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IS NATURAL CAPITAL REALLY SUBSTITUTABLE?

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Economics of Sustainability

Is Natural Capital Really Substitutable?

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Abstract

The extent to which natural capital can be substituted with physical or human capital in production is one of the main concerns for the possibility of long-run sustainable economic development. We review the empirical literature that assesses 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 econometric scrutiny. Moreover, accurate substitutability estimates are even more difficult to produce for unpriced or mispriced resources despite the availability of recently developed econometric methods. Finally, we provide evidence from case studies on the use of energy in industry and land in agriculture that suggests substitutability of natural capital with other forms of capital may be low to moderate.

Keywords: substitutability; natural capital; energy; agriculture; climate change

JEL codes: O44; Q10; Q40; Q50.

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1. Introduction

Growing population and economic development around the world is putting unprecedented stress on natural resources. Rainforests are being cut down (Hansen et al., 2013), many fisheries overfished (Worm et al., 2009), biodiversity loss is nearing another great extinction (Cardinale et al., 2012, Dirzo et al., 2014), clean groundwater is scarce (Vörösmarty et al., 2010), and the concentrations of atmospheric carbon are at dangerous levels (Allen et al., 2009, Meinshausen et al., 2009; IPCC, 2014). In many developing countries, natural capital degradation is already stunting economic development (Arrow et al., 2004). There is an urgent need to put the environment at the core of economic planning (Helm, 2015).

Whether or not economic development is *sustainable* in the long run depends crucially on *substitutability* between natural capital and other forms of capital (e.g. physical or human) in the production process. Unless natural capital is sufficiently substitutable, long-run economic growth cannot be sustainably maintained, without continued technological progress, since exhaustible natural resources will ultimately deplete (Solow 1974; Dasgupta and Heal, 1974; Weitzman 1976; Dasgupta and Heal, 1979; Arrow et al., 1995; Dasgupta and Maler 2000; Ruta and Hamilton, 2007; Arrow et al. 2012, Hallegate et al., 2012). Substitutability is therefore one of the key factors in the optimal investment of exhaustible resource rents (Hartwick, 1977; Asheim, 2013).

In this paper, we review empirical economic literature that looks at whether production can be rearranged such that output is maintained using less natural capital and more physical capital or labor. The degree to which the same output can be obtained with a different combination of inputs depends on the elasticity of substitution between inputs (Slutsky, 1915; Hicks and Allen, 1934; Arrow et al., 1961; Samuelson, 1974; Blackorby and Russell, 1976, 1981, 1989; Stern, 2011).[3] We show that most of estimates of the elasticities of substitution between natural, physical 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, input-neutral technical change (Griliches, 1967). Studies are even less reliable when they rely exclusively on cross-country differences or aggregate data,

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[3] For example, in the context of climate and *endogenous* economic growth, Acemoglu, Aghion, Bursztyn and Hemous (2012) convincingly show that the elasticity of substitution between clean and dirty energy is central to determine the ability of our economies to become sustainable, alongside the rate of technological development.

therefore assuming that it is equivalent to using more detailed, sector-specific data. Other studies heavily rely on a single functional form to determine substitutability estimates. To our knowledge, only two studies provide reasonably reliable estimates. The first one is by Dissou and Ghazal (2010). It shows that capital, labour, materials and energy are pairwise substitutes and finds that energy appears to be the most substitutable input. However, it is limited in scope since it focuses on the Canadian cement and primary metal industries. The second study is by Papageorgiou, Saam and Schulte (2017). It looks at the substitutability between clean and dirty energies in production and finds strong evidence of substitutability. It is however also limited in scope since it looks at substitution within one input category.

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 (Chirinko, Fazzari and Meyer, 2011; De Loecker and Warzynski, 2012; Karabarbounis and Neiman, 2014; Oberfield and Raval, 2014).

In the absence of a long list of robust econometric assessments, we then dive deeper into case studies of substitutability. Several technical, sector-level studies provide concrete information on whether natural capital is a high or a low substitute to other inputs. In general, these studies consider efficiency rather than substitutability. They look at whether the use of an input can be reduced in a cost-effective way while listing opportunities and barriers to efficiency. Clearly, if large efficiency gains can be acquired cost-effectively 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 cases. The first one is energy use in industry and the second one is land use in agriculture. We chose the first case study because reducing (fossil fuel) energy use is an essential component of climate change mitigation. The second case study is relevant because land will likely be under stress in the coming decades because of increases in the demand for food, energy, carbon sequestration services, ecosystem services and natural habitats. For example, projections show that food production will have to nearly double by 2050 to feed nine billion people (World Bank, 2008; Royal Society, 2009; Tilman et al., 2011).

In both cases, the empirical evidence suggests that substitutability between natural capital and other forms of capital can only be plausibly low to moderate. In industry, we find that the downward annual trend in energy intensity is about 1-1.5%. Between 1973 and 2014, energy demand from industry has increased by 79%. This is equivalent to an average 1.3% annual increase (IEA, 2016). 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. Energy and capital do not seem to be substitutable enough for energy consumption to reduce when the demand for energy-intensive products is rising. 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 US, 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 fertilised 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 either low economic or environmental cost.

The remainder of this paper is structured as follows. Section 2 displays 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 available in the cases of energy use in industry and land use in agriculture. Section 4 concludes.

2. Empirical estimates of substitutability of natural capital

2.1 Available estimates

Since the 1973 energy crisis, economic research examining substitutability between inputs other than capital and labour has tended to focus on capital-energy substitutability. This substitutability debate had strong policy implications. If energy could be substituted with capital, shocks to energy prices like the 1973 oil price crisis could be absorbed by the economy by replacing energy inputs with capital. On the other hand, if energy and capital were complements, any decrease in energy use would also reduce investments in capital and hinder economic growth.

Reviewed in Apostolakis (1990) and Kintis and Panas (1989), early studies about capital-energy substitutability showed contradicting results, setting up a "capital-energy substitutability controversy": some studies found that capital and energy are substitutes (e.g. Griffin and Gregory, 1976; Pindyck, 1979) while others found that they are complements (e.g. Hudson and Jorgenson, 1974; Berndt and Wood, 1975; Berndt and Khaled, 1979; Prywes, 1986).

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 and Taylor (1995) 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 amount of output. This is at odds with the motivation for looking at capital-energy substitutability: one would like to know if low substitutability might have an impact on economic growth once one factor becomes scarcer. Therefore, a more relevant measure of elasticity might be the one that measures the response of the capital-to-energy ratio: 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 and Taylor (1995) 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. Based on the information provided in prior studies, Thompson and Taylor (1995) report that capital and energy are Morishima substitutes in 144 cases out of 148. The latter means that an increase in the price of energy usually translates into an increase in the capital-to-energy ratio: more capital is being used for the same amount of energy.

Following Thompson and Taylor (1995), more recent studies have tended to favour Morishima elasticities to Allen elasticities. Table 1 reports the Allen and Morishima elasticity estimates found both in recent studies and in earlier studies. For earlier studies, we could sometimes back out the Morishima elasticities.[4] Among the most recent studies, Nguyen and Streitwieser (1999) 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, labour, energy and materials. They find that capital, labour,

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[4] In Table 1, we display Partial Allen elasticities of substitution for the studies that provide them. When possible, we calculated Morishima elasticities ourselves from the econometric estimates or tables present in the studies. Alternatively, we display some calculations done by other authors. Appendix A quickly displays differences in the methods used in the studies reported in Table 1.

energy and materials are substitutes in production. With Canadian data for the period 1961-2003, Dissou and Ghazal (2010) also find that capital and energy are substitutes. They confirm the results of Gervais et al. (2008) who found substitutability between energy and capital in the specific case of the Canadian food industry.[5] Lazkano and Pham (2016) 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 and Pedroso-Galinato (2007) use cross-country variations of the World Bank dataset on the wealth of nations and nested CES production functions to assess the substitutability between several forms of natural capital and other forms of capital. They find high degrees of substitutability between land resources, energy, and other factors of production.

In short, the majority of the estimates (see Table 1) suggest that capital, labour, energy and materials are Morishima substitutes. The values for the elasticity of substitution between capital and labour or capital and energy are comparable with the ones obtained by recent studies looking at capital-to-labour substitution. Using US firm level data, Chirinko, Fazzari and Meyer (2011) find capital-to-labour substitutability estimates between 0.37 and 0.70. Using national level data, Karabarbounis and Neiman (2014) find estimates in the range of 1.03-1.43. Looking at different levels of aggregation, Oberfield and Raval (2014) provide an estimate of 0.52 at plant level, 0.69 at industry level, and 0.71 at industry level for capital-to-labour substitutability in the US. Hence, the summary of our finding might initially suggest relatively high substitutability between energy, materials, capital and labour. The implications of such a finding in the current political context would be important. High substitutability means that the decoupling of economic growth and resource use might be possible.

Table 1: Estimates of the elasticities of substitution from a selection of economic studies

Inputs	Allen elasticity	Morishima elasticity	Study and coverage
Capital and Energy	-1.39	-0.09 to 0.24[a]	Hudson and Jorgenson (1974), US Manufacturing, 1947-71
	-3.53 to -3.09	0.27 to 0.34[b]	Berndt and Wood (1975), US Manufacturing, 1947-71
	1.02 to 1.07	0.33 to 0.92[a]	Griffin and Gregory (1976), Manufacturing in several countries
	-2.46	0.21 to 0.60[c]	Berndt and Khaled (1979) , US Manufacturing, 1947-71
	-1.39 to -0.65	-0.07 to 0.28[c]	Anderson (1981), US Manufacturing, 1948, 1960, 1971
	-22.40 to 8.05	-0.01 to 1.07[c]	Denny et al. (1981), 18 US Manufacturing sectors, 1948-1971
	-9.00 to 18.60	-0.07 to 2.32[c]	Denny et al. (1981), 18 Canadian Manufacturing sectors, 1948-1971
	0.01 to 2.44	0.06 to 3.42[b]	Walton (1981), Fuel or electricity, SIC 28, 29, 32, 33, US Regions.
	2.26	0.28 to 1.38[c]	Turnovsky et al. (1982), Australian Manufacturing, 1946-1975
	-1.35		Prywes (1986), US Manufacturing, 1971-1976
	2.17	0.87[d]	Chang (1994), Taiwanese Manufacturing, 1956-1971
		0.65[d]	Kemfert (1998), German Manufacturing, 1960-1993

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[5] Using CES production functions, Kemfert (1998) and Su, Zhou, Nakagami, Ren and Mu (2012) also find that energy is a substitute to labor or capital, respectively in the case of Germany and China.

Inputs	Allen elasticity	Morishima elasticity	Study and coverage
	0.59	1.25 to 3.78	Nguyen and Streitwieser (1999), US Manufacturing, 1991
		0.07 to 1.48	Gervais et al. (2008), Quebec meat, bakery and dairy sectors, 1990-1999
		0.13 to 0.69[e]	Dissou and Ghazal (2010), Canadian metal industry, 1961-2003
		0.16 to 0.53[e]	Dissou and Ghazal (2010), Canadian cement industry, 1961-2003
	0.67		Su et al. (2012), Chinese industry, 1979-2006
	0.30 to 0.66		Dissou, Karnizova and Sun (2015), 10 Canadian industries,1962-1997
Labour and Energy	2.16	-0.03 to 1.02[b]	Hudson and Jorgenson (1974) , US Manufacturing, 1947-71
	0.61 to 0.68	0.48 to 0.65[b]	Berndt and Wood (1975), US Manufacturing, 1947-71
	0.72 to 0.87	0.71 to 0.90[b]	Griffin and Gregory (1976) , Manufacturing in several countries
	2.37	0.82 to 0.83[b]	Berndt and Khaled (1979) , US Manufacturing, 1947-71
	-6.57 to 20.84	0 to 3.49[b]	Walton (1981), Fuel or electricity, SIC 28, 29, 32, 33, US Regions.
	-2.66	0.01 to 0.15[b]	Turnovsky et al. (1982), Australian Manufacturing, 1946-1975
Labour and Energy	0.88		Prywes (1986), US Manufacturing, 1971-1976
	0.35		Chang (1994), Taiwanese Manufacturing, 1956-1971
		0.42[d]	Kemfert (1998), German Manufacturing, 1960-1993
		0.40[d]	Manne and Richels (1992), Manufacturing sector in several regions
	4.06	2.07 to 3.79	Nguyen and Streitwieser (1999), US Manufacturing, 1991
		0.23 to 1.44	Gervais et al. (2008), Quebec meat, bakery and dairy sectors, 1990-1999
		0.29 to 0.73[e]	Dissou and Ghazal (2010), Canadian metal industry, 1961-2003
		-0.02 to 0.53[e]	Dissou and Ghazal (2010), Canadian cement industry, 1961-2003
	2.55		Su et al. (2012), Chinese industry, 1979-2006
	0.60 to 1.00		Dissou, Karnizova and Sun (2015), 10 Canadian industries, 1962-1997
Capital and materials	0.49 to 0.58	0.46 to 0.58[b]	Berndt and Wood (1975), US Manufacturing, 1947-71
	-0.18	-0.13 to 0.34[b]	Berndt and Khaled (1979) , US Manufacturing, 1947-71
	0.47; 1.08		Moroney and Trapani (1981), Estimates for Aluminium and Blast Furnace / Basic steel respectively, US, 1954-1974
	0.74	0.71 to 1.09[b]	Turnovsky et al. (1982), Australian Manufacturing, 1946-1975
	0.14 to 13.62	0.28 to 13.62	Nguyen and Reznek (1993), 5 US industries and 5 sizes, 1977 and 1982
	2.76	1.78 to 3.28	Nguyen and Streitwieser (1999), US Manufacturing, 1991
		0.01 to 0.41	Gervais et al. (2008), Quebec meat and bakery sectors, 1990-1999
		-0.10 to 0.68[e]	Dissou and Ghazal (2010), Canadian metal industry, 1961-2003
		-0.18 to 0.74[e]	Dissou and Ghazal (2010), Canadian cement industry, 1961-2003
Labour and materials	0.57 to 0.61	0.58 to 0.63[b]	Berndt and Wood (1975), US Manufacturing, 1947-71
	-0.10	-0.08 to 0.14[b]	Berndt and Khaled (1979) , US Manufacturing, 1947-71
	0.63 to 1.33		Moroney and Trapani (1981), Estimates for four mineral intensive industries (Aluminium, Blast Furnace / Basic steel, storage batteries and hydraulic cement), US, 1954-1974
	0.61	0.64 to 0.80[b]	Turnovsky et al. (1982), Australian Manufacturing, 1946-1975
	2.21 to 32.12	1.74 to 24.28	Nguyen and Reznek (1993), 5 US industries and 5 sizes, 1977 and 1982
		2.97 to 3.78	Nguyen and Streitwieser (1999), US Manufacturing, 1991
		0.25 to 1.01	Gervais et al. (2008), Quebec meat and bakery sectors, 1990-1999
		0.01 to 0.49[e]	Dissou and Ghazal (2010), Canadian metal industry, 1961-2003
		-0.08 to 0.88[e]	Dissou and Ghazal (2010), Canadian cement industry, 1961-2003
Energy and materials	0.74 to 0.77	0.48 to 0.71[c]	Berndt and Wood (1975), US Manufacturing, 1947-71
	0.33	0.18 to 0.73[c]	Berndt and Khaled (1979) , US Manufacturing, 1947-71
	0.79	0.24 to 0.73[b]	Turnovsky et al. (1982), Australian Manufacturing, 1946-1975
	7.98	3.91 to 5.35	Nguyen and Streitwieser (1999), US Manufacturing
		0.63 to 1.38	Gervais et al. (2008), Quebec meat and bakery sectors, 1990-1999
		-0.12 to 0.66[e]	Dissou and Ghazal (2010), Canadian metal industry, 1961-2003
		-0.06 to 1.09[e]	Dissou and Ghazal (2010), Canadian cement industry, 1961-2003
Nest of capital and human capital (or		0.48	Markandya and Pedroso-Galinato (2007), cross-country estimates using national data from 67 countries.

Inputs	Allen elasticity	Morishima elasticity	Study and coverage
labour) versus energy	0.77		Su et al. (2012), Chinese industry, 1979-2006. Nest is capital and labour.
	0.10 to 0.74		Dissou, Karnizova and Sun (2015), 10 Canadian industries, 1962-1997
Nest of capital and human capital versus land resources		1.14	Markandya and Pedroso-Galinato (2007), cross-country estimates using national data from 67 countries.
Capital and agricultural inputs	-0.82		Parks (1971) Swedish Manufacturing, 1870-1950
Labour and agricultural inputs	0.90		Parks (1971), Swedish Manufacturing, 1870-1950

Source: [a] As calculated by Kang and Brown (1981). [b] This elasticity is our own calculation. [c] As reported by Thompson and Taylor (1995). [d] As calculated by Markandya and Pedroso-Galinato (2007). [e] This range includes point estimates and 95% bootstrapped confidence intervals.

2.2 Substantial limitations of existing empirical estimates

However, substitutability estimates from Table 1 should be interpreted with caution. First, studies are not fully comparable since they cover different geographical areas or sectors, and the question of substitutability may depend both on the technologies used in production as well as on the sector. Also, the scale of analysis has an impact on substitutability, as found in Oberfield and Raval (2014). The substitution of inputs may be low at the plant level, where production technologies are fixed determined, but could increase at a sectoral level, as soon as we allow for changes in the composition of production from different plants. Let us take the case of electricity production, which is usually obtained from a mix of fossil fuels and renewable energies. Whereas coal-fired power plants may not substitute coal for any other resource to produce electricity without huge investment, the electricity sector *as a whole* can substitute away from coal use and into renewables. At 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.

Another concern is that, even when inputs are substitutable, switching from natural resources towards using of more labour or more efficient machines may not constitute the most profitable choice for manufacturers. Therefore, what consequences high substitutability should have for economic policies is ambiguous. First, increasing the stringency of regulation or the price of natural resources may not automatically lead manufacturers to substitute them for capital or labour. In particular, several studies have shown that, once a new environmental regulation comes into force, polluting industries may experience a reduction in exports and be confronted with an increase in imports from foreign plants (Aldy and Pizer, 2015; Levinsohn and Taylor, 2008; Ederington et al., 2005). This “leakage” phenomenon implies that regulation may not achieve its environmental goals because firms may relocate in areas with lower environmental regulation. Using longitudinal data on the outward FDI flows of German manufacturing industries, Wagner and Timmins (2009) find evidence of such an effect in the chemical industry. For the US, Kellenberg (2009) 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 destination countries. Kahn and Mansur (2013) use county-level US data and observe that energy-intensive industries concentrate in low electricity price counties, while labour-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.

Second, economic policies that are informed by substitutability and sustainability must depend on social costs of input use. Even in situations for which substitutability is low, decision-makers may aim to constrain production because the environmental and other social gains from substitution could be extremely high, e.g. in the case of a particularly polluting substance (e.g. mercury).

However, the main limitation of the existing estimates is methodological. We reviewed how methods employed in the studies from Table 1 hold up to standard econometric criticisms.[6] We provide information on the methods employed in each study in Appendix A and summarise the conclusions of our assessment in Table 2.

There at least nine reasons to believe that most estimates of Table 1 are not robust.

First, the majority of studies are based on either national-level or sector-level data (see Table 2, column 1). Aggregate data at national (Table 2, item A) or sector level (item B) is problematic because of *aggregation bias*: production consists of many products that have different land, resource and energy intensities. 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 (Solow, 1987). This is because changes in the composition of the goods produced will take place concomitantly to factor substitution occurring at the production level. Therefore, high substitutability would not only mean that supply adapts to changes in the price of factors, but also that there is a demand response.

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[6] A few studies reported in Table 1 are not reviewed in Table 2 (Turnovsky et al., 1982). This is because they come from a book that is no longer printed and that we could not find. The substitutability estimates could be displayed in Table 1 because they were mentioned in other studies.

Second, data aggregation creates serious *endogeneity* problems (see Table 2, column 2). Yet, most studies do not apply IV strategies and the ones that use 3SLS as an estimation method do not focus on the *exogeneity of the instruments* (item C).

Table 2: Identification of caveats in the studies reviewed

Authors	Publication year	Aggregation bias	Endogeneity issues	Specification concerns	Lack of external validity
		(1)	(2)	(3)	(4)
Parks	1971	A	D, E, F, G	H, I	J
Berndt and Wood	1975	A	C, (D), E, F, G	H, I	J
Griffin and Gregory	1976	A	D, E, F, G	H	J
Berndt and Khaled	1979	A	D, E, F	H	J
Pindyck	1979	A	D, E, F, G	H	J
Moroney and Trapani	1981	B	D, E, F, G	H, I	J, L
Walton	1981	B	C, (D), E, F, G	H	J
Turnovsky et al.	1982	A	D, E, F	H, I	J
Prywes	1986	(B)	(D), F	H	(J), K
Nguyen and Reznek	1993		E, F, G	(H)	K
Chang	1994	A	D, F, G	H, I	J, L
Kemfert	1998	A, B	D, E, F, G	H, I	
Nguyen and Streitwieser	1999		E, F, G	(H)	K
Markandya and Pedroso-Galinato	2007	A	D, E, F, G	H	K
Gervais et al.	2008	B	D, E, F, G	H	K, L
Dissou and Ghazal	2010		F		L
Sue et al.	2012	A	D, E, F, G	H, I	
Dissou, Karnizova and Sun	2015		E, F	H, I	

A: National-level data. B: Sector-level data. C: 3SLS but instruments may not meet exogeneity requirement. D: Unresolved input-output simultaneity. E: Risk of omitted variables. F: Measurement errors (not dealt). G: Input-neutral technical change. H: One (restrictive) functional form. I: Constant elasticities over long period. J: Data period before the energy crisis of 1973. K: Narrow time-period. L: Specific sector analysed. Anderson (1981), Denny et al. (1981) and Manne and Richels (1992) are not included in this table since we could not access them, even though the substitutability estimates were reported in other studies and, therefore, could be reported in Table 1.

Third, the endogeneity problem manifests itself in *the simultaneous determination of inputs and output* (item D). 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 analysed. The cost of natural resource extraction depends on the quantity that is being extracted in response to the demand formulated by manufacturers. Therefore, the price of natural resources is a function of expected output at national- or industry-level. Feedback effects are likely to be large at macroeconomic level and bias the estimates.

Fourth, any econometric exercise suffers from *omitted variable bias* (item E) whenever a key parameter is not included in the analysis. The risk of omitted variable bias is extremely high for any study that relies on broad aggregates. We identified a few studies that rely on cross-sectional variations caused by differences across countries (Pindyck, 1979; Prywes, 1986; Markandya and Pedroso-Galinato, 2007). They may present a strong bias since the units being compared are substantially different. Factors that are not accounted for in the econometric estimation could lead to biased estimates, e.g. the fact that U.S. and E.U. regulations are different and frame production choices. The risk of omitted variable bias is also very high in cross-sectional settings that rely on smaller units of observations (Nguyen and Reznek, 1993; Nguyen and Streitwieser, 1999) due to the strong assumption of comparability of units. Panel data setting that rely on national (e.g. Turnovsky et al., 1982; Chang, 1994; Sue et al., 2012) or regional (Walton, 1981; Gervais et al., 2008) aggregates are also likely to suffer from omitted variable bias, since many concomitant factors may explain year-to-year changes in output value. Risks can be mitigated with either IV strategies or panels relying on smaller units of observations, e.g. plants (as in Dissou and Ghazal, 2010 or Dissou, Karnizova and Sun, 2015). However, moving to smaller units and panel data is not sufficient if important variables are omitted in the estimation because of data limitations. Dissou, Karnizova and Sun (2015) estimate substitutability between capital, labour and energy, but omit materials in their estimation. This is likely to lead to biased estimates since energy use may be strongly correlated with material use (in particular in material- and energy-intensive sectors such as mineral transformation). Kemfert (1998) and Sue et al. (2012) faced the same problem while Moroney and Trapani (1981) and Nguyen and Reznek (1993) estimated substitutability between capital, labour and natural resources but did not include energy in their analysis.

Fifth, no reviewed study seemed to properly deal with *measurement error*. Nguyen and Reznek (1993), Nguyen and Streitwieser (1999), Dissou and Ghazal (2010) and Dissou, Karnizova and Sun (2015) use firm-level data and are therefore not impaired by aggregation bias. However, they are more likely to suffer from measurement error due to misreporting. These studies do not handle the pervasive risk of measurement error in output or in input values. When measurement error is on the dependent variable, estimates may lose efficiency and a relevant robustness check would be to look at alternative metrics. When measurement error is on the independent variables, not accounting for it may lead to an attenuation bias of the econometric estimates. Alternative metrics could be used if this endogeneity concern cannot be dealt with instrumental variables.

Sixth, several studies mentioned in Tables 1 often assume that *technical change is input-neutral* (item G). This assumption is unlikely to hold. Non-input neutral technical change may produce strong biases in estimated parameters (Griliches, 1967). For example, a country may have invested in technologies that increase the productivity of one input (e.g. capital for capital-rich economies). These technologies will encourage the use of an even larger share of this input in this county, making it non-comparable to other countries. This is likely to bias any estimate because input-biased technology adoption may be correlated with local input prices. What comes from non-neutral technological change could be misinterpreted as caused by the level of input prices in the present example. A way to partially deal with this could be to insert input-specific technological trends (e.g. as in Dissou, Karnizova and Sun, 2015).

Seventh, studies rely on specific functional forms to estimate elasticity parameters (see Table 2, column 3) (item H). Earlier studies usually relied on translog functions. Monte Carlo simulations found that the translog approximations of production functions were often not locally displaying the regularity conditions corresponding to utility maximization or cost minimization processes, especially when the Allen elasticities of substitutions moved away from unity (Wales, 1977; Guilkey and Lovell, 1980; Guilkey et al., 1983; Despotakis, 1986; and Kittelsen, 1989). This casted doubt on the ability of this flexible form to approximate the true production function. While this encouraged scholars to use CES functions, these might be too restrictive. Prywes (1986), Chang (1994), Kemfert (1998), Markandya and Pedroso-Galinato (2007) and Dissou, Karnizova and Sun (2015) use CES functions and do not check if changing the functional form leads to different results. A better practice would consist in reporting the results obtained with several functional forms, as done in Dissou and Ghazal (2010). Studies using a translog function could check that the underlying concavity assumptions are respected (Nguyen and Streitwieser, 1999).

Eighth, most studies also rely on long panels (see Table 1 for panel size). Since elasticities of substitution are dependent on production techniques, it is likely that they might change over time. Hence, assuming a constant elasticity of substitution over a long panel may *average out significant differences across time* (item I). In the above-mentioned studies, Dissou and Ghazal (2010) report changes in elasticity estimates over a 44-year window period. They report up to a tripling of Morishima elasticities between the 60s and the early 2000s.

Ninth, Dissou and Ghazal (2010) 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* (item J), since the economic circumstances radically changed after that point. More generally, it also implies that studies that rely on limited periods or snapshots (Prywes, 1986; Nguyen and Streitwieser, 1999; Markandya and Pedroso-Galinato, 2007; Gervais et al., 2008) might lack *external validity* (item K). This is true likewise or *a fortiori* for studies that may only observe situations with little variation in either output, inputs or input prices. Finally, a few studies are limited in the external validity of findings since they focus on a specific sector (Moroney and

Trapani, 1981; Nguyen and Reznek, 1993; Gervais et al. 2008; Dissou and Ghazal, 2010) or a small country (i.e. Taiwan for Chang, 1994) (item L).

In summary, even the most recent estimates are not often using the most up-to-date econometric methods. As a result, they fail to address many identification concerns. Estimating substitutability is difficult and there is a need for applying or developing new methods.

Our assessment indicates that the results from Dissou and Ghazal (2010) seem to be the most robust among the papers we have reviewed. Dissou and Ghazal (2010) conclude that capital, labour, 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 and Ghazal (2010) are not high enough to suggest that these two industries could adapt easily to high increases in energy prices.

While other studies looking at substitutability between different inputs seem to suffer from several biases, one study, not reported in Tables 1–2, looks at substitutability between two forms of energy, clean and dirty, with robust econometric methods.[7] Papageorgiou, Saam and Schulte (2017) use new sectoral data for the electricity-generating sector and for the non-energy industries in a panel of 26 countries for the years 1995-2009 and estimate nested CES specifications using nonlinear least squares. These authors furthermore 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. The conclusion of Papageorgiou, Saam and Schulte (2017) is 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).

In recent year, new methods to analyse labour-to-capital substitutability have been developed and applied by Chirinko, Fazzari and Meyer (2011), De Loecker and Warzynski (2012), Karabarbounis and Neiman (2014) and Oberfield and Raval (2014). All these methods model the firms' cost-minimising behaviour to derive estimable equations for substitutability.[8]

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[7] It is not included in Tables 1–2 because these authors do not look at substitutability between natural capital and other forms of capital, but at substitutability between two forms of energy.

[8] The methods by Chirinko, Fazzari and Meyer (2011), De Loecker and Warzynski (2012) and Oberfield and Raval (2014) rely on firm level data. Chirinko, Fazzari and Meyer (2011) exploit long-run panel variations to transform the firm's dynamic cost-minimisation problem into a static problem. To determine the firm's demand

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 that these authors heavily rely on the fact that labour 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.

3.3 Additional theoretical caveats

While we have focused on econometric caveats, at least four theoretical reasons may further limit the usefulness of econometric estimates.

First, substitutability estimates cannot be expanded to all forms of natural capital. Due to data constraints, econometric studies have traditionally focused on materials and energy. In addition, in order to accurately calculate estimates of substitutability econometric estimates usually need to assume that prices correctly reflect the scarcity of inputs. Unfortunately, this assumption is typically false for many types of natural capital. This is because property rights over much of natural capital – such as the atmosphere, oceans, and biodiversity – are not well established (Hardin, 1968). Therefore, the scarcity of natural capital is not reflected in its market prices which are too low from the society point of view (often they are zero) and encourage overexploitation. Therefore, firms observed to take decisions about natural capital inputs do not face appropriate prices and use too much natural capital. It is therefore rare to observe firms facing serious scarcity of natural capital and hence it is hard to correctly estimate substitutability across the entire range of natural capital quantity.

Second, even small changes in natural capital can lead to non-marginal impacts because of *tipping points* (Lenton et al., 2008; Lenton, 2011). Some natural capital is *critical* to the functioning of entire ecosystems (Chiesura and De Groot, 2003; Ekins et al., 2003). Hence, a small increase in the use of one natural capital input (e.g. clean water) has led to drastic, non-

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for capital and substitutability to labour, they calculate the marginal product of capital evaluated at the long-run levels of inputs and output. De Loecker and Warzynski (2012) suggest moment conditions that allow estimating firm mark-ups and capital-labour substitutability while making very little assumptions on the functional form of the production function. They furthermore overcome simultaneity problems by using materials usage (denoted m) to proxy productivity increases (denoted w) at firm level, under the assumption that dm/dw>0, i.e. that more productive firms increase material usage (e.g. to sell more units). Oberfield and Raval (2014) develop a framework to estimate aggregate capital-labour elasticity of substitution by aggregating the actions of individual plants. By allowing for reallocations across plants, they are able to distinguish between plant-level, industry-level and manufacturing-level substitutability. They apply this framework on microdata from the US Census of Manufactures. The originality of the method by Karabarbounis and Neiman (2014) is that it applies to aggregate data and relies on cross-sectional variation. These authors construct an economy-wide model to study the interactions between households and the demand and supply for intermediate and final goods. They make the assumption of CES production functions. From this model, Karabarbounis and Neiman (2014) derive consistent and easily estimable equations for the elasticity of substitution between capital and labour.

marginal changes in the availability of other factors (e.g. fish stocks) and to subsequent irreversible reductions in output. Near tipping points, we would therefore expect much less complementarity than away from the tipping points. If firms and sectors are not aware of the tipping points, they might well appear to act in much less prudent ways and treat natural capital as more substitutable. Hence, marginal analysis is only suitable in the absence of tipping points, which can be a very restricted assumption.

Third, as we explained earlier, the elasticity of substitution can vary dramatically across scale (or space), time, and available technologies. Substitutability also needs to be specified over a particular time period. Substitution is difficult on a short time scale because new technologies develop and diffuse slowly. Entrepreneurs need to expect scarcity of natural capital inputs over the long term in order to have an incentive to invest in new research and development. However, over longer periods, we might expect firms and sectors to be much more substitutable production functions 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 function. Once a fish species is extinct, one is no longer in a position to decide how much of that fish can be substituted with breadcrumbs in a fishcake.

Fourth, it is widely assumed that technological change will provide greater substitutability of natural capital for physical capital (e.g. Pacala and Socolow, 2004). For example, a more efficient use of many natural resources, such as fossil fuels and land, means that we are much less dependent on them to produce a single unit of output. However, a lot of 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, while batteries require lithium. Therefore, what might look like 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.

3. Two empirical case studies

The analysis in the previous section has shown that we lack robust estimates of the substitutability between natural capital and other inputs to production in most circumstances. Yet, the question of knowing whether natural capital is a strong or a weak substitute to other factors of production is essential since it largely determines the possibility of sustainable development.

Even if we are not able to come up with a unique set of substitutability estimation, we can 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 to other inputs. In general, these studies consider *efficiency* rather than substitutability. Increasing demand for products may completely cancel out efficiency gains: this is the 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 mentioned hereafter, authors analyse 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. On the opposite, 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 case studies: energy use in industry and land use in agriculture. We chose the first case study because climate change mitigation urgently requires that fossil fuels be consumed with parsimony. Looking at industry is important because it is a large consumer of energy (29% of all the energy used in the world, IEA, 2016). It is also insightful in the present case because industrial agents are more likely to rationally assess all available options and pick out the most profitable ones. This can directly inform us about the substitutability, abstracting away from consumer miscalculations and inattention to energy costs. The second case study on land allows us to focus on a renewable resource. We know that land will be under stress because world population is growing steadily and the demand for food will surge in the coming decades.

In this section, we focus exclusively on the supply side and aim to assess whether existing and future production processes could easily permit the substitution of natural capital with other forms of capital. We therefore ignore many other means of reducing the environmental footprint of human economic activities, such as changes in consumption patterns. In addition, the case study on energy does not look at the environmental impact of energy production, i.e. the possibility to sustain energy demand while producing energy with cleaner sources.

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 is the 2nd largest industrial consumer in the world; pulp and paper ranks 5th) (US Energy Information Administration, 2017) and/or use very energy-intensive processes (cement is the most energy intensive sector per ton of output produced) (IEA, 2013). Second, they produce homogenous goods with fairly homogeneous production processes, making the analysis of energy efficiency measures easier to track.[9] 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. (1997) compare production growth to energy consumption growth in eight OECD countries[10] between 1973 and 1991. They find average energy efficiency gains of around 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 UK and Australia in their sample). The potential for energy efficiency gains seems logically higher in energy-inefficient countries. Peng et al. (2015) show that the specific energy consumption of paper and paperboard production declined from 36.6Gj/t in 1985 to 11.4Gj/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. (2000) 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 show that there is an energy savings potential of around 16% if all the cost effective measures available to industrials to reduce energy use were implemented. On the other hand, they estimate 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. (2012) produced the same kind of techno-economic analysis for the case of Germany. They find that improvements in energy efficiency

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

[10] These are the US, Japan, Germany, France, the UK, the Netherlands, Sweden and Australia.

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.[11] Fleiter et al. (2012) also review the potential for the 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. (2001) 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 analysing 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 US seem to be in between the low potential in Europe and the high potential recorded in China.

Using European data, Pardo and Moya (2013) 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). On the other hand, 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 GHG emissions reductions. Nonetheless, Johansson and Söderström (2011) suggest that there is good potential for reducing GHG emissions, though not energy use, if alternative sources of energy or if heat generated by iron and steel plants are being better used. While looking at the case of two Swedish plants, they find high GHG emissions reduction potential if biomass, instead of traditional fossil fuels, were 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.

Like in the paper and pulp industry, the potential of substitutability in the iron and steel industry may be greater in emerging countries. Price et al. (2012) show that energy consumption per ton of steel produced has drastically decreased in China, from 920KgCE/t in 2000 to 630KgCE/t in 2008 (-31%). During this time, energy conservation technologies adopted in China included coke dry quenching; top-pressure recovery turbines; recycling converter gas; recycling waste

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

heat from converter steam; continuous casting; slab hot charging and hot delivery; coal moisture control; and recycling waste heat from sintering. Price et al. (2012) hence explain that the penetration level of energy-conservation technologies in the steel industry has improved greatly in China. There results align and complement the ones of Wei et al. (2007), 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. (2000) notice that the primary physical energy intensity for cement production dropped 30% in the US 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. (2010) survey 16 cement plants with new suspension preheater and pre-calciner 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. (2013) 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 90s, Liu et al. (1995) 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 around 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, one should be careful that 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 (Thollander and Ottosson, 2008). On the other hand, 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 physical capital or intellectual capital in the reviewed sectors. Between 1973 and 2014, energy demand from industry has increased by 79%. This is equivalent to an average 1.3% annual increase (IEA, 2016).[12] 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 are in a situation of low to moderate substitutability at plant level. This globally aligns with the more general conclusion of the US Energy Information Administration (2017), which predicts that world energy demand will rise by 48% between 2012 and 2040.

4.2 Land use in agriculture

In the coming decades, world agriculture will face several major challenges. First, evidence suggests that in order to match increasing food demand due to population growth, changes in diet, and the need to end hunger and malnutrition, food production will have to increase by 70% to 110% by 2040 (World Bank, 2008; Royal Society, 2009; Tilman et al., 2011). Second, the need to increase production will put higher stress on the environment. Agriculture already constitutes the human activity representing the greatest threat to biodiversity (BirdLife International, 2000; Green et al., 2005; U.K. Government Office of Science, 2011) 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 land use would be responsible for 24% of global GHG emissions (Smith et al., 2014). Agriculture alone represents around 10-12% of global GHG emissions (Smith et al., 2007; Smith et al., 2014). The other main contributor to GHG emissions would be the conversion of forests to cropland. Estimates of GHG emissions released because of deforestation vary but deforestation could represent around 15% of GHG emissions worldwide (Van Der Werf, 2009; IPCC, 2014). 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

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

from agriculture in developing countries. In 2010, some 900 million of the estimated 1.2 billion extremely poor lived in rural areas. About 750 million of them worked in agriculture, usually as smallholder family farmers (Olinto et al., 2013).

With current technologies and expected technological progress, there is global consensus that increasing food production to required levels is possible (Tilman et al., 2002), in particular because more land could be dedicated to agriculture through deforestation, more water could be pumped from the underground, more fertilisers could be disseminated on areas that currently convey low yields. The question is whether the increase food production can be done in a environmentally and economically sustainable way.

In this context, scientists have argued that boosting crop yields to meet rising demand, instead of clearing more land for agriculture, would constitute the most sustainable way to address the challenge of feeding nine billion people (e.g. Ewers et al., 2009; Tilman et al., 2002 and 2011; Ray et al., 2013). For the advocates of "land sparing", the main question is to know 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, labour) or develop the intellectual capital necessary to do so (e.g. genetic engineering).

Over the past 40 years, drastic improvements in crop yields of around 2-3% per year have been obtained, through greater inputs of fertilizer, water and pesticides, new crop strains and mechanisation (Waggoner, 1995; Matson et al., 1997; Goklany, 1998; Tilman et al. 2002; Balmford et al., 2005; Green et al., 2005). This has been observed concomitant to the development of options to harvest twice a year (or even three times a year) on the same plot of land. This unprecedented increase in agricultural productivity is often referred to as the "green revolution". As a result, cereal production per hectare has more than doubled since 1960 (Waggoner, 1995). Without these large efficiency gains, the pace of land conversion to produce an equivalent amount of food would have had to be massive (e.g. Ewers et al, 2009).

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, Green and Scharlemann (2005) predict that, in developing countries, meeting food demand should require a 23% extension of cropland assuming a moderate annual increase in yields.[13] In a high yield scenario, they find

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[13] The medium yields scenario assumes an improvement of 170,000 kcal per hectare per year on average for 23 crops, representing a 1.5% increase for the first year of their simulation, in 2001. Since the trend is linear, the percent increase progressively reduces. It corresponds to a 0.8% increase in 2050.

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. Yet, the evidence suggests that we might not be in the fortunate "high yield" scenario of Balmford, Green and Scharlemann (2005). Ray et al. (2013) find that current yield increases are not sufficient to sustain a doubling of food production. They estimate that global average rates of yield increase across13,500 political units are 1.6%, 1.3%, 1.0%, 0.9%, and per year for maize, soybean, rice, and wheat, respectively. On the opposite, they evaluate that a 2.4% per year rate of yield gains would be needed to double crop production by 2050.

What if the figures of Ray et al. (2013) can be enhanced through deliberate endeavour 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 limitation to any further increase in yields is that the "green revolution" of the past 40 years has mostly been possible thanks to a closing of "yield gaps", the difference between the genetic potential of plants to grow fast on a plot of land, and the realised outcome observed in farms, which is constrained by the availability of water, the use of fertilisers, pest control, and resistance to bad weather. In this spirit, Tilman et al. (2002) notice 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 around 45% of phosphorus fertilizer is taken up by crops. Likewise, the potential for increasing irrigation seems limited by water availability in many regions. While 40% of crop production comes from the 16% of agricultural land that is irrigated (Gleick, 1993; Postel et al. 1996), the rate of the increase in irrigated lands is decreasing and new dam constructions over the next 30 years may only allow for a 10% increase in water for irrigation (Dynesius and Nilsson, 1994; Postel et al. 1996). 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) (Seckler et al., 1999). The overpumping of groundwater is a serious concern in major water basins in the US, China, India, Pakistan and the Middle East (Famiglietti, 2014). On the other side, the external effects of intense agriculture and poorly managed land have contributed to a wide-spread degradation of soil quality. Since 1945, Oldeman (1994) estimated that 17% of soils had undergone 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, since droughts and floods may become more frequent, along with excessively hot days, which are usually associated with heavy production losses (Schlenker and Roberts, 2009; Lobell et al. 2011).

Making a similar appraisal, Cassman et al. (1999) already argued that achieving higher and higher yields will require constant improvements in soil quality and precise management of all production factors. While the potential to increase the genetic yield potential of plant appears to be limited, these authors thought that only major breakthroughs in plant physiology, ecophysiology, agroecology, and soil science could possibly deliver the 2.5% annual increase in yields necessary to meet expected food demand by 2050 without converting more land.

However, the potential of developing countries to supply agricultural products is still largely underexploited: many countries have crops that deliver very low yields, in particular in Sub-Saharan Africa. Mueller et al. (2012) show that the closing of yield gaps mostly occurred in the US, Western Europe, Argentina, Brazil and some regions of China and India. For the rest, these authors show that fertilisation and insufficient water provision have substantially undermined any effort to achieve high yields.[14] Closing the yield gap for maize in Sub-Saharan Africa would be possible by focusing first on nutrient deficiencies. In addition, many reasons that explain low yields are to be found outside agricultural systems and include lack of political stability or lack of infrastructure connecting crops to cities and ports (Godfray et al., 2010).

At the end of the day, the greatest challenges for agriculture in the next 30 years will be in developing countries. They are also the ones with the greatest potential to achieve them since yield gaps are wide. Hence, solutions to increase yields will need to tailor to their needs and specific contexts. In this direction, Pretty et al. (2006) suggest that resource-conserving agriculture will increase yields in developing countries. In Africa, the path taken towards the intensification of agriculture as experienced in the US and Western Europe over the past 40 years may not be adapted. It is both resource-intensive (in particular in water) and capital-intensive: it relies on machines rather than human labour which is abundant in developing countries. A fast mechanisation of agriculture as it has been implemented in high-income countries could have dramatic consequences for the families that currently live on subsistence agriculture.

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[14] Eastern Europe faces nutrient limitations for maize and wheat. West Africa also faces strong nutrient limitations for maize. In East Africa and Western India for maize; the US Great Plains and the Mediterranean basin for wheat; and in Southern Asia for rice, crop productivity has been inhibited by both insufficient water and fertiliser provision (Mueller et al., 2012).

Finally, while we can hope that a higher intensification of agriculture on the land that is already dedicated to it may lead to strong benefits in terms of food security, it could still come at the cost of unsustainable water use and overuse of fertilisers, with large impacts on biodiversity. Impacts may not only be on-site, but could also spread to nearby areas, e.g. through water contamination. The evaluation of the future negative impacts of higher intensification are hard to evaluate and may in fact be very heterogeneous according to the region and the management practices implemented to increase yields contamination (see Ewers et al., 2009, for a review of the critics to land sparing). To improve sustainability, "land sharing" consists in adopting production practices that are more respectful of the environment and therefore do not affect biodiversity in cultivated fields. Because it adds a constraint on how agricultural land has to be used, land sharing reduces yields (e.g. Hodgson et al., 2010; Phalan et al., 2011). Yet, it may be an essential part of sustainability since unreasonable intensification could cause strong negative environmental damages. Also, because interactions between cultivated and non-cultivated land are complex, intensification may come at high cost if it leads to strong environmental degradation or the development of new pests. Choosing between intensification or sustainable land management practices (with lower yields when there is a trade-off) may be highly 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 (Phalan et al., 2011). 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 (Hodgson et al., 2010). It may also pose strong ethics issues, e.g. for the welfare for domesticated animals (Garnett et al., 2013).

In summary, the stress put on land use by future demand for agricultural products is very high. Because yield gaps have been closing in the US, Western Europe and some parts of Asia and Latin America, further increases in yields may prove to be costly in the already well irrigated and intensively fertilised spots of 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 either low economic or environmental cost. In developed countries, our appraisal is that substitutability of land to other inputs of production, including R&D, is rather low. However, this is not where the main problem actually lies. Socioeconomic projections show that the real constraint on land use would occur in the developing world where yield gaps are still large and investments in infrastructure and access to fertilisers may considerably increase yields. Agricultural land management in developing countries is the priority for a sustainable agriculture that would feed 8 to 10 billion people. Therefore, the challenge of fashioning sustainable agriculture is a component of a greater challenge: the fair and sustainable economic development of the least developed and the lower middle-income countries.

5. Conclusion

Any estimates of substitutability of natural capital must be treated with great caution. In particular, market prices for different types of natural capital are either absent or incorrect, biasing any estimate. Second, data on many relevant types of natural capital are absent. Third, the estimates of substitutability apply only to marginal changes and therefore be uninformative for the real policy debates at hand, such as climate change mitigation or food security. Finally, econometric methods able to deal with all the statistical difficulties pervasive to the analysis of substitutability are yet to be applied on an economy with more than two inputs.

In the last section of this literature review, we looked at substitutability from a second-best approach. We gathered scientific data on two sectors, focusing on energy and land use. The overall conclusion of the empirical case studies was that substitutability seems low to moderate. Even though science and technology may yet push the technical frontier and allow for strong efficiency gains, this progress does not seem to be enough to free national economies from the constraints of the global carbon budget and the limited availability of land and water. If our economies were to exclusively rely on efficiency gains to ensure sustainability in agriculture and energy management, we would need to harbour hope for unpredictable, major, scientific breakthroughs. If substitution in production is low or moderate, as our case studies suggest, sustainable development is unlikely to be achieved within the next 30 years unless demand-side initiatives go along with efficiency gains on the supply side. It seems quite inevitable that our consumption patterns will have to change if we are to prosper in the distant future.

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Appendix A: Additional information on reviewed econometric studies

Table A.1: Summary of methods found in reviewed econometric studies

Authors and publication year	Panel data analysis	Cross-sectional analysis	Pooled cross-sectional time series	Econometric estimation method (s)	Functional form (s)	Allen and/or Morishima
Berndt and Khaled (1979)	X			Maximum likelihood	Generalized Box-Cox function	Allen
Berndt and Wood (1975)	X			Iterative three-stage least squares	Translog cost function	Allen
Chang (1994)	X			Indirect estimation of CES	Multi-level CES production function	Allen
Dissou and Ghazal (2010)	X			Linear and non linear iterative Zellner method	Translog and Symmetric Generalized McFadden cost functions	Morishima
Dissou, Karnizova and Sun (2015)	X			Non-linear seemingly unrelated regression method	Nested CES production function	Allen
Gervais et al. (2008)	X			Maximum likelihood	Translog cost function	Morishima
Griffen and Gregory (1976)			X	Iterative Zellner method	Translog cost function	Allen
Kemfert (1998)	X			Non linear estimation	Nested CES production function	Not in study[a]
Lazkano and Pham (2016)	X			Non linear least square	Variable elasticity of substitution production function	Not reported
Markandya and Pedroso-Galinato (2007)		X		Non linear estimation	Nested CES production function	Morishima
Moroney and Trapani (1981)	X			Iterative Zellner method	Translog cost function	Allen
Nguyen and Reznek (1993)		X		Zellner's seemingly unrelated regression method	Translog production function	Allen and Morishima
Nguyen and Streitwieser (1999)		X		Iterative Zellner method	Translog production function	Allen and Morishima
Papageorgiou, Saam and Schulte (2017)	X			Non linear estimation	Nested CES production function	Morishima
Parks (1971)	X			Zellner's seemingly unrelated regression method	Generalized Leontief function	Allen
Pindyck (1979)			X	Iterative Zellner estimation	Translog cost function	Allen
Prywes (1986)			X	Not known	Nested CES production function	Allen
Sue et al. (2012)	X			Linear estimation based on Kmenta approximation	Nested CES production function	Allen
Turnovsky et al. (1982)	X			Full information maximum likelihood	Translog cost function	Allen
Walton (1981)	X			Iterative three-stage least squares	Translog cost function	Allen

a: substitution elasticities are displayed in the study and Morishima elasticities can be calculated from displayed estimates.