century onwards, rulers in Europe and subsequently governments worldwide have allowed the issuance of paper money in addition to precious metal coins to monetize the growing national debt and reduce dependence on the availability of gold and silver [35,56,59]. To ensure acceptance of this new fiat money, value guarantees (gold and silver standards, colonial shareholdings) were issued to start with. A second change then followed with the reintroduction of intangible book money without value guarantees [35,56,59].

Today, central banks issue two types of money as legal tender: coins and notes (cash) and book money for commercial banks (reserves) [35,58]. For the provision of reserves, commercial banks normally pay interest. However, the interest rate level and thus the price for the

Fig 3. Macroeconomic relationships in the economy and with nature. The circles are interlocking gears. The arrows indicate the direction of rotation and at the same time the direction of influence, depending on whether the arrow is before or after the gearing. The gears with titles in italics, are located on a second or third level and are connected to the first level at the toothed points, but not at the crossing points. They illustrate further connections between the individual quantities of the first level (see description in 35 Appendix). Own presentation. LD = Liquidity Demand; LS = Liquidity Supply; IL&C = Interest Level & Creditworthiness; AD = Aggregate Demand of Goods and Services; AS = Aggregate Supply of Goods and Services; I&B = Infrastructure & Buildings; NR = Natural Resources; NRE = Natural Resource Efficiency; R & D = Research & Development; TFP = Total Factor Productivity; CL = Commercialization Level; APP = Aggregate Purchasing Power; AFP = Aggregate Financial Power.

https://doi.org/10.1371/journal.pstr.0000095.g003
state provided liquidity is not determined by supply and demand (cf. Fig 3) as in the neoclassical IS-LM model [23,61] for the commercial credit market, since the immaterial money supply of the central banks is unlimited and can be expanded at any time without cost. Rather, the central banks determine the interest rate level with their key interest rates based on political specifications (e.g. an inflation target close to 2%/a) [62] also referred to as policy rates [63].

The expansion of the overall amount of money has been strongly accelerated once more by the sight deposits of the commercial banks on legal tender. The transmission of these impersonal IOUs [59] via bank transfer is generally used and also officially accepted as a means of payment (especially for taxes and state wage payments), which is why these intangible bank claims are generally recognized as money too (deposit money) [1,32,34,35,57,58]. Commercial banks expand the money supply by granting a loan amount as a new demand deposit out of nothing [34,35,46,55–57,64–66]. For this commercial banks do not need to hold savings, cash or central bank reserves to the same extent, since demand deposits are regularly only transferred but not paid out and with the central banks there is a last resort lender, ensuring that commercial banks always have sufficient liquidity [35,60,64–66].

The ability to create money distinguishes both commercial banks from other financial institutions, which are merely money intermediaries without access to central bank liquidity (so-called shadow banks) [66,67], and bank loans from other forms of credit based on savings or deferrals [35]. For this purpose, commercial banks must comply with legal requirements on the amount of liquidity reserves and the equity to be maintained. However, the policy rates for the minimum amounts of reserves have been continuously reduced to a few percentage points in most countries and even completely dropped in some states, while the minimum equity rates under Basel III are 10.5% [68]. This enables commercial banks to expand the money supply with newly created deposit money at very little expense in line with the demand for bank loans. It explains why the money supply is growing hand in hand with bank borrowing (Fig 1) and why today deposit money now secures the vast majority of liquidity [35,58,66]. Unlike cash, however, deposit money disappears when the deposit expires (e.g. due to disbursement or loan repayment) [23,64].

Hereby, the credit-based money creation system contains a self-reinforcing loop, because increases in money growth fosters the demand for assets (e.g. real estate, gold, bonds, shares, collateralized debt obligations, cryptocurrencies). Due to a lower elasticity of asset supply, asset prices often rise faster than consumer prices, increasing the net wealth of the owners of physical capital (also referred to as real capital) (cf. [5,69–72]). Increasing asset prices do not take money out of the money circulation. As net wealth rises, the creditworthiness of companies, households and governments improves, as does the collateral and equity of banks. Thus, on the one hand due to asset inflation, the credit demand for asset purchases increases, while on the other hand banks can grant more newly created credit money due to higher collateral and equity without enhancing their default risk [35,53,55]. This self-reinforcing loop explains both the strong positive correlation between asset prices and bank debts [66,70] and the higher growth rates of the money supply and bank credit relative to GDP shown in Fig 1. The self-reinforcing loop is the reason for the recurring house price bubbles and subsequent financial crises, with the prominent example of the subprime market bubble in the U.S. that burst in 2007 leading to the subsequent credit and financial crisis [70,71,73,74].

Overall, the amount of money is thus largely determined by the liquidity demand of commercial banks against the central bank on the one hand and by the overall liquidity demand of companies, households as well as governments and their satisfaction by commercial banks on the other (cf. Fig 3). The demand for liquidity and the ability of commercial banks to lend and create deposit money depend largely on the policy rates: key interest rates and the minimum level for reserves and equity.
Furthermore, commercial banks also expand the money supply when they buy bonds or other financial products from governments, companies or shadow banks and pay for these assets with new deposit money [66,67]. Since the financial crisis of 2008, central banks have also been using the purchase of bonds (quantitative easing) as a way of increasing the liquidity of governments, commercial banks or even non-financial corporations, averting insolvencies and boosting economic growth [35,64,65]. All in all, unlike 300 years ago, money and thus liquidity is no longer scarce, but can be increased by central banks without limits and by commercial banks on a large scale at almost no cost [34,35,57]. To the extent that the standard model of mutually balancing economic flows and money circulation:

\[ Y = C + I + G + NX \]

(with \( Y = \text{National Income} = \text{GDP}, C = \text{Consumption Expenditures of Households}, I = \text{Financial Investments}, G = \text{Government Expenditures} \) and \(NX = \text{Net Exports}\)) excludes money creation (see Fig 2), it does not fully describe national economies and their cycles. It is indeed correct that money circulates throughout the economy as cash or deposit money from buyer to seller to the next vendor, from savers to investors, from consumers to producers, from taxpayers to the state and so on. What is misleading, however, is the assumption made by the economic mainstream that the financial resources required for maintenance and growth investments are generated solely by greater rates of household savings or export surpluses [1,23]. In reality, it is the opposite, namely that in modern economies it is not savings that make bank loans possible, but rather bank loans and the resulting money creation initially generating the liquidity gains from which savings then arise [35,66].

This becomes very clear when the model is applied to the global economy. Since at the global level, trade surpluses and deficits balance out, for the global economy the standard model is abbreviated to: \(Y = C+G+I\). Or as the OECD put it:

“The general equilibrium model brings all these nonlinear trends together into an internally consistent set of developments of all model variables. At the global level, this is a closed system: global exports equal global imports, global savings equal global investments.”

[21,48]

According to this equation, however, no growth of global GDP would be possible, since higher saving rates in favor of higher investment would reduce global consumptions expenditures. Therefore, the world economy can only grow because the total money supply \(M\) available for \(C, I\) and \(G\) is increased globally through the money creation \(MC\) of national, central and commercial banks [34,35,51,57,66]). By detaching money from precious metals, money creation and thus global economic growth is no longer limited by the extraction rates of gold and silver. The standard model should therefore be:

\[ Y_{\text{Global}} = MC \times (C_{\text{Existing}} + I_{\text{Existing}} + G_{\text{Existing}}) \]

Even in national economies, money growth enables economic growth through the simultaneous expansion of investment and spending by households and governments. This is especially the case when there are low export surpluses or even trade deficits, like in the USA (see S2 Appendix). The full standard model here is stated as follows:

\[ Y = MC \times (C_{\text{Existing}} + I_{\text{Existing}} + G_{\text{Existing}} + NX_{\text{Existing}}) \]
3. Do exponentially growing money supplies drive economic growth?

"Money makes the world go around" lyricized Fred Ebb in a song written for the movie "Cabarret" in 1972 [75]. Nevertheless, it remains controversial among economists whether the monetary expansion of the money supply also changes the real economy and, in particular, the aggregate demand \( AD \) and the aggregate supply \( AS \) of goods and services. Despite the day-to-day comprehensive use of money as a quid pro quo, for the economic mainstream the growing money supply is not considered to be a growth driver. According to the orthodox or neoclassical view, it does not even affect the real economy, since money supply growth is largely neutralized by inflation with a time lag of 2–3 years [1,23,32,76,77]. For heterodox economists the money supply is not neutral but also no growth driver, as the endogenous money supply only follows economic growth [24,51,52,56,60,65,78]. Both views are contrary to one another and ultimately cannot convincingly explain empirical developments.

3.1. The orthodox view and critique

Since Adam Smith, orthodox economists have assumed a far-reaching independence between real and nominal variables, regarding money merely as a neutral lubricant. Unlike previous views [30], classical economists assumed that due to a constant \( AS \) an expansion of the money stock merely increases prices and not \( AD \), whereby the purchasing power per monetary unit decreases and money growth is completely neutralized by inflation with a time lag of a few years (cf. reproduced quote from I. Fisher in S4 Appendix). For this neutrality assumption, they refer to the classical Quantity Theory of Money (QTM), which states that the money stock \( M \) multiplied by the velocity of money \( V \) is equal to the price level \( P \) multiplied by the aggregate volume of transactions \( T \) in an economy [32,77]:

\[
M \times V = P \times T
\]

Note: Many economists shorten the QTM by using the aggregate volume of real production output \( O \) [1 p. 490,79] labeled as \( Q \) or the real national income \( Y \) (alias real GDP) instead of \( T \) [23 p. 557,80 Appendix 1,81,82] and formulate:

\[
M \times V = P \times O \text{ or } M \times V = P \times Y.
\]

However, both equations do not include the transactions and price developments of assets, because \( O \) and \( Y \) do not record the dealings of existing assets (e.g. purchase of land, shares). Moreover, in the case of \( Y \), the national total income already includes the inflation-adjusted price level for the production output \( (Y = P_{GDP} \times O) \), which is why the actual formula here is \( M \times V = Y \).

The QTM is a convincing approach to describe the relationship between the money supply and money use as well as prices in the economy. However, it does not necessarily imply that money growth is almost completely neutralized by inflation. Because if the number and the volume of transactions \( T \) increase, then prices must rise more slowly than the money supply if the velocity of money in circulation does not increase sharply. This is precisely the case according to the empirical data. Although empirical studies have acknowledged a positive correlation between the nominal money growth and inflation, the rates of money growth and inflation are moving at different levels [81,83–88].

The empirical results show that long-term inflation is several percentage points lower than money growth in most of the countries studied. The 45-degree line of correlation for the average rates of change for money quantities and price levels calculated by McCandless and Weber (83) for 110 countries from 1960 to 1990 shifted by about 5 percentage points towards monetary growth rates, which can be clearly seen at the starting point with 0% inflation (see reprint Fig A in S3 Appendix). Similar shifts were observed in the studies by Vogel [87] for 16 Latin American Countries (reprinted in Lucas [86 Figure 1]) and Barro [88 Figure 7.1] for 79 countries (restated in Teles and Uhlig [81 Figure 1 and 2]). The development in the United States from
1867–1995 also indicate higher monetary growth rates over longer periods [84,85]. This corresponds to the data for the USA between 1961 and 2016, where money growth was 3.42 percentage points above the development of the CPI, but also to developments in China from 1991 to 2016, where money growth even exceeded inflation by more than 15 percentage points (see Table B in S2 Appendix). Global trends show that between 1971 and 2016 the growth rate of Broad Money was 8.94%/a, while the global GDP deflator used by the World Bank was only 4.05%/a, which corresponds closely to the Consumer Price Index (CPI) of the USA of 4.03%/a (see Table A in S1 Appendix).

The divergence between money growth and (consumer) inflation is based on two cumulative effects. One effect is the time delay in price adjustments to changes in the nominal money supply. This has also been recognized by neutrality advocates, who assume that it takes about 2–3 years to adopt prices to the money supply changes due to several reasons (e.g. long-term price and wage agreements, market imbalances) [1,23,53,77]. However, the alleged time period completely negates the fact that in reality the money supply does not grow on a one-time basis, but constantly, resulting in a permanent and cumulative delay.

The other more significant effect is the steady expansion of the production output as well as the supply of assets [71,89], whereby among assets, the volume of shares, bonds, collateralized debt obligations as well as build-up land (see Fig 1) and gold in particular increased [5,35P, 114–119,90,91]. Consumer inflation rates are lower than money growth because production output has expanded over 3% per year in real terms since 1950 [5] (cf. Fig 1 and Table B in S1 Appendix), so that the volume of goods and services has steadily increased. Consistent with the QTM, the nominal growth of the money supply of 8.94%/a between 1971 and 2016 is not completely neutralized by inflation resulting in an exponential real money growth of about 4.5%/a (see S1 Appendix).

Due to the fact, that the production output \(O\) does not comprise the asset trading \(T_{\text{Asset}}\) and that the developments in asset prices \(P_{\text{Asset}}\) are not included in the calculation of inflation rates for GDP goods and services \((P_{\text{GDP}})\), the QTM formula should be written as follows:

\[
M \times V = P_{\text{GDP}} \times O + P_{\text{Asset}} \times T_{\text{Asset}}
\]

If we rearrange this equation according to \(P_{\text{GDP}}\) it becomes clear that the (consumer) inflation of the production output prices does not only depend on the money supply. The Quantity Theory of Money therefore explains very well why inflation rates are lower than the rates of money supply growth:

\[
P_{\text{GDP}} = \frac{M \times V - P_{\text{Asset}} \times T_{\text{Asset}}}{O}
\]

All in all, the orthodox belief in an almost complete neutralization of money growth is empirically disproved, as inflation rates lag behind the growth rates of the money supply, not only in the short, but also in the long run. Since 1950, the growth rates of the money supply are on average about 5 percentage points higher than consumer inflation. This “minor” difference between growth rates means that the gap between the money stock and the price level increases exponentially over the years (cf. Fig B in S3 Appendix). As a result, the real money supply also grows exponentially with major implications for the real economy [34,35,92].

This raises the question as to whether the exponential growth in the money supply can stimulate a permanent expansion of the real economy (see section 3.3) and why production output on a global level has been able to grow for such an unusually long time (see section 4).
3.2. The heterodox view and critique

Since Keynes, heterodox economists reject this classic dichotomy and assume that money is endogenous and therefore not neutral for the real economy, whereby the money supply is not the cause but the outcome of economic growth, which increases the demand for liquidity [24,50–52,56,60,65,78]. J.M. Keynes argued that AS can be extended to full employment if there is unemployment, so that AD, which has increased as a result of higher liquidity, is matched by a higher supply (see reproduced quote from Keynes in S4 Appendix). Due to these changes in the real economy, prices do not rise to the same extent as the money supply and the purchasing power of money declines less by comparison. Neo-classical economists adopt this assumption in the AD-AS model and suppose that the expansion in money supply and the corresponding lowering of interest rates increases AD and thus due to growing investment AS expands until the natural unemployment rate reaches the potential production output and any further monetary expansion then only raises prices (Fig 4a) [1,23,53,61,77].

Unlike Keynes, who merely questioned and corrected the classical assumptions on the dynamics of individual QTM variables, post-Keynesian economists dismiss the QTM arguing with the endogeneity of money [36,60,93,94]. They argue mainly on the basis of the Monetary Circuit, according to which credit money is only created on the basis of credit request and disappears when the loan is repaid, which is why the money supply is only increased temporarily—almost as an aid or catalyst (cf. the summary quote from W. Godley [95] in S4 Appendix) [51]. This Monetary Circuit is to be distinguished from the circulation of money in the economy as in Fig 2. For heterodox economists, this circuit with the creation and extinction of deposit money is the reason why the economy drives the money supply and not vice versa. However, the extinction of deposit money accounts at the end of the circuit neither diminishes

![Diagram showing effects of money supply expansion in an AD-AS model](https://doi.org/10.1371/journal.pstr.0000095.g004)

**Fig 4.** Effects of the money supply expansion in an AD-AS model according to a) Neoclassical assumptions and b) assumption of a money-nature nexus. In Fig 4a), aggregate demand AD increases with monetary expansion, while potential output remains constant due to the natural unemployment rate, so that when full employment is reached, only prices increase. In Fig 4b), due to the financial investments in technical progress and resource exploitation, potential output will also increase, which is why the aggregate supply can grow in line with growing demand, while prices only rise moderately. Fig 4a) own presentation according to Samuelson & Nordhaus ([1] p. 488). Fig 4b) own presentation. AD = Aggregate Demand; AS = Aggregate Supply; E = Equilibrium Point of AD-AS; PO = Potential Output.
its function as a medium of exchange for investment or consumption nor its transfer to other market participants during its temporary existence phase. In this phase, the corresponding debt only reduces the net wealth of the debtors in their balances [56]. Furthermore, the growth effects of the money supply in the economy rise as long as the amount of credit-based deposit money increases in line with the growth of bank credit volumes (Fig 1). Thus, so far, the aggregate Monetary Circuit has not yet been closed in most countries all over the world.

Also their argument, that “the rise in production takes shape in the mind of producers before money is created and is effectively realized when credit is granted and money is created to finance it” [78] is misleading because as with all economic exchanges the relationship between liquidity demand $LD$ and liquidity supply $LS$ is interdependent [35]. Without a corresponding supply of money, the envisaged demand simply remains an idea with no prospect of realization. Thus, without growing demand for liquidity there would be no creation of deposit money; but without the creation of new money by central and commercial banks, there will be no additional liquidity to expand production or consumption. The inflation-adjusted quantity of money and the possibilities of its extension are thus crucial for the realization of investment and consumption desires [34,35,96] and their exclusion in most growth theories (cf. [24]) is incomprehensible. The decisive intermediary between demand and supply is the interest level $IL$ for liquidity ($LD = IL \times LS$), the price level $P$ for goods, services and assets ($AD = P \times AS$) and the wage level $WL$ for labor ($Labor\ Demand = WL \times Labor\ Supply$) (cf. Fig 3).

By overestimating the question of the exogeneity or endogeneity of money or money creation [35], post-Keynesian economists underestimate the economic and ecological significance of the quantity of money recognized by the state as a means of payment, which Keynes himself still saw [79] Ch.2. Post-Keynesian economists act as if other laws of economics apply to endogenous money. However, exogeneity or endogeneity is merely a question of perspective and not of the economic effects of money: Money is endogenous at the state level, as today the legislative of states create the respective national currency for their economies and allow central as well as commercial banks to put it into the economy as cash, reserves or deposit money. For the national economy and the free market on the whole, state-accepted deposit money is endogenous due to commercial banks create this money. However, for the level of non-banking corporations and all households both cash and also deposit money remains an exogenous quantity, which they are not able to create. They can only acquire it in exchange for work and services, goods and assets or borrowing it in the case of loans [35].

How money is created must therefore to be separated from the question of what effects existing money supply has. For the economy and the people it is not significant by whom or why money is created, but that money (liquidity) is available for the intended investments and consumption.

3.3. Why money growth stimulates the real economy

Due to the circulation of money in an economy (see Fig 2), neither consumer inflation nor asset price increases deactivate money. However, both rising consumer prices and rising asset prices reduce purchasing power in a society, because less can be bought for the same amount of money when prices rise [32]. Conversely, if like in the past the money supply rises faster than prices: the higher the quantity of money compared to the price level, the larger the quantities that can be bought and therefore the higher the aggregate purchasing power of the society (cf. reproduced 2nd quote from I. Fisher in S4 Appendix). The increase in purchasing power not only boosts aggregate demand, but also aggregate financial power for investments in production, infrastructure, resource extraction and assets.
The rising investment volume enables resource extraction and production capacities to be expanded, resulting in an increase in the aggregate supply of goods and services as well as assets (see Fig 1 and S1 Appendix). The Quantity Theory of Money can plausibly represent this effect of the growing money supply by rearranging the equation according to the production output $O$:

$$O = \frac{M \times V - P_{Asset} \times T_{Asset}}{P_{GDP}}$$

According to this, a growing money supply $M$ or a higher velocity of money $V$ increases production output as long as the expansion in available liquidity is not absorbed by a growth in asset prices $P_{Asset}$ or asset transactions $T_{Asset}$. Existing inflation minimizes output growth but does not bring it to a halt, provided that liquidity in an economy or in the global economy is expanding faster than inflation rates. Unlike in the days of pure gold and silver currencies, for the past 300 years the very cheap creation of money out of nothing has made it easy to expand the money supply (see section 2), as long as governments or their central banks do not restrict money creation or reduce the demand for liquidity through high key interest rates. At the same time, an expansion of production output causes inflation rates to lag behind nominal money growth. As a result, purchasing power and investment power increase in real terms, constituting a self-reinforcing feedback effect.

In contrast, the velocity of money in circulation cannot be increased at will. Therefore, the ideas of Silvio Gesell on the so-called “free money” or “stamp scrip”—with decreasing purchasing power by definition (“shrinkage money”)—and subsequent practical regional monetary experiments could increase economic activity only to a limited extent due to a one-off increase in the velocity of circulation (cf. [100–102]).

Contrary to earlier economic assumptions (see section 3.1 and 3.2), the expansion of production capacities as well as potential output is not (or at most only for a short time) restricted by the available number of the unemployed. On the one hand, global trade has resulted in a global division of labor with a previously non-exhausted and growing number of employable people available [1,35]. On the other hand and even more importantly, labor productivity and total factor productivity (TFP) could be increased on a large scale through automation, upscaling and technological progress, replacing or potentiating labor by physical capital and energy [15,22,25,51,103]. As a result, both actual production output and potential output could be steadily increased (cf. Fig 4b).

However, both the expansion of employed labor, physical and human capital, as well as TFP require a prior expansion of financial resources to pay for the people, assets, equipment, raw materials, and the energy needed to expand production [1,24,50,51]. The enhancement of TFP and of the availability of raw materials and energy is preceded by global financial investments from governments and companies in the exploration and extraction of natural resources [21] as well as in research and development (R&D) [104,105], whereby the influence of R&D investments on productivity growth is generally overestimated [106]. It is estimated that annual investment in resource extraction worldwide accounts for approx. $1 trillion, with a return on investment of $4 trillion/a (equivalent to 7% of global GDP) [107,108]. The exponential creation of liquidity at very low cost has enabled a steady expansion of these investments worldwide [34,35,51,57], also enabling the required maintenance investments, which account for about 10–15% of national income [5].

Overall, in an economy real money growth increases not only the aggregate demand, but also the aggregate supply due to growing investment power [30,33–35,55,57,65]. However, the channels of influence of the money supply are complex in national economies, as almost all
economic transactions (i.e. the purchase of mining licenses, land, raw materials, energy, machinery, equipment, consumer goods, services or labor) are carried out with money (see Fig 3). The more money that is available for transactions (liquidity), the more economic activity is possible, when inflation rates are lower than money growth rates.

4. Strong interactions between the growth of the money supply, the economy and the use of natural resources

There are complex interactions between monetary expansion, economic growth and increasing resource use, which are essential for the discussion on sustainability, especially on the global level (see Fig 5). A monetary expansion of the world economy exists if statistically the money aggregate or “broad money” (also referred to as M2 in the USA and M3 in Europe) increases globally in nominal terms (cf. [109]). From an economics perspective, the world economy grows when GDP increases on the global level in inflation-adjusted terms, which happens when production output increases on the global level and is taken up by a similar increase in demand (cf. [1]). The use of natural resources increases with every anthropogenic use of land, water and air (e.g. for agriculture, settlements, shipping, wind power), with the extraction of substances and organisms from soils, waters and the biosphere, with the harnessing of solar energy through photovoltaics, with emissions into the atmosphere and the discharge of waste and sewage into waters and soils (cf. [110–112]).

Fig 5. Money-nature nexus with money-resource rebound effect. Own presentation.

https://doi.org/10.1371/journal.pstr.0000095.g005
4.1. No production or consumption without natural resources

The interdependence between production and natural resources is nowadays generally recognized in the economic Production Function:

\[ O = A \times f(K, L, H, NR) \]

Due to this function, the production output of goods and services \( O \) are primarily determined by the supply of the following factors: physical capital \( K \), labor \( L \), human capital \( H \) (knowledge and skills) and natural resources \( NR \) (including energy) as well as the available production technology \( A \), represented by technological progress and an increase in total factor productivity \([1,23,24,34,51]\). Contrary to the former Neoclassical Production Function, which only includes \( K, L \) and \( A \) \([113,114]\), the modern Production Function recognizes that both human skills and natural resources play a crucial role in production. While the abiotic geosphere provides land and a multitude of raw materials \([3,115]\), the biosphere is responsible for extensive ecosystem services \([111,112,116]\), without which neither production nor human life would be possible. The use of natural resources in modern economies takes place in connection with consumption and at various levels of production:

1. The construction of production facilities, buildings and machinery as well as the necessary infrastructures in a national economy (roads, railways and waterways, electricity and communication networks) requires land as well as raw materials and energy. At the same time, emissions, waste and extensive changes to ecosystems already take place at this stage. This means the greater the expansion of physical capital \( K \), the larger the ecological footprint \([3,4,14,15]\).

2. The provision of goods and services in production facilities requires biological and mineral raw materials as well as energy, generating emissions and waste. Again, the higher the production output, the higher the use of natural resources \([16,17,117]\).

3. The provision of raw materials and energy for production in agriculture, forestry, fisheries, mining and the energy sector (hereinafter referred to as primary production) involves extensive changes to land and ecosystems, as well as causing significant emissions and waste (including greenhouse gases, nutrients, tailings and wastewater) \([2,118–120]\). Primary production takes up by far the largest areas of land and water \([3,121–124]\), while at the same time requiring a considerable input of energy and raw materials (e.g. for fertilizers, mining machinery, wind turbines).

4. Finally, the consumption and use of produced goods and services has various impacts on natural resources, especially due to the resulting emissions and waste (e.g. the greenhouse gases from cars and heating systems, household waste and sewage). Here, it is also the case that the more goods and services that are consumed, the larger the ecological footprint.

To date, technological progress has increased resource efficiency in primary production, commodity production and consumption, whereas recycling has reduced the use of new natural resources. Nevertheless, the total consumption of energy and raw materials has still not fallen, but continues to rise in correlation with GDP (see Fig 1 and S1 Appendix) \([3,15,16]\). Among the reasons for this are:

- Rebound effects, since efficiency improvements regularly lead to lower costs in production and operating, which in turn boosts aggregate demand \([2,18–20,125,126]\). This efficiency rebound effect correlates closely with the money supply, since the aggregate purchasing power of society is enhanced with the cost reductions as long as the nominal money supply
is not reduced to the same extent (Fig 6). However, the idea of using higher taxation to counteract cost reduction [125,127–129] fails in macroeconomic terms, since higher tax revenues increase government expenditures [130].

- Physical constraints to resource efficiency, since resource productivity in terms of matter and energy cannot be increased above 100 percent resource use, which corresponds to a complete utilization without any waste, emissions or exhaust heat. Furthermore, when approximating this absolute limit, the productivity improvements that can be achieved from constant effort become smaller and smaller, as with all limited growth processes. Practically, use-efficiency lies significantly below this limit due to the laws of thermodynamics, in particular of entropy [49,131,132] or as Georgescu-Roegen put it: "The impossibility of using machinery that produces no waste is [...] an inherent limitation of the human nature." [133P. 191]. Contrary to the pioneering picture drawn by McAfee [134], in the USA the share of lost energy is even more than two thirds of the generated energy [135].

- Physical and social constraints to recycling, since a 100 percent recycling cannot be achieved due to entropy and the mechanical, chemical, and biological aging processes (e.g., wear and tear, oxidation of metals, decay of plastics to micro plastics due to UV radiation) as well as social misconduct in disposal (cf. [136]). Current recycling rates are 60% for iron and
copper, 30% for sand, 16–25% for phosphorus and 15% for rare earths, and 0% for fossil fuels [137
\textsuperscript{p. 407}] (cf. also [138\textsuperscript{p. 176}, 139\textsuperscript{p. 70}]).

Thus, the use of natural resources is a key factor of production and can only be substituted to a very limited extent by human labor or skills. Its long-standing absence from the economic Production Function is responsible for many economic and social misconceptions about unlimited growth.

4.2. No increase in production and consumption without growing money supply

The economy and real GDP can only grow if the supply of goods, services and assets as well as the demand for these items grow by the same amount as far as possible. Otherwise, too much increase in supply will lead to deflation whereas too much increase in demand will cause inflation.

In monetary terms, this means that both consumer spending and financial investment in production and resource extraction must increase. In the global economy, this is only possible if the global amount of money expands, since unlike in national economies, no foreign investment or export surpluses are possible on a global scale (see section 2). The exponential increase in the global money supply has been possible due to the creation of money out of thin air.

Growing money supply increases economic activities within an economy as well as globally, since money growth is to date neither neutralized by inflation nor a merely temporary phenomenon of a Monetary Circuit (see section 3.1 and 3.2). Similar to the standard model of mutually balancing economic flows, the Production Function excludes money growth as a factor. The expansion of financial investments is hidden in the expansion of the dynamic quantities $A, K, L, H$ and $NR$. However, if an expansion of financial investments globally is only possible through an expansion of the total money supply, then money creation in the global economy is the decisive reason for the expansion of physical capital, paid labor, available natural resources, and the increase of technical progress and human capital (see section 3.3). Even in national economies, the expansion of the money supply significantly boosts productive investment [50].

In order to highlight this importance for the growth of production output, the Production Function should be supplemented by the factor money creation $MC$, taking into account that money creation is distributed between production and demand for goods, services and assets ($MC = MC_{production} + MC_{consumption} + MC_{asset}$). The production equation then could look as follows with respect to the production increase $O_{t+1}$:

$$O_{t+1} = O_t + MC_{production} \times A \times f(K, L, H, NR)$$

4.3. Self-reinforcing money-nature nexus

If money expansion promotes the growth of production and consumption (4.2) and this economic growth increases the use of natural resources (4.1), then there is also an impact relationship between the money supply and the use of resources (cf. Fig 3). This relationship is not one-way, but reciprocal and self-reinforcing and can be described as follows (cf. Fig 5):

- The nominal expansion of the money supply increases the demand for natural resources, but at the same time enables an expansion of investment in the exploration and exploitation of natural resources.
• The expansion of resource availability keeps the price of resources from rising, or at a slower rate than the money supply, while allowing production output to expand.

• The expansion of production output and resource availability prevent the prices of goods and services from rising as fast as the money supply, leading to an inflation-adjusted increase in the money supply and aggregate purchasing power.

• The increase in the money supply and aggregate purchasing power in real terms steadily enhance aggregate demand, so that firms continue to expand production and resource extraction by extending borrowing, which further increases the money supply in nominal terms as well as resource extraction.

It should be emphasized that there is an imbalance in this money-nature nexus. While the money supply as an artificial, immaterial construct can be expanded at will, the earth’s natural resources are absolutely limited. Even the steady input of solar energy is limited by the size of the Earth. If production output depends considerably on the use of natural resources and ecosystem services (see section 4.1), then without an expansion of the natural resource availability, money growth would only raise inflation rates, since production output could only be increased to a very limited extent through advances in resource efficiency and recycling. However, until now and contrary to the orthodox Hotelling-rule, the exploration and exploitation of raw materials and energy has been steadily increased through financial investment and technical progress by expanding or intensifying mining, drilling, agriculture and forestry [15,16] (Fig 1 and S1 Appendix), which is why resource prices remain low despite a growing demand in reality [16]. Additionally, many ecosystem services can still be used for free [4,57]. Therefore, growing investments in resource exploitation and R&D, not only increase production and TFP, but also potential output [50,51], keeping inflation low according to the AD-AS model (Fig 4b).

Already at the beginning of the Industrial Revolution J.W. von Goethe described in his dramatic work Faust [31] how the expansion of the money supply increases investments in production and resource exploitation through fiat money and how this simultaneously prevents inflationary development by matching the growing money supply with a correspondingly growing amount of real values (land, raw materials, energy, produced goods), giving the inherently worthless paper notes or immaterial deposits a stable monetary value [35,140]. This self-reinforcing relationship termed H.C. Binswanger as “growth spiral” [34].

The money-nature nexus describes the relationship between the total quantity of money and the total use of resources in an economy or in the global economy. Since money circulates within the economy, the money supply therefore determines the total circulation volume that can be used for economic transactions. The money-nature nexus does not describe the use of resources in individual economic transactions. The latter can have a quantitatively and qualitatively different ecological footprint depending on the scope and subject matter as well as on interests, incentives and other individual reasons for decision-making. For an ecologically sustainable global economy, only the total quantity of money is decisive, while the quantity per capita is of relevance for the social question of the distribution of wealth and the individual use of natural resources.

The money-nature nexus can be expressed by combining the Quantity Theory of Money \[ M \times V = P_{GDP} \times O + P_{Asset} \times T_{Asset} \] (see section 3.1) and the generally recognized Production Function \[ O = A \times f(K, L, H, NR) \] (see section 4.1). However, with regard to the overall ecological impact of mankind \[ I_{ECO} \], a distinction must be made between the resource use through the production output \[ NR_{GDP} \] and the direct resource use through subsistence activities \[ NR_{Subsistence} \] without any commercial transactions \( I_{ECO} = NR_{GDP} + NR_{Subsistence} \). The money-nature
nexus is restricted to $NR_{GDP}$. The monetary influenced resource use at a certain point in time can be expressed by the following formula:

\[ NR_{GDP} = \frac{M \times V - P_{Asset} \times T_{Asset}}{P_{GDP} \times A(K,L,H)} \]

### 4.4. Empirical visibility of the money-nature nexus

According to the QTM formula, real GDP and thus production output as well as global demand and supply of raw materials and the GHG emissions, have been steadily increasing worldwide over recent decades in line with monetary growth, while at the same time biodiversity and thus the quality or quantity of ecosystems have been steadily declining, and inflation has been significantly lagging behind monetary growth (Fig 1 and Table B in S1 Appendix). The increase in global GDP has been made possible by the expansion of money supply worldwide by central and commercial banks through money creation out of nothing [34,35,50,66]. Rising national incomes accompanied by rising aggregate demand and production are driving the increase in raw material consumption as well as ecological footprints [16,115,141–143]. Between 1990 and 2008, with every 10% increase in GDP, the average national material footprint of 186 countries has increased by 6% [17]. Therefore, countries with a high GDP per capita also have a high Ecological Footprint [144]. According to Beck et al. [50], expanding credit to households and businesses by up to 109% of GDP generates economic growth. Since an expansion of credit volumes is enabled globally by money creation alone, the money supply increases along with credit volumes (see Fig 1). The fact that nominal money growth was considerably higher than GDP growth and resource utilization (see section 1 and S1 Appendix) can be plausibly explained by the asset price inflation and the liquidity-asset rebound effect (see section 2).

The money-nature nexus became highly visible in the 2008 financial crisis, when a global shortage of liquidity from the commercial banks led to a decline in production and consumption [145], but also in the use of natural resources (e.g. raw materials, CO2-emissions, built-up land, available fishing biocapacities) (see Fig 1 and Table B in S1 Appendix as well as [146]). The bursting of the Dotcom Bubble in 2000 did not have a major impact on production, consumption and resource use, as particularly the trade and prices of intangible assets were affected.

All in all, the money-nature nexus appears billions of times every day around the world when companies, households or governments exchange cash or deposit money into newly produced goods or services that have been made by using natural resources, including energy. As with national GDP, the higher the individual income, the higher the resource use [27,28]. Global analyses show that in 2015, the world’s richest 10% were responsible for 49% of CO2 emissions, while the poorest 50% emitted only 7% [29]. Material desires do not seem to be limited [147] but grow with available liquidity (cf. [148,149]). Boosted by the low interest rates on loans worldwide and exponential money growth, e.g. in Europe the production of superyachts grew by 228% from 1998 to 2008 [150]. Even after an individual saturation of even relative needs [147] has been reached, money deposited at financial institutions or invested in companies continues to promote the use of natural resources.
5. Conclusions for future sustainable transformation policy

Money is a universal medium of economic exchange. If the money supply increases (whether exogenously or endogenously generated), then people, firms and governments can buy more goods, services and assets as long as inflation lags behind money growth, which is empirically the case on a global level and in most countries. This is based on a self-reinforcing interaction between the amount of money and the use of nature (the money-nature nexus), since the quantity of money in relation to the price level determines the extent of the economic activity and the overall resource use, whereby the possibility of expanding the use of resources in turn determines the price level. As long as growing liquidity increases investments in resource exploitation and the growing availability of resources conversely adds value to the money created, exponential money growth is not neutralized by inflation resulting in an increase of the aggregate purchasing power.

As long as for this growing purchasing power and aggregate demand the necessary resources can still be extracted from nature and the waste can be disposed of there, then economically it will also happen due to the economic incentive. Even a green purpose in money creation is only significant for the first use of the new money, but not for all subsequent uses during the circulation of money in an economy. Therefore, as long as the new money exists, it increases the overall use of natural resources in economies, even if the new money is to be used initially to improve resource efficiency or climate protection (see exemplary illustration in Fig 7). Therefore, contrary to growing political demands, necessary green investments [2,4] should not be financed by expanding the money supply, but by redirecting existing liquidity.

![Diagram](https://doi.org/10.1371/journal.pstr.0000095.g007)

**Fig 7. Increase in natural resource use due to money circulation in the case of a green purpose in money creation, illustrated by the simplified example of a wind power investment.** Own presentation.
All in all, the almost unlimited provision of money at very low cost in the form of bank notes, reserves and deposit money for 300 years is the decisive difference to pre-capitalist economies. This liquidity expansion has enabled rising consumption but also growing investments in production, real and human capital, R&D, technical and medical progress, labor productivity, resource efficiency as well as the increase in exploration and exploitation of energy and raw materials, which are all considered to be growth drivers. Therefore, money is not only a lubricant but the fuel in modern economies irrespective of whether the money is provided by the central bank or commercial banks, as both increase liquidity for companies, households and governments. This was clearly illustrated by the financial crisis in 2008, when a global shortage of liquidity by commercial banks led to a decline in production and consumption, but also in the use of resources, until growth resumed in 2010 due to massive liquidity injections by central banks and governments (cf. Fig 1, S1 and S2 Appendices).

The growth of the real economy will only come to an end when production and consumption can no longer be scaled up quantitatively due to the scarcity of natural resources or liquidity. However, money as an artificial construct is unlimited and so far resource exploitation has kept pace with the growing demand, even if finite resources decrease at a faster rate.

If the global quantity of money continues to grow exponentially, then there will be a rising depletion of natural resources and ecosystems. The ecological effects of liquidity decline if the nominal amount of money shrinks due to higher interest rates or if the real money supply declines through inflation (e.g. due to political constraints on the availability of resources). As money does not fall from the sky, but is created by central and commercial banks, governments have the power to limit the demand and supply of money to an environmentally compatible level by changing legal framework for banks and especially policy rates, instead of forcing further exponential liquidity growth to solve social, economic and ecological problems.

It is important to note that the growing liquidity cannot be effectively prevented by taxation as some authors [46,65] assume, since taxes do not reduce liquidity in an economy, as long as governments respend the tax revenues on investment, consumption or wage payments rather than eliminating the money.

If the money stock is decisive for the use of natural resources, then the money supply should not grow by more than 2%/a in nominal terms in view of the inflation target of 2%/a envisaged by many central banks to ensure that humanity’s use of natural resources does not increase any further in the short term. In the medium term the nominal money supply should be correlated with the available resources and ecosystem capacities of earth to ensure a sustainable balance of the world economy. As a balancing monetary rule the money supply could be calibrated to the ratio of the Ecological Footprint and the Biocapacity indicators of the Global Footprint Network [144], both comprising built-up land, atmospheric carbon surplus, crop-lands, fishing grounds, forest products and grazing land, supplemented by a safety buffer for uncertainties and a target value for biodiversity. The calibration formula for the global money supply $M$ could therefore be:

$$M_{t+x} = M_t \times 0.5 \left[ \frac{B_t \times SM_t \times EF_t}{LPI_{TV_t}} \right]$$

Note: $M_t$ is the global broad money supply measured e.g. by the World Bank in current US$ in the latest available year $t$; $M_{t+x}$ is the target global broad money supply for the year $t+x$ with $x$ as the desired transition period; $B_t$ is the Biocapacity and $EF_t$ is the Ecological Footprint in year $t$ (both measured in global hectares (gha) by GFN [144] and SM the safety margin (e.g. 0.75 for a 25% buffer)); $LPI_t$ is the Living Planet Index representing biodiversity loss and calculated by WWF/ZSL [151] in year $t$; $LPI_{TV_t}$ is the target value for this index (e.g. 0.8 for a maximum loss of 20% since 1970). In this formula, price changes are indirectly taken into account, since inflation (e.g. from the scarcity of raw materials)
reduces purchasing power and therefore economic activity and resource use when the money supply is limited, while deflation has the opposite effect.

Since no world currency exists, the calibration of the global money supply with nature’s capacities requires also an international regulation on the allocation of the global money budget to the individual currencies. The exact allocation is above all a question of the global distribution of wealth and resource consumption among the states. Currently, this distribution is extremely unfair, since encouraged by money growth high-income states disproportionately use globally limited resources at the expense of low-income states [3,117,152].

A global implementation of the suggested money supply rule could lead to a much fairer distribution of wealth and resource use than at present. On the one hand, for states whose Ecological Footprint already exceeds their Biocapacity (see [144]), a reduction in the national money supply is required due to the suggested rule. This will reduce the material prosperity of these societies, which raises social problems. Therefore, a money reduction should be gradual with the proposed formula as monetary sustainability target in the long run, allowing for sufficient time for economic and social adjustments. On the other side, countries with a low Ecological Footprint should be permitted to increase their money supply and economic activities further up to a higher but still sustainable level of prosperity and resources.

Calibrating national money supplies to ecological capacities would be a strong incentive to use existing financial resources specifically to reduce the ecological impact and restore ecosystems, instead of investing primarily in economic growth. The proposed monetary transformation requires accompanying government measures and adjustments [40,46,57]. Priority should be given to replacing fossil with renewable energies and protecting biodiversity, as climate change and biodiversity loss may irreversibly change current environmental conditions [2,3]. Subsidies and investments that damage the environment have to be abolished completely. To make the change socially acceptable for all people, the reductions in levels of prosperity should be mitigated by a better distribution of income, capital and labor as well as a promotion of non-material wealth factors [20,46,153].

**Data availability**

The Fig 1 in the main text as well as in the supplementary information the Figure A in S1 Appendix and the Figures A to D in S2 Appendix are based on publicly available sources. The data is available through the references [144,151,154–158].

**Supporting information**

S1 Appendix. Global development from 1971 to 2016.
(PDF)

S2 Appendix. Developments in China and the USA over the past decades.
(PDF)

S3 Appendix. Inflation rates that lag behind money growth.
(PDF)

S4 Appendix. Collection of quotations.
(PDF)

S5 Appendix. Description to Fig 3 | macroeconomic relationships in the economy and with nature.
(PDF)
Acknowledgments

I would like to thank the anonymous reviewers as well as Stefan Klotz, Till Markus, Sven Schaller, Ralf Seppelt and Josef Settele for their very helpful comments on the manuscript and Sarah Gwillym-Margianto for translation support.

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