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Is Natural Capital Really Substitutable?

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Abstract

The extent to which natural capital can be substituted with manufactured or human capital in production is a key determinant of the possibility of long-run sustainable economic development. We review empirical literature pertaining to the degree of substitutability between natural capital and other forms of capital. We find that most available substitutability estimates do not stand up to careful scrutiny. Moreover, accurate substitutability estimates are even more difficult to produce for unpriced or mispriced resources. Finally, we provide evidence from industrial energy use, and agricultural land use, that suggests substitutability of natural capital with other forms of capital may be low to moderate.

Contents

1. INTRODUCTION

Growing populations and economic development around the world are putting unprecedented stress on the natural world. Rainforests are being destroyed (1), fisheries are severely overfished (2), biodiversity loss is nearing another great extinction (3, 4), clean groundwater is scarce (5), and the concentration of atmospheric carbon is at a dangerous level (6–8). In many developing countries, this depletion and degradation was already stunting economic development 15 years ago (9). Some claim that the environment should now be at the core of economic planning (10).

Economists have been asking for decades (if not centuries) whether economic growth can be sustainable if it degrades "natural capital," commonly defined as the stock of renewable and nonrenewable resources, including minerals, soils, plants, animals, air, water, and energy. Given that natural capital provides resources for production, absorption of wastes, basic-life support functions, and direct contributions to human welfare (11, 12), it is obvious that there are some limits to substitutability. Economic production, let alone human existence, is not possible if nature is completely destroyed. But where are the limits?

Natural capital: natural capital encompasses the value of all natural assets and includes renewable resources—such as water, air quality, forests and biodiversity—and nonrenewable resources—such as fossil fuels, metals and minerals; is one asset category (along with produced capital or human capital, for example) that may be used to measure wealth

The limits to substitutability are an empirical matter, but the relevant data are frequently difficult to unearth. This is partly because understanding precisely where limits exist—before they are crossed—is inherently challenging. It is partly because the answer to the question may depend strongly on the geographical scale of analysis—an action that is sustainable within a portfolio of human activities might be highly unsustainable if it were replicated globally. It is also because there has been no long-run large-scale systematic collection of data to enable good answers to such questions.

Why does substitutability matter? How does it relate to sustainability? Sustainability is often defined by economists as maintaining a nondecreasing level of welfare across generations. Because nonrenewable natural capital (e.g., mineral commodities) is finite, an economy that relies on converting such natural capital into physical capital or energy is not sustainable in the long run. Furthermore, although renewable natural capital (e.g., fish, trees) can provide value to humans indefinitely, it can only do so if such capital is managed in a sustainable fashion, such that the underlying natural assets are maintained and humans only consume the income. To what degree can such assets be liquidated and human welfare continue to increase? The answer depends to a great extent upon the substitutability of different inputs. First, within-input substitution allows us to reduce environmental impacts if the same type of input can be obtained from different sources. Consider climate change, which is driven in large measure by burning fossil fuels to produce energy. Moving away from fossil fuels and toward renewable energy sources typically means transitioning from dirty to clean energy sources. Fortunately, substitutability is very high, notwithstanding significant differences between such sources of energy in their intermittency and inherent storage. Second, between-input substitution, e.g., from energy to manufactured capital, may be equally important to sustainability. For instance, it is not feasible to address climate change simply by cleaning up our energy; all medium-term strategies developed by the Intergovernmental Panel on Climate Change involve a diversified portfolio of interventions and technologies across several sectors (13). Mitigation strategies include a reduction in energy demand via energy efficiency measures, alternative processes to produce energy-intensive goods (e.g., recycling), the take-up of technologies such as carbon and storage, or solutions, such as reforestation, to capture the carbon in the atmosphere.

Recall the famous Brundtland Commission definition of sustainable development: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (14). To be useful to an economist, we can translate this definition into an objective of nondecreasing per capita consumption or utility (broadly understood). If we assume for the moment that the various capitals—manufactured, natural, human, etc. (15)—are substitutable—such that production depends only on the total capital—then economic growth is said to be weakly sustainable when the total capital stock is nondecreasing. Weak sustainability requires only that the aggregate savings rate exceeds the combined depreciation rate on all forms of capital (16–20). More precisely, weak sustainability is possible with technological progress, and is even possible in a model without technological progress and only two capitals—manufactured (e.g., machines) and exhaustible natural capital (e.g., oil)—provided the elasticity of substitution between manufactured and natural capital is at least one (21–23). In other words, without technological progress, sufficient substitutability between manufactured and natural capital is necessary for maintaining economic development in the long run.

The weak sustainability view has received serious criticism because it tolerates arbitrarily high substitution of natural capital with manufactured capital. Clearly this is not plausible: natural capital provides basic-life support systems—food, water, breathable air, and a stable climate—that appear very hard or impossible to substitute (24–26). The "strong sustainability" view holds that minimum levels of natural capital must be maintained to sustain production and consumption in the long run (12, 27), because natural capital provides functions that are not substitutable by manufactured capital. If the "strong sustainability" view is correct, and the elasticity of substitution between manufactured and natural capital does indeed turn out to be very low, it is impossible to maintain economic production and consumption in the long run, without maintaining natural capital stocks.

Understanding the relationship between substitutability and sustainability is thus critical. However, it is complex. Four considerations illustrate the challenge. First, much of the natural capital that is under threat is renewable, rather than exhaustible, natural capital. If renewable natural capital regenerates sufficiently quickly, then sustainable development may be possible even at low levels of substitutability. However, renewal functions of different forms of natural capital are heterogeneous and uncertain (28). Second, substitutability is not constant over space and time. Third, technological change might be the ultimate arbiter of sustainability. If technological progress enables production to depend less and less on natural capital over time—i.e., if technology increases substitutability quickly enough over time—it might be possible to protect enough natural capital and maintain growth in the long run, even if the current level of substitutability is low (see, e.g., 29 for a review on the importance of endogenous growth for substitution between clean and dirty energy). Indeed, to maintain many forms of natural capital (e.g., climate stability), rapid increases in technological change (e.g., more efficient and cleaner technologies) is necessary.[1] Fourth, the analysis of natural capital substitutability is usually performed with aggregate data for broad categories such as "energy" or "materials." However, these categories bundle together a vast number of heterogeneous inputs, which implies that substitutability levels between or within categories crucially depend on the definition of the categories employed. For example, adequate substitutes exist for some components of natural capital (e.g., water filtration facilities for water purification provided by intact ecosystems), whereas there may be no cost-competitive substitute for other components (e.g., soil microbes to maintain soil fertility and nutrient recycling).

In this article, we first review the empirical literature examining whether production can be maintained with less natural capital and more manufactured capital or labor. We also look at within-input substitutability in the case of energy given its central role in climate change mitigation. The degree to which the same output can be obtained with a different combination of inputs depends on the elasticity of substitution between inputs (35–42). We show that most estimates of the elasticities of substitution between natural, manufactured, and human capital are either unreliable or uninformative for key issues in economic development, such as climate change mitigation or sustainable agriculture. Most estimates are based on old studies using econometric methods that are not able to deal with pervasive endogeneity issues, including the simultaneous determination of the output and the inputs used in production, measurement error, and input-neutral technical change (43).[2] Some of the shortcomings of previous work on natural capital substitutability could be alleviated by several new econometric methods that have been applied to estimating labor-to-capital substitutability (46–49).

In the absence of a long list of robust econometric assessments at the economy-wide level, we then dive deeper into specific sector-level studies of substitutability. These studies tend to directly consider efficiency—whether an input can be reduced in a cost-effective way—rather than substitutability. However, if large efficiency gains can be achieved through investments in the best available technologies, then substitutability is high. Conversely, if the potential to reduce input use is constrained by the low availability of options, then substitutability must be low.

We focus on two sectors. The first is industrial energy use, which is also relevant to climate mitigation, and the second is agricultural land use, selected because land will likely be under pressure as demand increases for food, energy, carbon sequestration services, ecosystem services, and natural habitats.

In both the energy and agricultural sectors, the empirical evidence suggests that substitutability between energy and land (both key forms of natural capital) and other forms of capital can only be plausibly low to moderate. To see this at a macro level, observe that industrial energy intensity has been falling by approximately 1–1.5% annually, while industrial energy demand increased by 1.3% annually between 1973 and 2014 (50). Energy and capital are not currently substitutable enough for energy consumption to fall, given rising demand for energy-intensive products. When it comes to agriculture, the stress put on land use by future demand for agricultural products is very high. Because yield gaps have been closing in the United States, Western Europe, and some parts of Asia and Latin America, further increases in yields may prove to be costly on already well-irrigated and intensively fertilized land. Several additional constraints, in particular water scarcity and the need for proper soil management practices, limit the potential for drastic increases in yields at low economic or low environmental cost. We open the discussion by looking at other forms of

[1] Substitutability between clean and dirty energy inputs is crucial in debates around so-called green growth (30–34).

[2] Two notable exceptions are the robust studies by Dissou & Ghazal (44), who show that capital, labor, materials, and energy are pairwise substitutes in the Canadian cement and primary metal industries, and Papageorgiou et al. (45), who find strong substitutability between clean and dirty energies in production.

substitutability, especially within-input substitutability in the case of energy, and, for agriculture, whether it is possible to move away from the consumption of more environmentally-damaging products. We find that both options have a strong environmental potential, but that their take-up requires similarly strong policy interventions.

The remainder of this article is structured as follows. Section 2 presents a synthesis of the currently available estimates of substitutability and explains why most are not reliable, from either an empirical or a theoretical perspective. Section 3 reviews the available techno-economic evidence on energy use in industry and land use in agriculture. Section 4 concludes.

2. EMPIRICAL ESTIMATES OF SUBSTITUTABILITY OF NATURAL CAPITAL

Historical empirical work provides estimates of substitutability between capital, labor, energy, and material inputs in production processes. Energy and materials are provided by nature, but they are by no means the only components of natural capital. The available estimates (Section 2.1) thus provide a very partial picture. The estimates all suffer from a set of general caveats (Section 2.2), and all of them have one or more issues of internal validity (Section 2.3).

2.1. Available Estimates

After the 1973 energy crisis, economic research examining substitutability between inputs other than capital and labor tended to focus on capital-energy substitutability since reducing energy use was on top of the policy agenda. As reviewed by Apostolakis (51) and Kintis & Panas (52), early studies of capital-energy substitutability showed contradicting results, setting up a "capital-energy substitutability controversy": Some studies found that capital and energy are substitutes (e.g., 53, 54), whereas others found that they are complements (e.g., 55–58). Substitutability would imply that capital can simply replace energy in production. Complementarity, however, would mean that a decrease in energy use (e.g., due to an energy price increase) would decrease the use of capital, thereby necessitating a reduction in output.

The 1970s controversy about the substitutability of energy and capital was resolved, eventually, with the conclusion that capital and energy are substitutes, but not before several valuable insights had emerged. In particular, almost all earlier studies reported Allen partial elasticities of substitution. The Allen elasticity measures the percentage change in the quantity of input i resulting from a 1% change in the price of input j, holding constant total output and the price of all other inputs, e.g., the percentage change in the quantity of capital inputs when energy prices increase by 1%. A positive elasticity indicates the inputs are substitutes; a negative elasticity indicates the inputs are complements. Thompson & Taylor (59) point out two empirical problems of using the Allen elasticity in the context of capital-energy substitution: First, the energy share of total costs tends to be very small (<3% in most industries). Because of this, small variations in the energy share can result in high variations in the estimates of Allen elasticities. Second, in the early studies, the elasticities of substitution are calculated for a fixed level of output. This is at odds with the motivation for looking at capital-energy substitutability: discovering whether low substitutability has an impact on economic growth once one factor becomes scarcer. Often, the more relevant measure of elasticity measures the response of the capital-to-energy ratio to an energy price increase: With energy supply fixed at some level, an increase (or decrease) in the share of capital would indicate an increase (or decrease) in the demand for capital. Thompson & Taylor (59) suggest using Morishima elasticities of substitution. Morishima elasticities measure the percentage change in the ratio of input j to input i when the price of input i varies, e.g., the percentage change in the capital-to-energy ratio when energy prices increase by 1%. Results with Morishima elasticities tend to be less variable and also much less conflicting. On the basis of information provided in prior studies, Thompson & Taylor (59) report that capital and energy are Morishima substitutes in 144 cases out of 148. In other words, an increase in the price of energy usually translates into an increase in the capital-to-energy ratio: More capital is used for the same amount of energy.

Supplemental Material >

Following Thompson & Taylor (59), recent studies have tended to favor Morishima elasticities to Allen elasticities. **Supplementary Appendix A** reports the Allen and Morishima elasticity estimates found in both recent studies and in earlier studies. The majority of the estimates suggest that capital, labor, energy, and materials are Morishima substitutes (see **Supplementary Appendix A**). Among the most recent studies, Nguyen & Streitwieser (60) use a cross section of 10,412 plants, appending data from the 1991 Manufacturing Energy Consumption Survey and the 1991 Annual Survey of Manufactures and report Morishima elasticities for capital, labor, energy, and materials. They find that capital, labor, energy, and materials are substitutes in production. With Canadian data for the period 1961–2003, Dissou & Ghazal (44) also find that capital and energy are substitutes. They confirm the results of Gervais et al. (61), who found substitutability between energy and capital in the specific case of the Canadian food industry.[3] Lazkano & Pham (64) also find that energy and capital tend to be substitutes, and that this relationship would be positively related with a country's income and environmental regulation. Finally, Markandya & Pedroso-Galinato (65) use cross-country variations of the World Bank dataset on the wealth of nations and find high degrees of substitutability between land resources, energy, and other factors of production.

Overall, the values for the elasticity of substitution between capital and labor or capital and energy are relatively high (>0.5). This finding might initially suggest relatively high substitutability between energy, materials, capital, and labor. The implications of high substitutability would be important: The decoupling of economic growth from resource use might be possible.

2.2. General Caveats

All the substitutability estimates listed in **Supplementary Appendix A** suffer from seven general challenges that imply they should be interpreted with great caution.

First, all of the studies concerned bear upon the substitutability of natural capital as an input into production processes. However, natural capital also provides three other services—it also provides waste management, life-support systems, and direct benefits to human welfare. None of the studies bear on the substitutability of natural capital for three functions, and hence a finding of high substitutability, for instance, as an input production does not preclude there being strong limits to substitutability of natural capital for the management of human wastes or the provision of life-support systems.

Second, the scale of analysis has an impact on findings of substitutability, as Oberfield & Raval (49) find. The substitutability of inputs may be low at the plant level, where production technologies are fixed, but could be higher at a sectoral level, once changes in the composition of production from different plants are possible. For instance, coal-fired power plants may not substitute coal for any other resource to produce electricity without huge investment, but the electricity sector as a whole can substitute away from coal use. At the plant level, substitutability between coal and capital may be low, whereas at an industry or an economy level, substitutability between capital and coal is likely to be quite high.

[3] Using constant elasticity of substitution (CES) production functions, Kemfert (62) and Su et al. (63) also find that energy is a substitute for labor or capital, respectively, in the case of Germany and China.

Third, even when inputs are apparently substitutable, switching from natural resources toward using more labor or more efficient machines may not constitute the most profitable choice for manufacturers at current prices. For instance, increasing the stringency of regulation or the price of natural resources at the national level may not automatically lead, at the global level, to a substitution toward capital or labor. Reasons include "leakage effects," whereby polluting industries facing environmental regulation at home find exports reduced and increased imports from foreign plants (66–68). Using longitudinal data on the outward FDI flows of German manufacturing industries, Wagner & Timmins (69) find evidence of such an effect in the chemical industry. For the United States, Kellenberg (70) finds that foreign country subsidiaries of US multinationals exploit less stringent environmental regulation, and attributes 8.6% of the growth of these subsidiaries to the falling levels of environmental regulation in such countries. Kahn & Mansur (71) use US data and observe that energy-intensive industries concentrate in counties with low electricity prices, whereas labor-intensive industries avoid pro-union counties. They also find mixed evidence that pollution-intensive industries may locate in counties with relatively lax clear air regulations.

Fourth, economic policies that are informed by substitutability and sustainability would ideally be based on the social costs of input use. Market prices for natural capital frequently do not reflect its full social value. As a result, estimates of substitutability may provide an unreliable guide for policy. This is because property rights over much of natural capital—such as the atmosphere, oceans, and biodiversity—are not well established (72). Therefore, firms observed to take decisions about many natural capital inputs do not face appropriate prices and use too much natural capital. It therefore makes it hard to correctly estimate substitutability across the entire range of natural capital quantity if users do not pay for the environmental damages they cause.

Fifth, even small changes in natural capital can lead to nonmarginal impacts because of tipping points (73, 74). Some natural capital is critical to the functioning of entire ecosystems (12, 75). Hence, a small decrease in one natural capital input (e.g., clean water) has led to drastic, nonmarginal changes in the availability of other factors (e.g., fish stocks) and to subsequent irreversible reductions in output. Marginal analysis is only suitable in the absence of tipping points. However, the absence of tipping points is a poor starting point for the analysis of any ecological systems.

Sixth, substitutability also needs to be specified over a particular time period. Substitution might be difficult on a short timescale because new technologies develop and diffuse slowly. However, over longer periods, we might expect firms and sectors to have much more substitutable production possibilities, as they are able to adapt with new resource availability conditions. Nevertheless, greater substitutability across time is not unconditional. In the presence of tipping points, small changes in natural capital availability can lead to irreversible changes in production possibilities.

Finally, it is widely assumed that technological change will provide greater substitutability of natural capital for manufactured capital (e.g., 76). For example, more efficient use of natural resources means that we are less dependent on resources for any single unit of output. However, technological progress can also (perhaps temporarily) make us more dependent on natural resources. Production of photovoltaic cells and semiconductors depends on the supply of silicon; batteries require lithium. An increase in substitutability between two types of capital can lead to an increase in complementarity between others. Without properly accounting for all types of natural capital (as well as other capitals), these important relationships can be missed and lead the analyst to incorrect conclusions.

Taking the seven caveats as a whole, it becomes clear that existing studies may not generalize outside the specific sector (44, 61, 77, 78), small geographical area such as Taiwan (i.e., 79), or technology under analysis. At the same time, due to data constraints, econometric studies have traditionally focused on materials and energy. The available substitutability estimates therefore do not inform us about substitutability of all forms of natural capital.

2.3. Internal Validity

Supplemental Material >

All of the reviewed studies (see **Supplementary Appendix A**) suffer from at least one of eight methodological problems, as set out in detail in **Supplementary Appendix B**. First, the majority of studies are based on either national-level or sector-level data. Aggregate data at the national or sector level is problematic because of aggregation bias: Aggregate data does not allow distinguishing between supply-side effects (of factor substitution) and demand-side effects (of changes in the composition of production) with traditional statistical methods (21). Second, data aggregation creates a serious statistical problem called endogeneity, especially because of the simultaneous determination of inputs and outputs. The applied estimation methods assume that the outcome variable is obtained from a set of determinants and that there is no feedback effect. This assumption does not hold when large economic agents are analyzed: A sector-wide or nation-wide increase or decrease in output could affect prices as much as prices affect output. Methods to deal with endogeneity, such as instrumental variables, are now prevalent but some of the older studies applying these methods do not provide sufficient detail on the instrumental variables used, and results may in fact only hold under very strong assumptions. Third, any econometric exercise suffers from omitted variable bias whenever a key parameter is not included in the analysis. For example, Dissou et al. (80) estimate substitutability between capital, labor, and energy, but omit materials in their estimation. Fourth, no reviewed study seemed to properly deal with measurement error. When measurement error is on the independent variables, not accounting for it may lead to an attenuation bias of the econometric estimates. Fifth, several studies assume that technical change is input-neutral. This assumption is unlikely to hold, and noninput-neutral technical change may produce strong biases in estimated parameters (43). Sixth, studies rely on specific functional forms to estimate elasticity parameters. The degree to which the result depends on the chosen functional form is uncertain. A good practice would be to report the results obtained with several functional forms, as Dissou & Ghazal (44) have done. Seventh, most studies also rely on long panels. Because elasticities of substitution are dependent on production techniques, it is likely that they might change over time. Hence, assuming a CES over a long panel may average out significant differences across time. In the above-mentioned studies, Dissou & Ghazal (44) report changes in elasticity estimates over a 44-year window. They report up to a tripling of Morishima elasticities between the 1960s and the early 2000s. Eighth, Dissou & Ghazal (44) also report a jump in elasticity estimates after the 1973 energy crisis in the case of the metal industry. This indicates that all studies performed with data from before the 1973 energy crisis are likely to be uninformative about decisions post 1973, given that the economic circumstances radically changed after that point. More generally, it implies the need for caution with all studies that rely on limited periods or snapshots (58, 60, 61, 65).

In summary, even the most recent estimates are often not using the most up-to-date econometric methods. As a result, they fail to address many identification concerns. The first three problems of aggregation bias, endogeneity, and omitted variable bias are particularly serious. Depending on context, the next three (measurement error, input-neutral technical change, and specific functional forms) can produce biased estimates. The past two (that relate to changes in substitutability over time) may lead to the wrong conclusions if substitutability has evolved substantially, e.g., because of changes in technical change or in the level of prices. Estimating substitutability is a huge econometric challenge and there is great scope for developing and applying new methods.

Our assessment indicates that the results from Dissou & Ghazal (44) seem to be the most robust among the papers we have reviewed. They conclude that capital, labor, materials, and energy are pairwise substitutes and that energy seems to be the most substitutable input in the case of the Canadian Primary metal and cement industries. However, the estimated elasticities in Dissou & Ghazal (44) are not high enough to suggest that these two industries could adapt easily to high increases in energy prices.

In recent years, new methods to analyze labor-to-capital substitutability have been developed and applied by Chirinko et al. (46), De Loecker & Warzynski (47), Karabarbounis & Neiman (48), and Oberfield & Raval (49). These methods all model the firms' cost-minimizing behavior to derive estimable equations for substitutability (see **Supplementary Appendix C** for a brief description). Extending these existing frameworks to look at energy or materials consumption within production may be possible and should be part of the future research agenda in the field. However, researchers should be cautious given these authors heavily rely on the fact that labor and capital are well-defined categories. Their estimations rely on the fact that prices are available and their role in production can be synthetized in simple production functions.

Supplemental Material >

Thus far, we have focused on between-inputs substitutability since this is what macroeconomic studies have been primarily interested in. However, there is substantial heterogeneity within macroeconomic aggregates, and questions of within-inputs substitutability may rise, especially if the same input can be obtained from clean and dirty sources. In that respect, Papageorgiou et al. (45) use new sectoral data for the electricity-generating sector and for the nonenergy industries in a panel of 26 countries for the years 1995–2009 and estimate nested CES specifications using nonlinear least squares. Furthermore, these authors test for different specifications for the functional form and the effect of changing output definitions. Because these authors look at modalities of substitution between two sources of energy, instead of two different inputs, endogeneity issues are less strong. The main limitation is that neutral technical change is assumed. There is also a risk of aggregation bias since the data is sector-level. Papageorgiou et al. (45) conclude that clean and dirty energies are fairly substitutable. This is not surprising, however, since we are looking at the same input (energy) but produced differently (which can still create new constraints, e.g., since renewables can be intermittent).[4]

3. EMPIRICAL RESULTS IN TWO SECTORS

The review and synthesis set out in the previous section have demonstrated that we lack robust estimates of the substitutability between natural capital and other inputs to production in most circumstances. However, understanding whether natural capital is a strong or a weak substitute for other factors of production is important, given its significance to the possibility of sustainable development.

Given that overall aggregate measures of substitutability are elusive, we turn to explore the second-best option of looking at the available information within specific sectors. On a case-by-case basis, several technical, sector-level studies provide concrete information on whether natural capital is a strong or a weak substitute for other inputs. In general, these studies consider efficiency rather than substitutability. Increasing demand for products may completely cancel out efficiency gains: This is currently the case for energy use for many energy-intensive sectors. The same logic holds in agriculture where yields are improving but more land is being cleared for intensive food production. Therefore, these sectors only truly substitute away from natural capital if the efficiency gains are large enough to absorb increasing demand. In the technical studies

[4]Although it is part of our literature review on substitutability, this study is not included in the appendices because it has a different focus and objective to the other economic studies. These authors do not look at substitutability between natural capital and other forms of capital, but instead at substitutability between two forms of energy.

mentioned hereafter, authors analyze whether it is or will be cost-effective to use alternatives to natural capital in production (e.g., better equipment and less energy). Clearly, if it is cost-effective to move away from the use of natural capital by investing in the best available technologies, then substitution is high. Alternatively, if there are not many affordable options to reduce the use of natural capital in production, then we are in a context of low substitutability.

We now review the evidence focusing on two sectors. First, we examine industrial energy, not least because of climate change concerns, where industrial energy demand is 29% of the global total (50). Second, we examine land, as this allows us to focus on a renewable resource. We know that land will be under stress because the world population is growing steadily and the demand for food will surge in the coming decades.

3.1. Energy Use in Industry

To look at past efficiency gains in industry, we provide succinct techno-economic information from three sectors: pulp and paper, iron and steel, and cement. These three sectors have been selected for several reasons. First, they are large consumers of energy [iron and steel being the second-largest industrial consumer in the world and pulp and paper the fifth) (81)] and/or use very energy-intensive processes [cement being the most energy-intensive sector per ton of output produced (82)]. Second, they produce homogeneous goods with fairly homogeneous production processes, making the analysis of energy efficiency measures easier to track.[5] Third, these sectors are not involved in the production of energy itself (unlike refineries or power plants) so their demand does not directly depend on the use of energy from other sectors.

For the pulp and paper industry, Farla et al. (83) compare production growth to energy consumption growth in eight OECD countries between 1973 and 1991. They find average energy efficiency gains of approximately 1.6% annually because energy consumption increased at a slower pace than production. However, energy intensity levels and energy efficiency gains were variable across countries, with stronger gains in the least efficient countries (the United Kingdom and Australia in their sample). The potential for energy efficiency gains seems logically higher in energy-inefficient countries. Peng et al. (84) show that the specific energy consumption of paper and paperboard production declined from 36.6 GJ/t in 1985 to 11.4 GJ/t in 2000 in China, reflecting a huge energy efficiency improvement.

A few studies have also assessed the potential for future energy savings in this industry. Martin et al. (85) show that the primary energy intensity in the US pulp and paper industry has declined by an average of 1% per year over the past 25 years. Their techno-economic analysis of 45 commercially available state-of-the-art technologies shows that there is an energy savings potential of approximately 16% if all the cost-effective measures available to industrials to reduce energy use were implemented. They estimate, however, that applying the best available technologies (with no consideration to cost-effectiveness) would reduce energy use by 31%. These estimates do not account for an increase in recycling. In this case, overall technical potential energy savings rise to 37%. Fleiter et al. (86) produced the same kind of techno-economic analysis for the case of Germany. They find that improvements in energy efficiency in the German paper industry have been slow over the past 20 years: The specific energy consumption per ton of paper produced has only reduced by 5.7% between 1991 and 2008.[6] Fleiter et al. (86) also review the potential for the

[5]The chemical sector is, however, the largest industrial consumer of energy, but it encompasses the transformation of raw materials into tens of thousands of heterogeneous products.

[6]Many reasons can explain this rather slow increase in efficiency, e.g., that the German industry was already quite efficient and also that the composition of demanded goods may have changed toward more energy-intensive goods.

diffusion of 17 process technologies that would improve energy efficiency in the German pulp and paper industry. By 2035, they evaluate that specific fuel consumption could reduce by 21% and specific electricity consumption by 16%. The authors argue that most of the improvements would be cost-effective from the firm's perspective.

In the iron and steel industry, Worrell et al. (87) find that energy intensity for US iron and steelmaking dropped 27% between 1958 and 1994. With 1994 data, assuming a payback period of 3 years and analyzing 47 specific energy efficiency technologies and measures, they found that this sector had the immediate potential for cost-effective energy efficiency improvements of 18%. The potential found in the United States seems to be in between the low potential in Europe and the high potential recorded in China.

Using European data, Pardo & Moya (88) find that there is a low impact of the current best available technology in reduction of energy and CO_2 emissions in integrated steel mills (that use raw materials to produce steel). However, their results suggest that the best available technologies in the electric route (to produce steel from recycling scrap) have higher potential to enable energy and greenhouse gas (GHG) emissions reductions. Nonetheless, Johansson & Söderström (89) suggest that there is good potential for reducing GHG emissions, although not energy use, if alternative sources of energy or if heat generated by iron and steel plants are being better used. Looking at the case of two Swedish plants, they find high GHG emissions reduction potential if biomass, instead of traditional fossil fuels, was used as an input. They also find that options to produce electricity from low-grade heat and heat radiation, as well as integrating steel manufacturing with district heating, could cause a reduction in GHG emissions.

Similar to the paper and pulp industry, the potential of substitutability in the iron and steel industry may be greater in emerging countries. Price et al. (90) show that energy consumption per ton of steel produced decreased by 31% in China between 2000 and 2008, thanks to the penetration of energy-conservation technologies. Their results align with and complement those of Wei et al. (91), who estimated that the energy efficiency in China's iron and steel sector increased by 60% between 1994 and 2003.

For the cement industry, Worrell et al. (92) notice that the primary physical energy intensity for cement production dropped 30% in the United States between 1970 and 1997. They also estimate the technical feasibility of 30 measures that could further reduce energy intensity in the sector and find that cost-effective measures could further reduce energy intensity by 11% if fully diffused to the US cement industry. Assuming an increase in the production of blended cement, the technical potential for cost-effective energy savings would increase to 18% of the energy used by this sector. In China, Hasanbeigi et al. (93) survey 16 cement plants with new suspension preheater and precalciner kilns, and compared the energy use of these plants to the domestic and international best practice using a benchmarking and energy-saving tool for cement. They find that energy consumption could be reduced by 12% and 23%, respectively, if domestic or international best practice levels were being implemented in the surveyed plants. In a follow up study, Hasanbeigi et al. (94) identify 23 energy efficiency technologies and measures applicable to China's cement industry and confirm that the highest fuel savings will be achieved by increased production of blended cement during 2010–2030. In the 1990s, Liu et al. (95) were also arguing that the Chinese cement industry could improve its energy efficiency in a cost-effective way (by 10–30%) if it renovated most vertical-kiln plants.

In general, the historical figures on energy efficiency improvements mentioned above suggest that energy-intensive sectors reduced energy intensity by approximately 1–1.5% every year on average in developed economies. In the future, our general impression from the above-mentioned studies is that this trend seems to be sustainable for the next decades in the context of high-income countries, and could be higher in emerging countries as they should catch up with high-income countries and use the best available technologies. However, prospective analyses cannot accurately predict the exact improvements that will be made. In particular, such analyses may include hypotheses on technology diffusion that may be inaccurate. For example, price decreases for these technologies could be underestimated or, on the opposite, the difficulties of implementing energy efficiency measures on site may not be captured. Technical barriers may include the risk of production disruptions, cost of production disruption/hassle/inconvenience, lack of time for staff and other priorities, lack of access to capital, and slim organization (96). However, such analyses cannot possibly account for major technological breakthroughs.

Nonetheless, this rule-of-thumb figure of a 1–1.5% downward annual trend in energy intensity is quite informative about current capacity to substitute energy for manufactured capital or intellectual capital in the reviewed sectors. Between 1973 and 2014, energy demand from industry increased by 79%. This is equivalent to an average 1.3% annual increase (50).[7] In the future, a slow but steady increase in world demand for energy-intensive products will be enough to offset the energy savings obtained from energy efficiency measures. This scenario is more than likely considering the fast development of East Asian, Latin American, and African countries. Hence, pulp and paper, iron and steel, and cement industries seem to be in a situation of low to moderate substitutability at the plant level. This globally aligns with the more general conclusion of the US Energy Information Administration (81), which predicts that world energy demand will rise by 48% between 2012 and 2040. Forecasts provided by techno-economic studies mentioned above need to assume some energy price trends. If energy prices were to soar, the best available technologies could become cost-effective and more substitution would be likely. Best available technologies tend to lead to double the energy efficiency savings compared to cost-effective measures in the studies reviewed. Therefore, it is possible that periods of high energy prices could in fact stabilize global energy demand. This possibility aligns with the scenarios developed by the Intergovernmental Panel on Climate Change for pathways limiting global warming at 1.5°C above preindustrial levels (13).

Furthermore, the low or moderate substitutability of energy with other factors is only an environmental concern because energy is produced in a dirty way. Fossil fuel combustion is the main emitter of the GHG emissions responsible for climate change, but there are clean energy inputs (e.g., solar and wind) that are very good substitutes for fossil fuels, as shown in Papageorgiou et al.'s (45) sector-level analysis. In this context, an essential question is whether reliance on dirty sources of energy can be reduced.

Looking at historical trends, Nakićenović (97) found that the GHG emissions associated with the production of one unit of energy (e.g., a kWh) have slowly, but consistently, decreased over the past two centuries, at 0.3% annually. Recent assessments suggest a deviation from this trend. The fifth assessment report of the Intergovernmental Panel on Climate Change (8) finds that the carbon intensity of energy actually increased worldwide between 2000 and 2010, due in part to the uptake of coal-fired power plants in emerging countries. Davis & Socolow (98) show that more new coal plants were built in the decade leading up to 2014 than in any previous decade. The authors also emphasize the importance of considering future emissions related to new capital investments, finding that the total committed GHG emissions related to the power sector are growing annually at approximately 4%.

Despite current trends, deep decarbonization, i.e., a drastic reduction in the carbon content of energy inputs, has been found to be technically feasible by 2050 (99). However, the technical potential for decarbonization is heterogeneous across sectors. The electricity sector is generally

[7]The IEA figure accounts for known technological and demographic trends and for the anticipated effects of current policies.

expected to experience the quickest reduction in carbon intensity (8, 98, 99), partly thanks to the sector's ability to utilize increasing availability of wind and solar. Other energy-intensive industries may have lower potential for decarbonization. The steel and iron sector is likely to prove difficult to decarbonize, particularly in the short term: 70% of steel is made from pig iron produced by reducing iron oxide in a blast furnace using coke or coal, before reduction in an oxygen blown converter (100). The coal and coke used in the majority of production is very carbon-intensive. Moving to gas-powered production is possible, but this has only occurred at a smaller scale (101). The Ultra-Low CO_2 Steelmaking program identified four production routes for further development, but the first three of these routes would require CCS and may therefore only be viable in the medium and long term (8).[8] The cement industry presents the same constraint as the iron and steel industry, given that approximately 50% of the total sector emissions are unavoidable because they result from the calcination of limestone, clay, and sand (8). A sector such as pulp and paper may adapt more easily. It has already access to biomass resources and uses this to generate approximately one-third of its own energy needs globally and 53% in the European Union (102). If electricity generation is decarbonized as expected, then electrification will become a clean alternative for the remainder of energy needs (103). A few other possible routes toward a clean energy supply exist, such as the diffusion of solar thermal energy in processes such as drying, washing, and evaporation.

In this general context of increasing energy needs, the uptake of clean technologies solutions to mitigate climate change will have to be very steep. This will require ambitious policy intervention, including higher energy prices. However, no single policy can address all of the barriers to clean production facing industry (8). In practice, a package of policies aiming at increasing energy efficiency, encouraging fuel switching, and fostering R&D in clean technologies will be necessary. Unfortunately, climate policies are not ambitious enough at present. Current pledges by signatories to the Paris Agreement add up to no more than one-third of the reductions needed to limit temperature increases to 2°C compared to preindustrial times (104).

3.2. Land Use in Agriculture

In the coming decades, world agriculture will face several major challenges. First, food production will have to increase by 50% to 110% by 2040 to meet increasing food demand, driven by population growth, changes in diet, and the need to end hunger and malnutrition (105–110). Second, such increases in food production risk placing higher stress on the environment. Agriculture is already the greatest anthropogenic threat to biodiversity (111–113) because of deforestation, as well as land and water contamination. It is also a large contributor to GHG emissions worldwide. Agriculture, forestry and other changes in land use are responsible for 24% of global GHG emissions (114). Agriculture alone represents approximately 10–12% of global GHG emissions (114, 115). The other main contributor to GHG emissions is the conversion of forests to cropland. Estimates of GHG emissions released because of deforestation vary, but deforestation could represent approximately 15% of GHG emissions worldwide (8, 116). Finally, the challenge of reaching high levels of food production in a sustainable manner furthermore needs to be accomplished while enhancing the living standard of the people that derive their livelihoods from agriculture in developing countries. In 2010, some 900 million of the estimated 1.2 billion extremely poor lived in rural areas. Approximately 750 million of them worked in agriculture, usually as smallholder family farmers (117).

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[8]The four production routes are top-gas recycling applied to blast furnaces, HIsarna (a smelt reduction technology), advanced direct reduction, and electrolysis.

With current technologies and expected technological progress, increasing food production to required levels appears possible (118), but this involves more land being dedicated to agriculture through deforestation, greater use of underground water sources, and more fertilizer use on areas that currently convey low yields. In other words, the key question is whether increases in food production can be achieved in an environmentally and economically sustainable way (119).

Advocates of so-called land sparing argue that boosting crop yields to meet rising demand, instead of clearing more land for less-intensive agriculture, is the most sustainable way to address the challenge of feeding nine billion people (e.g., 107, 118, 120, 121). In particular, clearing lands in tropical regions with low yields provides little nutritional gain and can therefore be avoided cost-effectively (122). The main question is whether yields can be substantially increased on the land already used for agriculture. Usually framed as a matter of efficiency, our capacity to increase yields per hectare implicitly depends on our ability to substitute space with other inputs (water, fertilizers, machines, labor) or develop the intellectual capital necessary to do so (e.g., genetic engineering). While intensification might indeed spare land for natural habitats, it has other adverse effects on the local environment, such as local biodiversity loss, and as such there is debate about the optimal level of intensification.

Over the past 40 years, crop yields have increased dramatically by approximately 2–3% per year, through greater inputs of fertilizer, water and pesticides, new crop strains, and mechanization (112, 118, 123–126). Many land areas can now be harvested twice a year (or even three times a year), and cereal production per hectare has more than doubled since 1960 (123). This unprecedented overall increase in agricultural productivity is often referred to as the Green Revolution. Without these large efficiency gains, the land area required for food production would have been very large indeed (e.g., 120).

Today, scientists wonder if such high trends in crop yield increases can be sustained for the next 30 to 40 years. The stakes are inevitably high. Balmford et al. (126) predict that, in developing countries, meeting food demand should require a 23% extension of cropland assuming a moderate annual increase in yields (by 170,000 kcal per hectare per year). In a high yield scenario, they find that only a 1% increase in cropland would be necessary whereas, in a low yield scenario, a 53% land extension would be required to double food production from these 23 crops. Their results for developed countries suggest that land use for growing crops should slightly reduce. However, we might not be in the fortunate high yield scenario of Balmford et al. (126). Ray et al. (121) find that current yield increases are not sufficient to sustain a doubling of food production. They estimate that global average rates of yield increase across 13,500 political units are 1.6%, 1.3%, 1.0%, and 0.9% per year for maize, soybean, rice, and wheat, respectively. However, they estimate that an annual yield increase of 2.4% would be needed to double crop production by 2050.

Might Ray et al.'s (121) estimates of 2.4% annual yield increases be achieved through deliberate endeavor in the coming years? Increases in crop yields depend on the barriers that farmers face on the ground, and their capacity to address them with the support of decision makers.

The major barrier to further yield increase is that the Green Revolution of the past 40 years has mostly been achieved by closing yield gaps, i.e. the difference between the genetic potential of plants to grow rapidly on a given plot of land, and the realized outcome observed in farms constrained by the availability of water, the use of fertilizers, pest control, and resistance to bad weather. In this spirit, Tilman et al. (118) observe that further increases in nitrogen and phosphorus application are unlikely to be as effective at increasing yields because of diminishing returns. Today, only 30–50% of applied nitrogen fertilizer and approximately 45% of phosphorus fertilizer is taken up by crops. Likewise, the potential for increasing irrigation appears limited by water availability in many regions. Although 40% of crop production comes from the 16% of agricultural land that is irrigated (127, 128), the rate of the increase in irrigated lands is decreasing, and new dam constructions over the next 30 years may allow for only a 10% increase in water for irrigation (128, 129). In addition, water is scarce in several regions of the world and several countries already fail or may soon fail to deliver enough water to the amount of irrigated land they have [e.g., China, Pakistan, India, the Middle East, North Africa (130)]. The over-pumping of groundwater is a serious concern in major water basins in the United States, China, India, Pakistan, and the Middle East (131). Furthermore, such intensive agricultural practices on poorly managed land have contributed to a wide-spread degradation of soil quality. In 1994, Oldeman (132) estimated that 17% of soils were in a state of human-induced degradation, usually because of poor fertilizer and water management, along with erosion and hastened fallow periods. Furthermore, climate change may also negatively affect crop productivity and require a renewal of agricultural practices, given that droughts and floods may become more frequent, along with excessively hot days, which are usually associated with heavy production losses (133, 134).

Similarly, Cassman et al. (135) argued that achieving 2.4% annual yield increases to meet 2050 food demand—without further land conversion—would require constant improvements in soil quality and precise management of all production factors, along with major breakthroughs in plant physiology, ecophysiology, agroecology, and soil science.

However, developing countries still have unexploited potential to supply agricultural products. Many countries have crops that deliver very low yields, in particular in Sub-Saharan Africa. Mueller et al. (136) show that the closing of yield gaps occurred mostly in the United States, Western Europe, Argentina, Brazil, and some regions of China and India. They show that for other regions, fertilization and insufficient water provision have substantially undermined any effort to achieve high yields. Closing the yield gap for maize in Sub-Saharan Africa would be possible by focusing on nutrient deficiencies. In addition, overall agricultural productivity is affected by factors beyond the farm, including political stability or lack of infrastructure connecting crops to cities and ports (137).

The greatest challenges and opportunities for agriculture in the next 30 years will be in developing countries. Such countries have the greatest potential for progress, given that their yield gaps are widest (122). Solutions to increase yields will need to be tailored to specific contexts. For instance, Pretty et al. (138) suggest African agriculture might not follow the intensification model of the United States and Western Europe over the past 40 years, which is both resource-intensive (in particular in water) and capital-intensive. Human labor, rather than physical capital, is relatively abundant in developing countries. The rapid mechanization of agriculture, as implemented in high-income countries, may therefore not be as economically rational.

In parallel, although intensification of agriculture on existing agricultural land may increase food security, it may involve unsustainable water use and overuse of fertilizers, which themselves impact biodiversity. Impacts could spread to nearby areas, e.g., through water contamination. The evaluation of the possible negative impacts of higher intensification is difficult. Results are heterogeneous according to the region and the management practices implemented (see 120 for a review of land sparing).

An alternative to land sparing and associated intensification of agriculture is so-called land sharing, which consists of production practices that are more respectful of the environment and do not affect biodiversity in cultivated fields. Land sharing adds constraints on the use of agricultural land, and can thus reduce yields (e.g., 139, 140). However, it may be a key part of a sustainable agricultural system if intensification itself causes large environmental damage. The choice between land sparing (intensification) or land sharing (management to maintain local biodiversity) is likely to be context-dependent. A study in Northern India and Ghana finds that land sparing offers the best potential to achieve biodiversity objectives while producing enough food (140). However, preferable solutions may be very different from one ecosystem to another, or from one country to another, depending on the yield reduction and biodiversity gains from sustainable agricultural practices (139). It may also pose ethical issues, e.g., for the welfare of domesticated animals (141).

In short, considerable key questions remain about the substitutability of land with other inputs. The increase in food demand in the coming decades is likely to affect the environment substantially if the composition of food baskets remains constant, as we have assumed thus far. However, the same caloric content can be obtained from a wide diversity of food products, with highly differentiated consequences for land use and biodiversity. In particular, beef production requires much more land than cereal production per calorie, because the conversion efficiency of grain and plant-based feed into animal matter is only approximately 10% (137). Meat production currently imposes very significant demands on land use. De Sy et al. (142) estimated that approximately 71% of rainforest conversion in South America has been for cattle ranching and only 14% for commercial cropping.

The gains from reducing meat consumption are not limited to efficient land use. The food system is responsible for more than one-quarter of all GHG emissions globally, with meat production making up 80% of this total (143). Meat production, and in particular that of ruminants, is the single most important source of methane globally. Ruminant production tends to result in more emissions than other mammals, which in turn result in more emissions than poultry production (144). In parallel, shifting to alternative nonanimal sources of protein could allow 4–21% water savings (145). Reducing the fraction of animal-source foods in our diets has profound health implications too. Springmann et al. (143) find that the monetized value of the improvements in health might even exceed the value of the environmental benefits. Transitioning toward more plant-based diets based on standard dietary guidelines could itself reduce food-related GHG emissions by 29–70% compared with a reference scenario in 2050 (143).

Future trends in meat consumption will therefore be a key determinant of the environmental footprint of food production. Since 1980, consumption of meat has been rising globally by nearly 4% (144). However, trends differ by country. Per capita and total consumption of meat consumption are static or declining in high-income countries and in India, but increasing in the rest of the world. The strongest increases have been found in Asia (excluding India) and in South and Central America. Gill et al. (146) study commodity supply data for 1961 and 2011 from FAOSTAT for Brazil, China, and India. Brazil showed marked increases in beef and poultry meat supply, while China saw significant increases in poultry and pig meat.

The mainstreaming of plant-based diets could have a strong impact on reducing meat consumption and thus on the environment and biodiversity. The shift in preferences toward plant-based diets is likely to be strongly driven by personal health considerations. While the medical community historically believed vegetarian diets to be lower in nutritional quality than meat-based diets (147, 148), it now firmly supports shifting diets away from meat products. For example, in their "*2015–2020 Dietary Guidelines for Americans*," the US Department of Health and Human Services and US Department of Agriculture promote a "healthy vegetarian eating pattern" as one of their recommended healthy diets (149).

There is a long way to go, however. In the European Union, 45% of total agricultural sales in 2014 resulted from animal products (150). The trend toward the consumption of vegan and vegetarian food might trigger considerable resistance in various forms from the agricultural sector. Consumers' habits may take time to change. Although statistics on vegetarianism are patchy, Reinhart (151) reports that the US share of vegetarians remained constant and low (at 5–6%) between 1999 and 2018. In Europe, averages are also low, although they vary substantially by country. Statista (152) reported that the total share of European consumers avoiding red meat was 13% in 2017. Nonetheless, many consumers now report to be willing to reduce meat consumption substantially. Already, 31% of Americans claim to practice meat-free days (153), and 35% of evening meals are reportedly meat-free in the United Kingdom (152). Although the proportion of those following vegan diets is still small, the recent growth of this group may be an indicator of a future trend (154). Radnitz et al. (155) argue that the influence of those with plant-based diets on the food sector will continue to grow; Janssen et al. (156) point out that both organic and fair-trade products were also once used by very few consumers.

In summary, the stress put on land use by future demand for agricultural products may be very high. Meeting future demand for foods and achieving sustainable development goals is likely to require substitutability of different factors and fundamental changes in food systems (109). Socioeconomic projections show that major changes in land use are likely to occur in the developing world. There are opportunities in low- and middle-income countries too, where yield gaps are still large and investments in infrastructure and access to fertilizers may considerably increase yields—substituting human intelligence and industrial practices instead of more land to increase production. As discussed, several key environmental considerations are driven by preferences for meat products. Erb et al. (157) find that feasible scenarios that meet food demand for feeding the world without deforestation entail either high cropland-yield levels or significant dietary changes. Significantly changing diets—substituting plant-based products for meat-based products—would have important positive health implications as well as environmental benefits. The challenge of fashioning sustainable agriculture is therefore a combination of other challenges, all involving considerations of substitutability. None of these is easy, but each is feasible.

4. CONCLUSION

The somewhat dismal conclusion from this review and synthesis is that estimates of substitutability of natural capital must be treated with great caution. We identified four general caveats applicable to all substitutability estimates. Furthermore, all studies examined suffered from at least one of eight internal validity problems and four external validity problems. Some of these problems are very difficult to resolve (e.g., identifying future structural breaks), some will take time (e.g., more and more data on flows and prices of natural capital are becoming available), and others can already be solved with straightforward econometric strategies.

Given these challenges, as a second-best, we took a closer look at the scientific data for two sectors—energy and land. Even in this area, the overall conclusion of the empirical evidence for energy and land was that substitutability seems low to moderate, but again this conclusion warrants care. Backward-looking estimates do not provide a reliable guide as to whether technological progress will alleviate pressures on the carbon budget and the limited availability of land and water. However, modest efficiency gains are clearly inadequate to deliver sustainable energy and agricultural systems: Other major changes such as scientific breakthroughs are required. Absent these, and with only low or moderate substitutability, sustainable development is unlikely to be achieved in the long run unless shifts in preferences accompany substitutions on the supply side. Our prospects of prospering in the distant future would benefit from a significant improvement in the current state of knowledge of the substitutability of natural capital.

SUMMARY POINTS

1. We review the empirical literature examining whether aggregate production levels can be maintained as natural capital declines, by using more manufactured capital or labor.
2. Most econometric estimates are based on old studies using methods that are not able to deal with pervasive endogeneity issues.

3. In the absence of a long list of robust econometric assessments, we dive deeper into specific sector-level studies of substitutability relating to energy efficiency in industry and land use in agriculture.
4. In both the energy and agricultural sectors, the evidence suggests that substitutability between energy and land (both key forms of natural capital) and other forms of capital can only be plausibly low to moderate.

FUTURE ISSUES

1. Low to moderate substitutability levels suggest that strong policy involvement will be required to protect natural capital in order to sustain economic development.
2. The protection of critical natural capital will require that other levers of actions, such as changing consumption patterns, be triggered alongside natural capital substitution.
3. Some of the shortcomings of previous work on natural capital substitutability could be alleviated by new econometric methods that have been applied to estimating labor-to-capital substitutability.

DISCLOSURE STATEMENT

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