Economic and environmental implications of a target for bioplastics consumption: A CGE analysis

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Abstract

Bioplastic production is a small but fast growing sector in the Bioeconomy despite the so far limited policy support. We simulate the expansion of bioplastic supply towards a 5% target relative to current total plastic consumption in leading producing regions. We introduce *fossil-based plastics* and *bioplastics* in the GTAP 9 database, coupled to greenhouse gas (GHG) indicators; then simulate two policy scenarios, where scenario 1 subsidizes bioplastics consumption, while scenario 2 increases taxes on fossil plastics. Both alternatives promote bioplastic production, with subsequent price effects due to the increase in demand for starch- and sugar-based feedstocks at global scale. The tax in scenario 2 makes plastics as an aggregate more expensive, leading to a contraction of all sectors that employ plastics either directly or indirectly. Global real GDP stays almost constant in scenario 1, but drops by -0.07% in scenario 2, implying greater distortions by differentiated taxation of a larger sector.

Our study is the first to quantify emissions from indirect Land Use Change (iLUC) due to growing bioplastics demand. Given the current production technologies relying on food crops, the target triggers cropland expansion and increased GHG emissions globally. The latter increase by +1.44% in scenario 1 and by +2.07% in scenario 2, where a greater loss of carbon stocks from managed forest areas is observed, due to the lower wood demand for energy and material uses in other sectors. The cost-effectiveness of the bioplastic target is calculated at -14.53 and -61.59 US$ per t CO_2-eq. for scenarios 1 and 2, respectively. We show that CGE models are useful to analyze economic and environmental impacts of Bioeconomy transformations and more generally the food-fuel-fiber debate. Future bioplastic strategies should focus on biodegradability rather than on the biological origin of the feedstock, in order to drive the transition to resource-efficient and low-carbon economies.

1. Introduction

Plastics are highly demanded by many economic sectors across the economy due to their versatility and durability, together with relatively low production costs. Conventional plastics are mostly based on heavy crude oil such that their production is linked to fossil resource depletion and climate change. Indeed, it is estimated that 90% of plastics are produced from fossil fuel feedstock and production gives rise to approximately 400 million tonnes of greenhouse gas (GHG) emissions per year globally. Worldwide plastic production has been growing exponentially and could reach up to 1.2 billion tonnes annually in 2050, then accounting for 20% of the global oil consumption and releasing 15% of the annual CO_2 emissions (EC 2017). Non-biodegradability and long durability of conventional plastics generate additional environmental problems after end-of-life as plastic debris pollutes the oceans, as well as natural terrestrial and freshwater ecosystems. Between 60% and 90% of marine debris is manufactured using one or more petroleum-based resins with a long degradation time (UNEP 2016).

The disadvantages of conventional plastic explain the growing interest for polymers produced from biomass, hereinafter called *bioplastics*, which can be either biodegradable or not. The global production capacity of bioplastics has increased from 1.5 to 1.9 million tonnes in the period 2012-2015, and is forecasted to reach 6.7 million tonnes in 2018 (Rivero et al. 2016). Still, this barely represents 1% of total production of plastics and is mostly non-biodegradable, providing mainly drop-in products such as bio-polyethylene (bio-PE) and bio-polyethylene terephthalate (bio-PET) as direct substitutes for the most common fossil-based plastics. The share of plastics that are both bio-based and biodegradable, such as polylactic acid (PLA) or polyhydroxy butarate (PHB), is however meant to increase to 2.5% of the total plastic production by 2020 (European Bioplastics 2016a; van den Oever et al. 2017), mainly for packaging. China-Korea, the United States (US), the European Union (EU) and Brazil are currently the leading bioplastic producers, with capacity increases also expected in other countries of the Asian-Pacific region (European Bioplastics 2016a). Future market developments will depend on international trade, new conversion technologies fostering feedstock diversification, and not at least policies. For instance, plastics are identified as one of the five priority areas in the "EU Action Plan for the Circular Economy" (EC 2015). This led to a first European roadmap for a Plastics Strategy (EC 2017), aimed at a) decoupling plastics production from fossil feedstock and reducing its life-cycle GHG impacts, b) improving the economics, quality and uptake of plastic recycling and reuse, and c) reducing plastic leakage into the environment. Although policy support to bioplastics has been very limited until now (OECD 2013), it is increasingly demanded by producers worldwide, who refer to the various large-scale support initiatives existing for other renewables, such as biofuel or biogas.

1.1. Food vs fuel vs material

While the main feedstocks currently used for bioplastic production differ between regions, these are essentially all conventional food crops. The so-called second generation technologies that rely on non-edible biomass, with limited competition with food production, are not yet implemented on a commercial scale (Lewandowski 2015). Although bioplastic producers claim that the biomass currently employed in all material uses employs no more than 2% of the global agricultural area (European Bioplastics 2016b), increased bioplastic production will certainly put additional pressure on limited resources such as land and water. Increasing global biomass demand for bioenergy and biomaterial purposes can only be met through agriculture intensification, land expansion, and/or a reduced availability for food and feed uses;

with all the options having negative implications in terms of food security, climate change, biodiversity and, more generally, on the environment. The extent of the impacts depends essentially on biomass conversion efficiencies, product functionalities and technical substitution rates in the industry.

Impacts of replacing fossil-based with bio-based plastic are mostly analyzed so far on a case-by-case basis by means of Life Cycle Assessment (LCA), with a focus on potential GHG savings (Groot and Borén 2010; Philp et al. 2013; Tsiropoulos et al. 2015). A comprehensive evaluation of an increased market penetration of bioplastics at global scale is so far lacking, since the existing case studies neglect economy-wide interactions, especially the associated land use change (LUC). While direct LUC refers to the direct land conversion to grow, in this case, bioplastic feedstock, indirect LUC (iLUC) refers to the successive adjustments in land use for other crops, forestry and grasslands due to price changes. Analyses of biofuels programs has shown that iLUC-induced GHG leakage may offset presumed carbon savings (Lapola et al. 2010); it should hence be considered for an accurate assessment of bioplastics. As a market-mediated effect, iLUC is frequently addressed by Computable General Equilibrium (CGE) models (Henders and Ostwald 2014; Lambin and Meyfroidt 2011), such as in the case of biofuel mandates (Banse et al. 2008; Doumax et al. 2014). When coupled to biophysical extensions, these allow for the environmental and economic impacts of supply (e.g. technological innovation) and demand (e.g. targeted policy) drivers to be simultaneously quantified, which makes them especially useful for the evaluation of bio-based transformations.

When it comes to bioplastics, CGE analysis is far from being straightforward as neither fossil- nor bio-based plastics are explicitly represented in the latest version 9 of the GTAP database (Aguiar et al. 2016) which basically underlies all global CGE studies (Timilsina et al. 2011). To the best of our knowledge, only Lee (2016) made an attempt to implement "bioplastics" as a sector in GTAP 8 (Narayanan et al. 2012), which dates back to 2007. The resulting augmented database was subsequently used to analyze economic effects from an increased bioplastic sector in key Asian countries, without considering environmental effects. Against the background of the existing literature, i.e. the work of Lee (2016) and the aforementioned LCA case-studies, our study has three main objectives: a) to quantify global economic, land use and GHG implications of bioplastic consumption targets in the leading producing regions; b) to assess economic vs. environmental trade-offs of these targets; and c) to improve both the GTAP 9 database (Aguiar et al. 2016) and the CGE model CGEBox (Britz 2017) by introducing conventional and bioplastics as additional sectors. Thus, this study strives to provide science-based evidence on the contribution of bioplastics as part of the Bioeconomy to the Sustainable Development Goals (SDGs). The main caveat is that available data prevent us from taking into account different biodegradability characteristics.

2. Methods

2.1. Data

The study utilizes the GTAP 9 database (Aguiar et al. 2016), which depicts the world economy in 2011. For the present analysis, a spatial aggregation to 35 regions has been applied, keeping full sectoral detail. However, the original 57 sectors do not explicitly capture the "conventional" fossil-based or the emerging bio-based plastic sectors; they are comprised with other sectors in the "chemical industry" aggregate. Hence, a disaggregation into three new sub-sectors was necessary, namely "fossil-based plastics", "bio-based plastics” and “rest of chemicals”. The disaggregation is carried out following the “top-down” approach proposed by Lee (2016), by means of the split utility in CGEBox (Britz 2017). To this aim, output and feedstock cost shares were calculated for the leading producing regions, namely, the US, the EU, China and Brazil. Data suggest that Brazil is focused on bio-PE, although PHB is also produced in small amounts, both from sugarcane; the EU utilizes mainly wheat for thermoplastic starch (TPS) blends; China relies on corn and other cereals for the production of both PLA and PHB, while the US mainly uses domestic corn for the same purposes. Further details are documented in the Annex.

2.2.Model setup

Our CGE analysis departs from the standard GTAP model (Hertel 1997), as implemented in CGEBox (Britz 2017). This is a global, comparative-static, multi-regional CGE model assuming competitive markets and constant returns to scale in all sectors. Drawing on neo-classical microeconomic theory, it assumes rational, fully informed decision-making by aggregate firms, factor suppliers and consumers. Bilateral trade flows are depicted by the Armington approach treating goods produced in different regions as imperfect substitutes. Depending on the given production technology and the input prices they face, firms choose the cost-minimal combination of domestic and imported intermediates and primary factors; consumers purchase goods under their budget constraints to maximize utility. The competitive market assumption implies that all agents (households, firms and government) are price-takers. After a shock, all prices and quantities adjust endogenously to clear both product and factor markets; ensuring that demand is equal to supply at global, country, and industry level. Policies are in the standard model depicted by *ad-valorem* taxes and subsidies. A so-called “regional household approach” implies that the sum of factor and direct tax income in each region is distributed to savings, government and private household consumption.

In addition to the standard GTAP model, we employ various extensions available with CGEBox, namely: GTAP-Agr (Keeney and Hertel 2005) to better represent the characteristics of the agricultural sector; GTAP-E (Burniaux and Truong 2002) to incorporate substitution between energy sources in production and to calculate CO_2 emissions from the combustion of fossil fuels; GTAP-AEZ (Lee 2005) to capture competition for land between uses at the level of agro-environmental zone (AEZ) and to quantify CO_2 emissions from LUC, when coupled to carbon stock data from Aguiar et al. (2016). Non-CO_2 emissions from consumption (e.g. fertilizers), endowment use (land and capital), and production are also quantified according to Aguiar et al. (2016). As combined, these features allow for a comprehensive evaluation of the spillover effects of increased demand for bioplastics across the economy.

A composite commodity “bioplastics and fossil-based plastics” is introduced in the CES intermediate demand structure of firms (see Fig. 1), which constitutes an improvement relative to Lee (2016). This nest captures if and how easily firms can switch between the two types of plastics. A substitution elasticity of 15 is initially introduced, representing an optimistic assumption compared to that of Nowicki et al. (2010). It must be born in mind that Nowicki et al. 2016 focused on PLA, with a lower substitution potential than drop-ins such as Bio-PE, also covered in our analysis. The influence of this parameter on the environmental and economic outcomes will be further discussed in section 4.

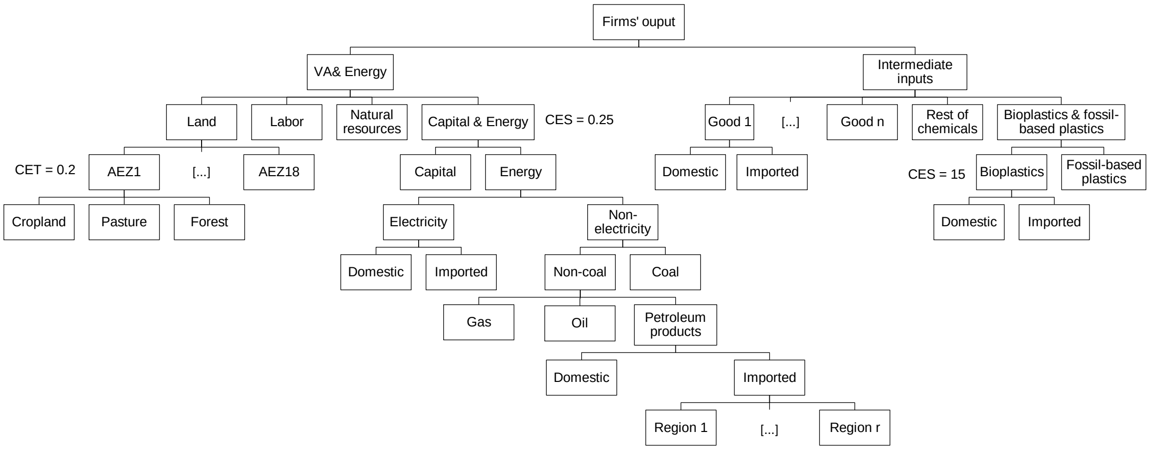

Figure 1. Improved nested production structure based on GTAP standard plus extensions.

2.3.Scenarios

Both experiments implement a 5% target for bioplastic consumption in the aforementioned major producing regions simultaneously, relative to overall plastic demand at the benchmark. Our assumed target reflects the current state of technology (Morone et al. 2017), although is conservative compared to other studies that point to substitution potentials between 10-50% in 2050 (Schipfer et al. 2017). Specifically, the aggregated Armington bioplastic demand for all uses (firms, government, households and investment) is fixed to the target such these uses can and will show different expansion rates. The target is enforced by subsidies to bio-based plastic consumption (scenario 1) or by taxes to fossil-based plastics (scenario 2), which endogenously adjust. These endogenous economic (dis-)incentives driving the model to the desired market penetration of bioplastics could be understood e.g. as specific sales-tax or value-added tax rates for plastics. Note that the regional household approach in combination with standard closures implies changes in total tax income and government consumption, both in values and quantities as a consequence of the adjusting tax rates.

3. Results

The target drives up bioplastic consumption exogenously in both scenarios, such that production has to adjust. The subsidy to bioplastic consumption in scenario 1 lowers the average consumer price of all type of plastics, hence promoting aggregate plastic consumption in the four regions considered; as a consequence, world plastic demand increases by +0.50%. The tax on conventional plastics in scenario 2 has the opposite effect: it pushes up the average plastic price for consumers such that the world plastic market shrinks by -6.31%. Further responses can be explained by firstly analyzing the *immediate effect* of the target, which expands the bioplastic market segment, and secondly, by the *side effects* due the contraction of the fossil-plastic market segment. *Immediate effects* trigger increased demand for feedstock used in bioplastic production worldwide, with the associated spillover effects in terms of food prices, LUC and derived emissions, same as observed for biofuel mandates. *Side effects* emanating from changes in the conventional plastic segment trigger responses across all the sectors in which plastics are employed; with greater environmental implications mainly through energy markets, since conventional plastics do not only use fossil feedstocks, but are also energy intensive.

Note that taxing conventional plastics in scenario 2 reduces the competitiveness in production of the focus regions, relative to the rest of the world, leading to leakage effects into other regions which expand their fossil-plastic production. However, global output of plastic production decreases by -9.26%, as the tax reduces the use of plastics across the economy as a "non-environmentally-friendly" input and affects with the US, China, the EU and Brazil a larger of the global economy directly. This leads to quite strong *side effects* in scenario 2, since plastics are ubiquitous in many sectors; *side effects* are of minor importance in scenario 1, where the fossil-based part of the economy remains largely untouched. The tax scenario 2 drives down oil prices (-0.08%) and oil demand (-0.22%) compared to scenario 1, where oil prices (-0.05%) and especially demand (-0.01%) are almost stable. The combination of the immediate and *side effects* generates a global real GDP reduction of -0.07% in the tax scenario 2, while it is hardly affected (-0.01%) in scenario 1. In both cases, the greatest GDP loses are observed for China and the EU, where the plastic sector represents a larger share of the economy. We next present key market effects: changes in production and demand of both bio- and fossil-based plastics and related prices; and ultimately GDP. The market effects drive environmental spillover effects, namely global LUC, including dLUC and iLUC, and GHG emissions. The reader is reminded that the analysis departs from the GTAP 9 database where all values are in constant US$ 2011, such that endogenous variables are not measured in some physical unit, in contrast to the derived environmental indicators. We therefore report for market effects mainly percentage changes.

3.1.Market effects

The target implies the same global increase in the aggregated demand for bioplastics from $3.76 billion[1] to around $56.0 billion in both scenarios (see Table 1). Note that in each region, the 5% target in consumption can be reached by either increased domestic production or increased imports. The highest absolute expansion is observed for the EU, where bioplastic consumption grows from $0.44 billion to around $23.50 billion, followed by China, where it expands from $0.31 billion to approximately $15.85 billion. Increases in the US and Brazil are still significant, but smaller in relative terms, since both countries depart from a higher share of bioplastics in the baseline. In these two countries, also the share of the plastic sector in total economic output is smaller compared to China and the EU (Fig. A1), hence the target is less ambitious. Table 1 shows that the additional enforced demand for bioplastics is mostly absorbed by intermediate use, i.e. by firms, while final demand stays rather constant. The export demand share is greater in the EU than in the other regions and increases accordingly in the two scenarios, depicting a highly export-oriented chemical sector. For further information see Fig. A2 in the Annex.

The fossil plastic market is affected by the tax in scenario 2 to a larger extent. This reflects how substitution in demand is depicted by the CES-representation: in order to reach the fixed target quantity, the tax resp. subsidy must adjust the price relation between conventional plastics and bioplastics to yield the desired use shares. Given the by far larger share of fossil-based plastics in the benchmark, rather high tax rates are necessary to achieve this. World demand for conventional plastics drops from $1787.7 billion to $1744.5 billion in scenario 1 and to $1622.2 in scenario 2, with the highest contraction observed in Brazil in scenario 1 (-4.24%) and in the EU in scenario 2 (-15.32%). Overall, demand for plastics as an aggregate increases in scenario 1 (+0.50%), where a small part of overall plastic use is subsidized; while it decreases in scenario 2 (-6.31%), where the largest part of plastic consumption is subject to taxes.

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[1] All quantities are measured in constant US$, i.e. at prices of the benchmark.

Table 1. Demand of bioplastics and fossil-based plastics (constant US$), by economic agent.

	Baseline					Scenario 1: subsidy on bioplastics					Scenario 2: tax on fossil-based plastics				
	World	**US**	**Brazil**	**China**	**EU28**	**World**	**US**	**Brazil**	**China**	**EU28**	**World**	**US**	**Brazil**	**China**	**EU28**
Demand for bioplastics	3.76	1.99	1.02	0.31	0.44	56.00	13.29	3.57	15.84	23.30	56.21	13.29	3.57	15.87	23.48
Final demand	69.7%	89.4%	70.6%	6.5%	25.0%	5.7%	16.8%	21.8%	0.1%	0.6%	4.7%	13.3%	19.9%	0.1%	0.5%
Intermediate demand	25.3%	9.5%	29.4%	90.3%	38.6%	79.0%	75.2%	77.0%	97.9%	68.8%	79.7%	78.7%	78.7%	97.7%	68.3%
Export demand	5.1%	1.0%	0.0%	3.2%	34.1%	15.3%	8.0%	1.1%	2.0%	30.6%	15.6%	8.0%	1.1%	2.2%	31.2%
Demand for fossil-based plastics	1787.7	254.5	56.5	331.5	469.2	1744.5	245.8	54.1	318.7	452.9	1622.2	216.8	51.1	293.7	397.3
Final demand	19.5%	34.6%	24.4%	6.1%	25.2%	20.0%	35.8%	25.5%	6.4%	26.1%	18.5%	32.0%	24.6%	6.1%	23.0%
Intermediate demand	60.8%	47.6%	70.6%	85.6%	43.1%	60.3%	46.0%	69.4%	85.1%	42.0%	61.6%	48.1%	70.1%	84.6%	43.7%
Export demand	19.7%	17.8%	5.0%	8.3%	31.7%	19.7%	18.2%	5.1%	8.5%	31.9%	19.9%	19.9%	5.3%	9.3%	33.4%

In order to reach the 5% target, the consumer price of bioplastics has to drop globally by around -22.8% under the subsidy scenario 1 (Fig. 2a). The necessary decrease and hence the subsidy (or tax rebate) required is greater in China (-23.3%) and the US (-21.9%), while it is the lowest for Brazil (-14.3%). This outcome reflects the costs shares and market feedback impacts in each region. As expected, the consumer prices of fossil-based plastics are hardly affected in scenario 1 (Fig. 2a). On the contrary, scenario 2 has to push up fossil-based plastic prices to the point where the relative advantage of using bioplastic is large enough to reach the 5% target; the largest price increases are found for China (+31.2%), the US (+26.7%) and the EU (+25.3%). These differences can be firstly explained by changes in the average price levels for plastics as an aggregate. A tax on conventional plastics increases the costs of plastic production as an aggregate and reduces overall plastic demand, and consequently production. Secondly, as already pointed out, stronger price effects are necessary to yield the targeted level of bioplastics used in scenario 2, especially in China, due to the nested CES structure that governs the substitution between the two types of plastics in agents' demand.

Bioplastic production has to expand to reach the same target in both scenarios such that production costs of bioplastics increase. As a consequence, producer prices, which reflect per unit production costs of bioplastics, rise by +1.1% in scenario 1 and +0.9% in scenario 2 (Fig. 2b). The average increase is slightly smaller in scenario 2 due to *side effects*, because the tax reduces non-biomass input costs also for bioplastics, and more generally for all inputs relevant in plastic production as overall plastic production shrinks. This is also the cause of the price drop in the cost of producing conventional plastics in China with the tax in scenario 2 (-0.6%), the economy of which relies heavily on fossil-based inputs including plastics. Thus, the target implies larger adjustments in China compared to the other regions, where the feedstock cost share in bioplastic production is around 1.5 times larger than in the rest of countries; hence, greater price impacts are expected in the Chinese food market. Despite the greater increase in production costs in scenario 1, consumer prices of bioplastics drop when consumption is subsidized; while they increase in scenario 2, in which increased production costs are passed through to the consumer.

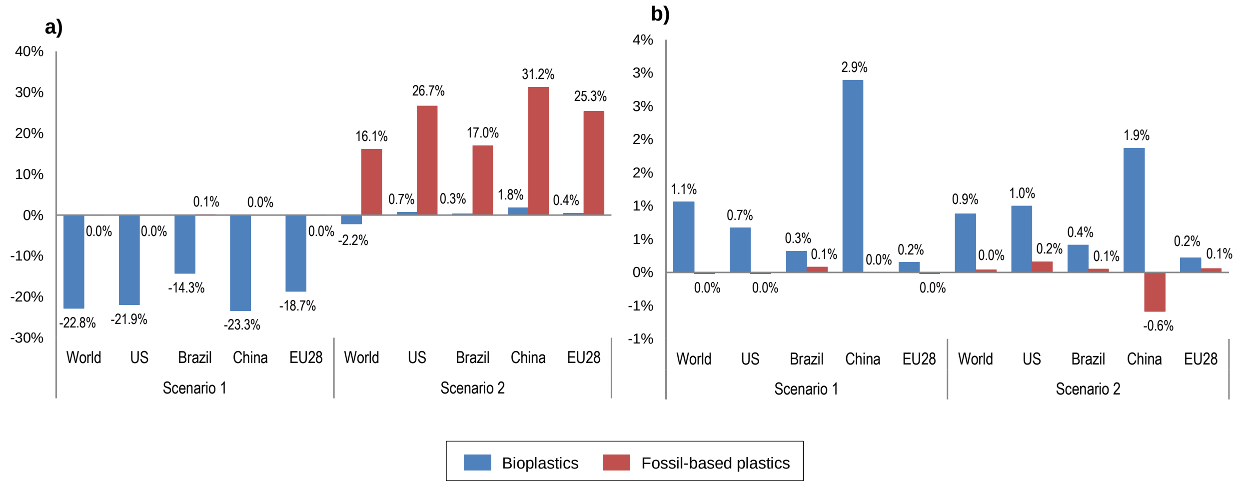

Figure 2. Changes in consumer prices (tax inclusive) (a) and producer prices (net of taxes) (b), relative to the benchmark, under the subsidy in scenario 1 and the tax in scenario 2.

In relative terms, total output of bioplastics increases globally by around +1400%, as shown in Table 2, from the observed levels of production in 2011 to the imposed 5% share. Relative changes are even higher for China and the EU where the original market penetration was below the global average. Following the introduction of substitution between bioplastics and conventional ones, the target comes at the cost of the fossil-based plastic sector, which shrinks globally by -2.4% in the subsidy scenario 1 and by -9.3% in the tax scenario 2. The average contraction for all the bioplastic producing regions is around -4% in scenario 1; while it varies in scenario 2 between -9.5% for Brazil to -15.3% for the EU, where the production of plastics from petroleum derivatives implies higher costs. Furthermore, scenario 2 makes the four regions less competitive relative to the rest of the world, where fossil-based plastics become cheaper as total production shrinks. These changes have associated *side effects*, especially in sectors with a high demand for plastics; namely textile, machinery and equipment, motor vehicles, and construction, among others, depending on the region (see Table A2 in the Annex). As for the *immediate effects* of the target, the intermediate demand for agricultural feedstock in the bioplastic industry increases sharply following the expansion in production, but to a lower extent in those regions already produce relevant amounts of bioplastics in the baseline, namely the US and Brazil (Table 1). The production of the most important feedstocks expands globally and especially in the bioplastic producing regions, shown in Table 2, i.e. cereal grains in China (+11.1%) and the US (+5.0%), sugarcane in Brazil (+1.7%), and wheat in the EU (+2.6%); scenario 2 delivers similar figures.

Table 2. Supply and demand effects in the sectors directly affected by the shock, as a % change relative to the baseline.

	Scenario 1: subsidy on bioplastics					Scenario 2: tax on fossil-based plastics				
	World	**US**	**Brazil**	**China**	**EU28**	**World**	**US**	**Brazil**	**China**	**EU28**
Aggregated Armington demand										
Bioplastics	1389.5%	567.1%	250.3%	5029.6%	5200.5%	1395.2%	567.3%	250.4%	5027.6%	5240.6%
Fossil-based plastics	-2.4%	-3.4%	-4.2%	-3.8%	-3.5%	-9.3%	-14.8%	-9.5%	-11.2%	-15.3%
Intermediate demand for feedstock in the bioplastic sector										
Sugar	251.3%		250.1%			251.5%		250.3%		
Wheat	5112.2%			5033.3%	5132.5%	5093.1%			5047.5%	5104.9%
Cereal grains (inc. corn)	1286.9%	565.7%		4960.9%	5133.0%	1289.2%	566.4%		4976.9%	5106.0%
Total sector's output										
Bioplastics	1222.9%	567.4%	250.3%	5014.9%	5141.2%	1222.2%	567.9%	250.5%	5027.6%	5115.5%
Fossil-based plastics	-2.5%	-3.3%	-4.3%	-3.8%	-3.4%	-9.7%	-14.5%	-9.7%	-11.2%	-15.0%
Sugarcane	0.6%	-0.2%	1.7%	-0.2%	0.1%	0.5%	-0.1%	1.6%	0.2%	0.0%
Wheat	0.8%	-0.2%	0.0%	0.7%	2.6%	0.7%	-0.2%	0.7%	0.6%	2.8%
Cereal grains (inc. corn)	3.5%	5.0%	0.1%	11.1%	1.9%	3.5%	5.0%	0.1%	11.0%	1.9%

The impacts of the bioplastic demand target on factor and food markets are ultimately linked to the cost structure of the bioplastic sector in each region, together with feedback responses across input markets. Primary factors, namely land, capital and labor, are relocated into those sectors in which the marginal value product increases (relatively), mainly bioplastics and the associated feedstocks. Changes in world factor prices are included in Table A3 of the Annex. On the one hand, the target pushes factor prices up in the emerging bioplastic sector (*immediate effects*), which is the case for skilled and unskilled labor in scenario 1. On the other hand, the contraction of the fossil plastic sector frees up resources and drives all the primary factor prices down, not only in the fossil-based plastic sector but also in the bioplastic one (*side effects*). These effects are more evident in scenario 2 due to the sharper contraction of the demand for conventional plastics. Hence, the increase in factor prices in agricultural sectors is more moderate in scenario 2. In spite of the *immediate effects* that drive up land prices (especially for wheat, cereal grains and sugarcane), competition for land with other uses (food, feed, fuel) is lower in scenario 2, in which other agricultural sectors are shrinking, e.g. oilseeds. As a result, the average price of land increases by +0.90% in scenario 1 and +0.52% in scenario 2. Given that plastics are used in almost every sector, *side effects* spread across all supply-chains, e.g. livestock production, for which land prices decrease in scenario 2, with the exception of raw milk (Table A3). As a result, in scenario 2, the *side effects* of the target across the economy are larger than the *immediate effects* in feedstock markets.

The increased demand for land for material uses drives up crop prices, at the world level and especially in the bioplastic producing regions, as shown in Fig. 3. The only exception is China in scenario 2, in which the *side effects* of the tax to fossil-plastics are especially large, generating a contraction of all the sectors that employ plastics either directly or indirectly, including food production. As a result, the tax even generates a decrease in the price of other crops in the domestic market. The *immediate effects* however trigger increases in the price of corn in China around 6.7% and 5.2% in scenario 1 and scenario 2, respectively; corn prices in the US only increase by 2% due to the less ambitious target relative to the baseline (Table A1) and a small share of total corn demand being used as a feedstock in plastic production. Furthermore, China is the country where imports of the main bioplastic feedstocks increase the most, around 19.6% in scenario 1 and 16.9% in scenario 2, triggering effects in world prices. This value is much lower for the rest of regions, e.g. around 8.5% in the US for corn or 4.2% in the EU for wheat. As a consequence, the price of sugarcane goes up by less than 0.9% in Brazil, while the prices of wheat and other cereals increase by 0.8% and 0.7% in the EU, respectively. The prices of cattle and other animal products are especially affected in the US and Brazil in scenario 2, since these sectors rely on domestic grains to a large extent.

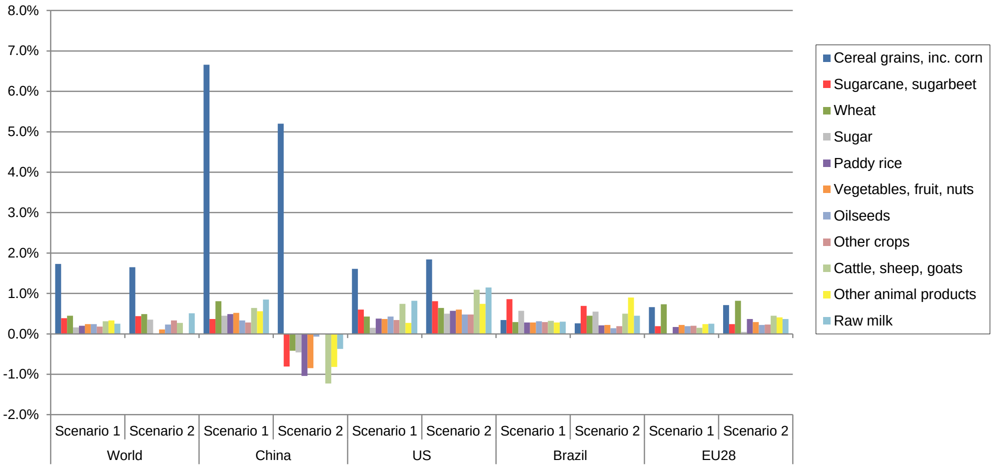

Figure 3. Changes in consumer prices (tax inclusive) of food products, as a % change relative to the baseline.

3.2.Economic impacts

The relocation of production factors across economic sectors and related price responses also explain differences in both economic and environmental implications between the two scenarios. Income effects across the focus regions are shown in Table 3, in terms of real GDP and GDP per capita. The tax on consumption of fossil-based plastics in scenario 2 reduces global GDP, due to distortive effects of a rather high tax on plastic use and the subsequent strong reduction in total plastic output. The GDP loss is the strongest in China in scenario 2 (-0.20%), followed by the EU (-0.16%), while smaller decreases are found for the US (-0.06%) and Brazil (-0.05%). In the US, the sharp decrease in conventional plastic consumption (Table 2) requires a large increase in consumer prices (Fig. 2a); in Brazil, the shrinkage of the conventional plastic sector is the smallest, hence consumption taxes adjust to a lesser extent in order to fulfill the target, as already mentioned.

Table 3. Income effects in terms of GDP (billion US$) and GDP per capita (US$), and changes relative to the baseline (%).

	Scenario 1: subsidy on bioplastics					Scenario 2: tax on fossil-based plastics				
	World	**US**	**Brazil**	**China**	**EU28**	**World**	**US**	**Brazil**	**China**	**EU28**
GDP real (billion US$)	71471.0	15532.8	2476.7	7318.6	17663.6	71427.4	15524.5	2475.4	7307.5	17638.5
GDP per capita (US$)	10276.0	49851.1	12576.1	5444.9	34787.0	10269.8	49824.8	12569.8	5436.6	34737.6
Change relative to the baseline (%)	-0.01%	-0.01%	0.00%	-0.05%	-0.02%	-0.07%	-0.06%	-0.05%	-0.20%	-0.16%

3.3.Environmental impacts

The environmental implications of the target are analyzed in terms of changes in land area extension, i.e. total LUC (direct and indirect) and GHG emissions. The latter include CO_2 emissions from LUC, non-CO_2 emissions, i.e. N_2O and CH_4 mostly from agriculture and livestock, and CO_2 emissions from energy consumption across all the economic sectors. The difference in CO_2-eq. before and after the experiment can be interpreted as the life cycle emissions associated to the increased demand of bioplastics, reflecting related adjustments in material and factor use in the global economy. GHG emissions from LUC arise from carbon stock changes before and after the land conversion across 18 Agro-Ecological Zone (AEZs), by taking into account different land use transitions and carbon fluxes, which do not include primary forests, i.e. unmanaged forests (Plevin et al. 2014). Land conversion depends on differential land rents based on relative returns to land. Marginal carbon stocks are generally scale-dependent, i.e. the marginal land source (and hence emissions) varies as more land is utilized in a region. In this way, the GTAP model captures GHG leakage due to extensification and also intensification of agriculture at a global scale.

3.3.1. Land use changes

As a consequence of the market responses described in section 3.1, cropland expands by +0.14% globally in the two scenarios, at the cost of both managed forest and pasture. While the contraction in managed forest area is around -0.05% in scenario 1, it reaches -0.08% in scenario 2; pastureland decreases by -0.05% and -0.03% in scenarios 1 and 2, respectively. Changes in land cover per AEZ are shown in Fig. 4-6. Specifically, Fig. 4 captures changes in cropland area in scenario 1 (a) and scenario 2 (b), relative to the benchmark; Fig. 5 (a,b) captures changes in forest area, while Fig. 6 (a,b) focuses on pasture land.

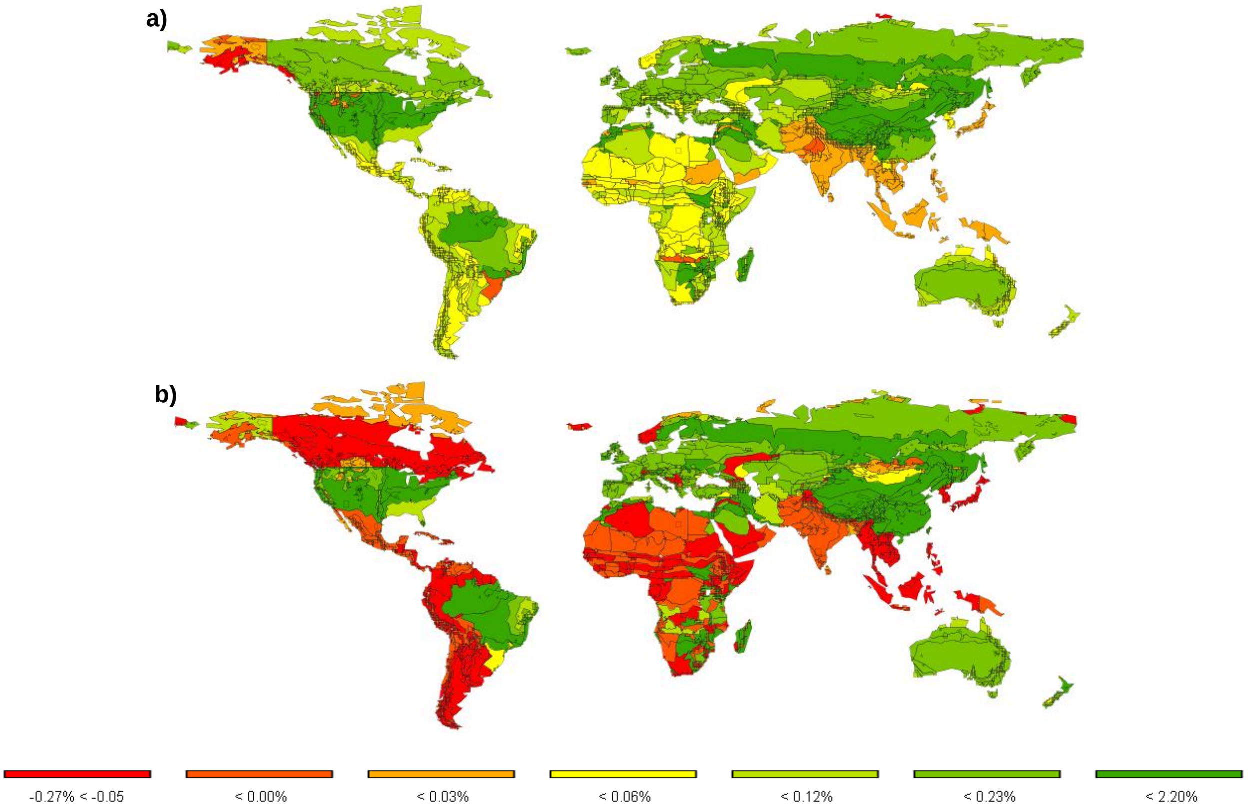

Figure 4. Changes in cropland extension across AEZs in scenario 1 (a) and scenario 2 (b), relative to the baseline.

Scenario 1 points to greater increases in cropland area (between 0.12% and 2.20%) in the EU, East of Asia, North America and Brazil, together with Oceania and some specific regions of Eastern and Southern Africa (Fig. 4a). Changes in cropland hence reflect which countries provide the additional feedstock to boost bioplastic production, namely sugarcane, wheat and corn (domestic or imported). Cropland equally expands (up to 0.12%) in the rest of the world, and more intensely in the Middle East, Africa, and Central and South America, due to the subsequent effects across agricultural markets to produce biomass for other uses. Thus, it can be said that LUC in scenario 1 mostly arises from the *immediate effects*. In the US, corn expands mainly at the expense of oilseeds, vegetables, animal products, raw milk and also wheat. In Brazil, the expansion of sugarcane mainly occurs at the cost of oilseeds, other crops, cattle and animal products. In the EU, some relevant reductions are observed in the output of vegetables, other crops, animal products, and milk; same as in China, where paddy rice and oilseeds are largely affected too. Further information on agricultural sectors' output is included in Table A4 in the Annex.

Scenario 2 generates similar *immediate effects* but greater *side effects*, which deliver even opposite outcomes in terms of cropland area expansion in some regions, reflecting a shrinking global economy. Whereas cropland expands again under a consumption tax to fossil plastics, mainly in the EU, China, the US, and Brazil (Fig. 4b); a contraction is observed in India, most of Africa, and Central America (between 0% and -0.05%), and especially in Southeast Asia, Japan, Canada and South America (between -0.05% and -0.27%). This translates into a reduction in the production of crops such as oilseeds. Global oilseed production decreases by -0.22% in scenario 2 and by -0.06% in scenario 1.

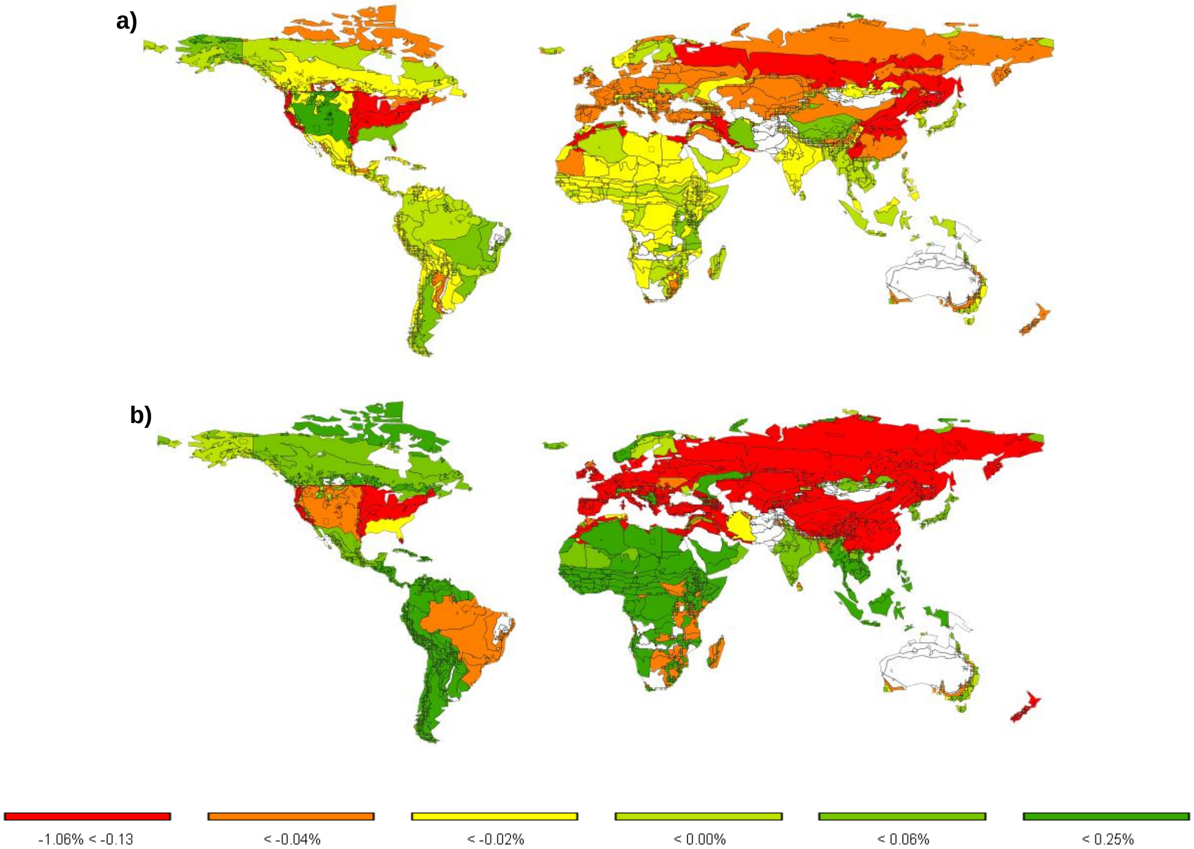

Figure 5. Changes in forestland extension across AEZs in scenario 1 (a) and scenario 2 (b), relative to the baseline.

The two scenarios deliver again different outcomes when it comes to LUC at the expense of managed forest, with more extreme effects in scenario 2. In scenario 1, forestland area decreases as a consequence of the *immediate effects* up to -0.13% in large areas of Europe, Asia and Africa; while the strongest decrease (between -0.13% and -1.06%) is mainly limited to the US Corn Belt, Central Asia and Northeastern China (Fig. 5a). The drop in managed forest land and forest outputs triggers economic incentives leading to afforestation (up to +0.25%) in other regions, including parts of China, the US and Brazil, where forest expands at the expense of pastureland (Fig. 6a). In scenario 2, deforestation (up to -1.06%) spreads across the US, Brazil and Eurasia, being especially intense in the EU and China (Fig. 5b). This is due to *side effects*: the contraction in all the sectors that rely on fossil-based plastics also reduces the intermediate demand for forest products, which is substantial in sectors such as construction or manufacturing, which also rely on plastics as inputs. Intermediate demand for forest products for energy uses decreases as well, which is notable in many industrial sectors of the US, EU and especially China. As a result, intermediate demand for forestry decreases by -0.34% in scenario 2 on a world average, while it hardly changes (-0.03%) in scenario 1, in which the fossil-based share of the economy is mostly unaffected. Forestland increases up to +0.25% in large extensions of Canada, Southeast Asia, Central and Andean America and again, Scandinavia (Fig. 5b). The bioplastic target clearly comes at the cost of pastureland in Europe, North America and Central and Northern Asia in the two scenarios, with greater decreases (between -0.02% and -0.75%) in scenario 1. Pastureland area also decreases (up to -0.02%) in Brazil, most of Africa and South and Southeast Asia (Fig. 6a). The contraction is more moderate in scenario 2, even generating an expansion in pastureland (up to +0.20%) in Southern Asia and South America (Fig. 6b). Results highlight the potential of the target to generate greater spillover effects when enforced through a tax on fossil-plastics consumption.

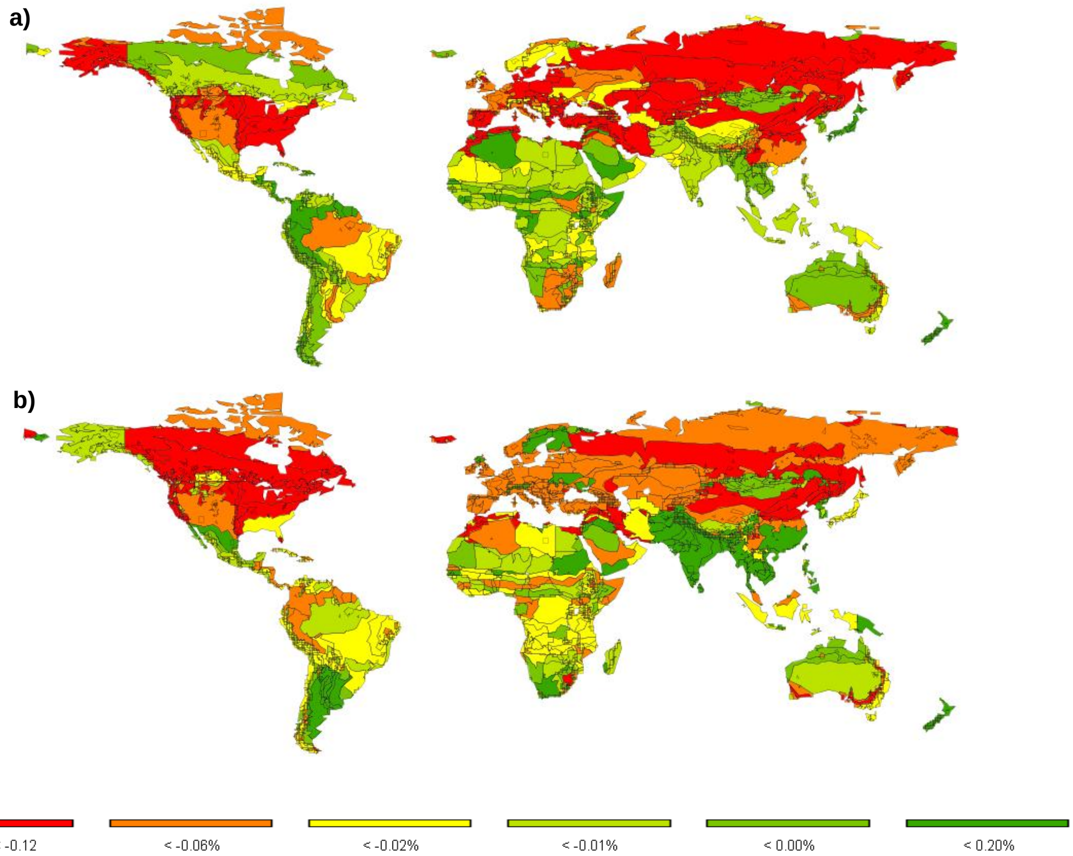

Figure 6. Changes in pastureland extension across AEZs in scenario 1 (a) and scenario 2 (b), relative to the baseline.

3.3.2. Greenhouse gas emissions

The difference in CO_2-eq. emitted annually before and after the experiment is calculated in Table 4, as a measure of the climate change mitigation potential of the bioplastic target in the two scenarios. The calculation also includes changes in carbon stocks as a one-time effect from land conversion, which are ultimately annualized by considering an amortization period of 30 years (Plevin et al. 2014). Hence, both economic and environmental outcomes from the model are annual ones and can be directly compared between the benchmark and the counterfactual scenario. The comparative-static character of the analysis does however not depict the path of adjustments that occur after the shock, either the accumulated changes over the transition period.

If emissions from LUC are not considered, the tax in scenario 2 generates a slightly stronger mitigation of global GHG emissions (-0.18%), due to the contraction of all the sectors that are intensive in the use of fossil-based plastics. Hence, demand for energy decreases as well, which constitutes the biggest source of GHG emissions both at the world and country levels, except for Brazil. The reduction is the greatest in China (-0.41%), where the target triggers greater *side effects*. Scenario 1 entails minor adjustments in material and factor use across sectors, which only generate a -0.01% reduction in GHG emissions globally. It must be borne in mind that in the GTAP model the stock of primary factors is fixed; this means that the availability of managed land and natural resources such oil and gas (Fig. 1) does not change in our experiment. Differences in GHG emissions thus only arise from factor reallocation and demand shifts across all the sectors and industries.

When emission from total LUC (both direct and indirect) are included, both scenarios deliver higher GHG levels, with larger increases for scenario 2 due to the land cover changes described above. Deforestation is especially intense in the regions that enforce the target, including carbon-rich ecosystems such as the Amazon. In scenario 2, cropland expansion comes at the cost of managed forest to a larger extent, mainly due to *side effects* through to sectors employing forest products either for energy or material uses. As a result, GHG emissions increase especially in Brazil (+8.84%) and China (+4.73%) in scenario 2, with a world average of +2.07%. It should be noted that the contribution of LUC to overall emissions in Brazil is much larger than in the rest of regions, which explains the sharpest increase. Scenario 1 implies an increase in global GHG emissions of +1.44%, being the greatest in the US (+3.15%) and the EU (+2.25%), where deforestation is equally more intense. The reduction in pastureland is stronger in scenario 1, but implies smaller changes in land carbon stocks when converted to cropland.

Table 4. Total greenhouse gas (GHG) emissions from the entire economy (Tg of CO_2-eq), broken down by source.

		Emissions from LUC (Tg CO_2-eq.)	**Non-CO_2 emissions (Tg CO_2-eq.)**	**CO_2 emissions from energy consumption (Tg CO_2-eq.)**	**Total GHG emissions (Tg CO_2-eq.)**	**% change (without LUC)**	**% change (with LUC)**
Baseline	**World**	0.00	12961.84	27941.49	40903.33		
	US	0.00	975.17	4996.75	5971.92		
	Brazil	0.00	614.25	356.80	971.05		
	China	0.00	2743.54	6974.75	9718.29		
	EU28	0.00	1183.03	3596.83	4779.86		
Scenario 1	**World**	590.81	12955.20	27944.29	41490.30	-0.01%	1.44%
	US	185.24	973.65	5001.16	6160.05	0.05%	3.15%
	Brazil	15.00	613.63	356.77	985.40	-0.07%	1.48%
	China	147.44	2739.47	6974.34	9861.25	-0.05%	1.47%
	EU28	107.25	1182.73	3597.48	4887.46	0.01%	2.25%
Scenario 2	**World**	919.38	12927.52	27903.48	41750.38	-0.18%	2.07%
	US	230.96	967.74	4994.43	6193.13	-0.16%	3.70%
	Brazil	87.96	613.27	355.61	1056.84	-0.22%	8.84%
	China	499.66	2724.36	6954.21	10178.23	-0.41%	4.73%
	EU28	148.21	1180.29	3587.69	4916.19	-0.25%	2.85%

4. Discussion

4.1. Cost-effectiveness of the target

Results described in section 3 show that a 5% target for bioplastic consumption does not abate GHG emissions once impacts of LUC are included. As already observed for biofuels (Plevin et al. 2010; Searchinger et al. 2008), LUC emissions offset GHG savings from a reduction in fossil feedstock use, so far discussed as a positive contribution of bioplastics (Groot and Borén 2010; Tsiropoulos et al. 2015). The negative climate change impact is even greater when a tax on fossil-based plastics is enforced for fulfilling the target. Furthermore, both policy scenarios imply a decrease in GDP, especially in the leading producing regions. Global CGE models are well suited to analyze trade-offs between economic and environmental impacts, provided that a high level of technological or regional detail is not required for the policy and environmental assessments, as is usually the case for climate change as a global externality (Povellato et al. 2007). The economic vs. environmental trade-offs are jointly evaluated to quantify the cost-effectiveness of the bioplastic target under the two policy scenarios, expressed as the ratio of the change in real GDP (Table 3) to the change in GHG emissions (Table 4). When LUC emissions are neglected, the target leads to abatement costs of +2.22 and +0.72 US$ per kg CO_2-eq. in scenarios 1 and 2, respectively. This indicates the tax on fossil-based plastics (scenario 2) would be more cost-effective than the consumption subsidy on bioplastics (scenario 1), on a world average, since it entails a smaller GDP loss per unit of CO_2-eq saved. However, when LUC is included, the policy does not only incur costs as seen from the dropping real GDP, but also increased GHG emissions. This shows that there are not abatement costs as such under this setting, since both scenarios entail income losses as combined with a negative environmental impact.

Trade-offs of the policy intervention can be equally interpreted from the absolute changes in both GDP and GHG (including LUC emissions) in each country relative to the benchmark, shown in Figure 7. These calculations should however be interpreted with care, as both GDP and GHG changes include impacts of the policy and subsequent adjustments in other regions. Brazil is the country where total CO_2-eq. increase the least regardless the scenario, also at the expense of the smallest GDP loss. On the contrary, China and the EU are the two regions for which scenario 2 generates much greater emissions at the cost of GDP, driving larger negative trade-offs at the world level. These extreme cases are associated to a cost-effectiveness of -31.22 and -208.54 US$ per t CO_2-eq. in the EU and +0.70 and -14.45 US$ per t CO_2-eq. in Brazil, for scenarios 1 and 2, respectively. It is observed that Brazil is the only country for which the target would deliver a positive cost-effectiveness when enforced through a consumption subsidy on bioplastics. Our results suggest that, in order to incorporate the costs of carbon emissions accurately, bioplastic policies must be extended to capture the net GHG emission from LUC, including iLUC that occurs at global level. Similar scientific evidence encouraged the consideration of iLUC emissions factors to be included in biofuel directives as “sustainability requirements”, based on life cycle principles (Finkbeiner 2014; Gawel and Ludwig 2011). Khanna et al. (2017) estimate the cost-effectiveness of a national Low Carbon Fuel Standard in the US that encompasses iLUC emission factors with the biofuel mandate at between +61 and +187 US$ per t CO_2-eq. They use an integrated modeling approach for feedstock-specific biofuel production in the US, which however neglects further potential market feedback effects.

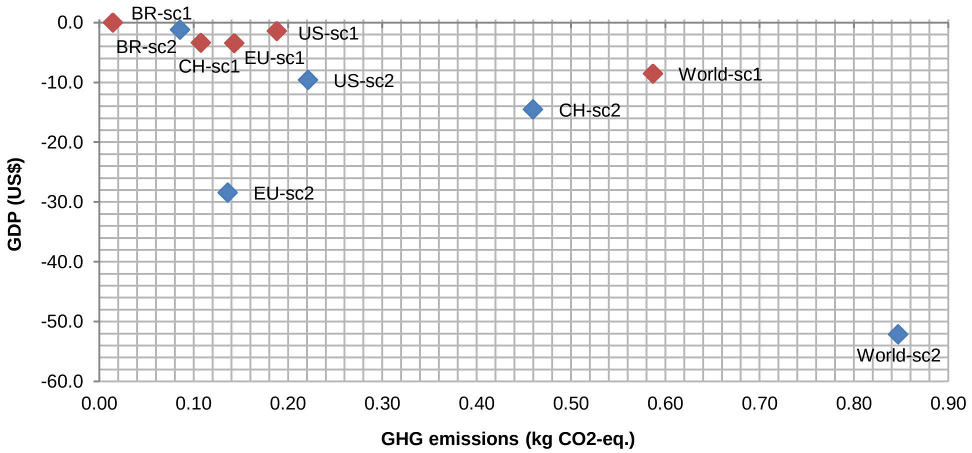

Figure 7. Absolute changes in GDP (US$) and GHG emissions (kg CO_2-eq.) in each region and scenario, relative to the baseline.

The cost-effectiveness ratio of the bioplastic target presented in this section does not account for the costs saved through increased recyclability and biodegradability during end-of-life, two characteristics associated to bio-based plastics. On the one hand, this could translate into lower costs from waste treatment, which are often borne by governments. On the other hand, increased recyclability would imply a smaller demand for raw materials by implementing closed-loop approaches in the industry. Further benefits from reduced resource extraction could not be however assessed with the GTAP model, which assumes fixed stocks of natural resources, as already mentioned. Thus, without further extensions, it does not provide an adequate framework to analyze economic and environmental gains brought about by policies aimed at transitioning to a Circular Economy.

4.2.Leakage effects

GTAP 9 does provide an adequate basis for the quantification of policy-induced leakage in terms of land cover and GHG emissions, when coupled to biophysical data. Leakage occurs when the scale of intervention i.e. the bioplastic target, is smaller than the scale of the overall impact, i.e. climate change, and should be accounted at full global level (Kim et al. 2014). In our experiment, GHG emissions do not only arise from iLUC but also from adjustments in material and factor use in the global economy. In this way, the bioplastic target delivers changes in GHG emissions in the countries that enforce it but also foreign emissions or “carbon leakage” through changes in the structure of supply and demand due to price dynamics. Outcomes are however subject to uncertainty in model parameters such as emission factors and land productivity (Henders and Ostwald 2014) and model assumptions, such as how technology changes (or not) due to the shock (Gerlagh and Kuik 2014). A mandate for bioplastic consumption is very likely to trigger technological innovation aimed at enhancing technical substitutability of bioplastics for their fossil counterpart, mainly in the industry, while adding new functionalities in final demand. The real substitution potential should ultimately depend on the specific bioplastic family, being 1:1 for drop-in products such as bio-PE (Posen et al. 2017), although this distinction is not yet possible at the current level of detail in the benchmark.

The bioplastic target in the leading producing regions is evaluated in terms of land and GHG leakage into the rest of the world (ROW) by considering two additional elasticities of substitution between bio- and fossil-based plastics for sensitivity analysis, namely 10 and 20 as lower and upper bounds, respectively. The ratio of the GHG increase (cropland expansion) generated by the bioplastic target in the ROW to the GHG (cropland expansion) change in the countries that enforce the target as a whole is calculated as shown in eq. 1 and eq. 2:

$$GHG\ leakage\ (\%) = \frac{\Delta GHG_{ROW}}{\Delta GHG_{US}+\Delta GHG_{BR}+\Delta GHG_{CH}+\Delta GHG_{EU}} \qquad \text{eq.1}$$

$$Land\ leakage\ (\%) = \frac{\Delta Cropland_{ROW}}{\Delta Cropland_{US}+\Delta Cropland_{BR}+\Delta Cropland_{CH}+\Delta Cropland_{EU}} \qquad \text{eq. 2}$$

It must be noted that higher substitution elasticity does not translate into a higher market share of bioplastics since this is given by the unchanged absolute target of 5% of the base plastic demand. The substitution elasticity determines the ability to substitute for fossil-plastics in order to reach the target in total aggregated demand. As shown in Fig. 8, it matters mainly in scenario 2, which promotes the consumption of bioplastics by taxing the substitute, while in scenario 1 the consumer price of fossil-plastics is barely affected (see Fig. 2).

In scenario 1, the land leakage is around 20% in all cases, which means that the expansion of cropland in the ROW is one fifth of the increase in the cropland area in the bioplastic producing regions. The GHG leakage (including CO_2-eq. from LUC) is around 30%, being the lowest for the lowest elasticity of substitution. This is because the lower the substitution elasticity, the smaller the amount of fossil plastics replaced in the market when the consumer price of bioplastics decreases. In other words, the leakage comes from *immediate effects* to a larger extent, since the GHG saving due to the *side effects* is lower. On the contrary, leakage in scenario 2 mainly arises from the *side effects*, which decrease (in absolute terms) with enhanced substitutability between conventional plastics and bioplastics. This is because smaller adjustments in the tax are needed to fulfill the target with the highest substitution elasticity; smaller is then the contraction of the aggregate plastic demand and hence the *side effects;* also the *immediate ones*, but in this case these play a minor role by increasing agricultural area.

It must be recalled that the taxes endogenously adjust in the two scenarios; thus, using different substitution elasticities leads to different price changes. As a result, the land leakage is negative under the tax scenario 2 with substitution elasticities of 10 and 15 (-14.58% and -4.68%, respectively), in which the model simulates an overall area contraction in the ROW; while cropland area expands in the bioplastic producing regions. The land leakage becomes positive with the elasticity of 20 (+0.61%), which means that cropland also expands in the ROW, as a high substitution elasticity implies a lower tax, and subsequently less contraction in fossil plastic production and, more generally, the overall economy. As for the GHG leakage, it is always negative and increasing with the substitution elasticity (from -14.81% to -0.74%), since the contraction in the use of energy sources (including biomass) in the economy is less intense, generating smaller *side effects*. The leakage is however smaller in scenario 2 because the *side effects* are even larger in the countries that enforce the target. Further assessments envisage the possibility of analyzing the leakage effects of the target in each region individually to assist policy making.

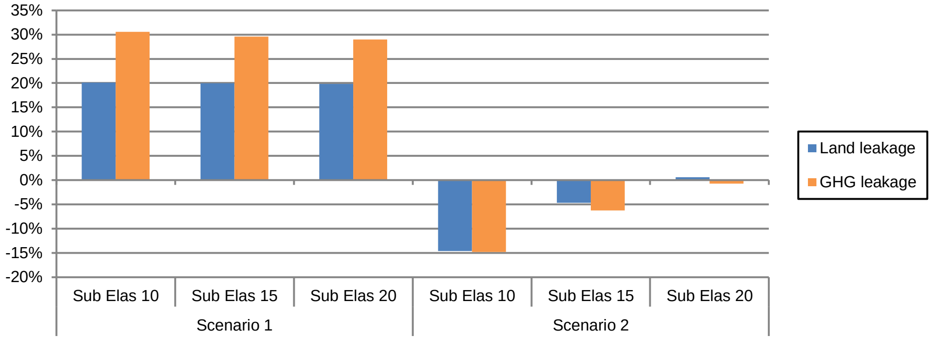

Figure 8. Cropland and GHG leakage of the bioplastic target in the leading producing regions into the rest of the world.

5. Conclusions

A 5% target for the market penetration of bioplastics relative to a 2011 benchmark in leading producing regions, i.e. the US, the EU, China and Brazil, has been analyzed by means of the broadly used CGE model GTAP. To this aim, the GTAP 9 database has been extended by disaggregating two additional sectors namely "fossil-based plastics" and "bioplastics"; this constitutes a relevant contribution since it is based on real production capacities. The ultimate goal is to investigate whether such a target effectively contributes to climate change mitigation, besides quantifying market and welfare impacts. Two different policy instruments have been endogenously determined in scenarios 1 and 2 allowing for the target to be reached. Both the subsidy to bioplastics consumption (scenario 1) and the tax to conventional plastics (scenario 2) clearly generate an expansion of the bioplastic sector, with the subsequent effects in food markets due to the increased demand for starch- and sugar-based feedstocks in the bioplastic industry. The price of corn increases by +1.73% at the world level, while the price of wheat and sugarcane increase by +0.45% and +0.39%, respectively. Besides the *immediate effects* in feedstock markets, the tax in scenario 2 has also important *side effects* across the rest of the economy, since plastics as an aggregate become more expensive and consumption decreases at the given target for bioplastic use. This generates a contraction of all the sectors that employ plastics either directly or indirectly, including food production, especially in China where the target is more ambitious. As a consequence, global GDP drops by -0.01% in scenario 1 and -0.07% in scenario 2, in which the policy creates greater inefficiency in the use of primary factors.

The target has also important implications of iLUC and associated GHG emissions. Although cropland expands by +0.14% globally in the two scenarios, scenario 2 delivers +2.07% increased GHG emissions when global LUC is considered, as compared to +1.44% in scenario 1. This is because scenario 2 causes greater deforestation at the expense of managed forests (-0.08%) due to the *side effects*, since intermediate demand for forest products decreases across sectors. Moreover, deforestation is especially intense in the regions that enforce the target, including carbon-rich ecosystems such as the Amazon. The target has leakage effects in terms of agricultural land and GHG, which are greater in scenario 1. The *side effects* lead to area contraction in the ROW in scenario 2, with the associated negative carbon leakage representing 6.2% of the GHG increased in the bioplastic producing regions as a whole. In scenario 1, the GHG leakage is around 30%, while the cropland leakage is around one fifth. Finally, the cost-effectiveness of the bioplastic target, as the ratio of the change in real GDP to the change in total GHG emissions, is calculated at -14.53 and -61.59 US$ per t CO_2-eq. in scenarios 1 and 2, respectively. This means that the GDP drops less in scenario 1 per unit of GHG increased globally. Brazil is the only country for which the target would deliver a positive cost-effectiveness when enforced through a consumption subsidy on bioplastics. A greater target would deliver greater spillover economic and environmental effects, which do not increase in a linear fashion in CGE analysis.

Our study is the first to quantify global LUC emissions (both direct and indirect) from an increased demand for bioplastics and shows that a 5% target in the leading producing regions is not effective for climate change mitigation, if met with food-based feedstock. As already observed for biofuels, which constitute the most articulated form of Bioeconomy, iLUC emissions can offset the GHG abatement presumed for first generation bioplastics; even more if land expansion at the expense of natural ecosystems was considered. On the one hand, results are meant to encourage research in second generation technologies, which do not compete with food and feed uses. From the policy perspective, results show that promoting bioplastics, either by means of a consumption subsidy or a tax on fossil-based plastics, would change the relative prices; thus, leading to a suboptimal factor allocation and GDP loss. Although this effect is greater with the tax, revenues could be used to finance GHG mitigation activities, such as improvement of conversion efficiencies to bring further environmental gains (Timilsina 2011). The improved CGEBox (Britz 2017), based on GTAP 9 (Aguiar et al. 2016), constitutes a valuable tool to simulate bioplastic policies in a CGE setting, by considering different substitution potentials. Of course any expansion in the market share of bio-based materials would come together with increasing demand for food and (bio)energy, implying additional competition between uses. Further experiments consider the combination of bioplastic and biofuel targets simultaneously, in order to bring insights into the food-fuel-fiber debate, provided that biofuel sectors are also disaggregated.

Policy implications of the present study are non-trivial for the Bioeconomy. Results prove that “bio-based” does not necessarily mean environmentally sustainable, while also bringing social and economic challenges. Our recommendation is that future bioplastic strategies focus on biodegradability rather than on the biological origin of the feedstock, in order to increase resource efficiency through closed-loop approaches. Reuse and recycling should be the paramount priority in developing a sustainable Bioeconomy, hand in hand with Circular Economy principles in order to replace fossil resources and drive the transition to low-carbon societies. This ultimately points to the need for clear support frameworks that adhere to cascading uses and feedstock diversification, as already suggested in the EU Action Plan for Circular Economy; to deliver environmental, economic and social gains derived from end-of-life options but also from resource savings in manufacturing. In this way, bioplastics could effectively contribute to SDG12 (13) in transitioning to more sustainable consumption and production systems.

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Annex

Section 1. Baseline data

Section 2. Results

References

Section 1. Baseline data

The disaggregation of "bio-based plastics", "fossil-based plastics" and "rest of chemicals" is carried out based on output and feedstock cost shares for the leading bioplastic producing regions, namely, the US, the EU, China and Brazil. The output shares are calculated as follows. Firstly, the share of the plastic sector relative to overall chemical production in the original database is estimated based on output values for the year 2013 (Lee 2016; PlasticsEurope 2015). Secondly, the share of bioplastic production relative to total plastics is calculated from nameplate capacities in the year 2013 (Shen et al. 2009). The following assumptions have been taken to map feedstocks and regions, given the diversity of biopolymer families and the limited data availability for being a strategic market segment. Data suggest that Brazil is currently focused on bio-PE, although PHB is also produced in small amounts, both from sugarcane; the EU utilizes mainly wheat for thermoplastic starch (TPS) blends, although other coarse grains may be employed if intermediate demand for bioplastic production increases; China relies on corn and other cereals for the production of both PLA and PHB, while the US mainly uses domestic corn for the same purposes. Output shares of the three new sectors are calculated according to Eq. 1 – 3, by using bioplastic prices from OECD (2013) and 2013 crop prices from FAO (2017) for the output values. Only first generation biopolymers, i.e. derived from annual crops, are considered, since second generation technologies based on lignocellulosic feedstocks are not yet implemented for large scale production.

$$biop(r) = \frac{output(r,biop)}{output(r,plas)} \times \frac{output(r,plas)}{output(r,chem)} \qquad \text{(eq. 1)}$$

$$plas(r) = \frac{output(r,plas)}{output(r,chem)} \qquad \text{(eq. 2)}$$

$$otherchem(r) = 1 - plas(r) \qquad \text{(eq. 3)}$$

Where biop(r) refers to the output share of bioplastics in each producing region (being zero in non-producing ones); plas(r) is the output share of total plastics; and otherchem(r) is the share of other chemicals, all of them relative to the chemical sectors' output. Output(r,biop), output(r,plas) and output(r,chem) are simply the calculated output values of bioplastics, total plastics and chemicals in the baseline, respectively; these are shown in Table A1. As a rule of thumb, it has been assumed that plastic production represents 20% of the chemical sectors' output in all the regions. After all these adjustments, the contribution of the four focus regions to the world's overall plastic output in the baseline, including both fossil-based and bio-based plastics, is shown in Fig. A2.

Table A1. Calculated output shares (%) for total plastics and bioplastics.

	US	**Brazil**	**China**	**EU28**
Share of total plastics in the chemical industry (%), plas(r)	18.21	16.78	19.5	15.89
Share of bioplastics in the chemical industry (%), biop(r)	0.18	0.4	0.02	0.02
Share of bioplastics in the plastic industry (%), biop(r)/plas(r)	1.00	2.38	0.10	0.13

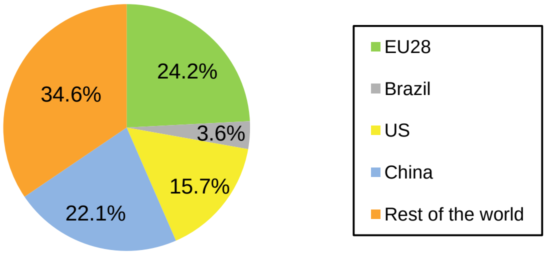

Figure A1. Regions' market shares (in million US$) of total plastic production in the baseline, after disaggregation of the fossil-based plastic and bioplastic sectors in GTAP 9.

Modifications in the cost structure of the two newly implemented industries are then necessary in order to capture differences between the production technologies. While the fossil-based plastic sector employs crude oil, assumed equal to the extent it is used in the parent chemical sector, the bio-based plastic sector is shifting to biologic raw material, i.e. crop biomass. The share of agricultural feedstock relative to overall production costs in the aforementioned focus regions has been updated based on technical conversion efficiencies from IfBB (2016) and the same price information as used for the output values, depending on the bioplastic type. When a region produces more than one type, average feedstock prices and quantities are weighted by production capacities for the different bioplastic families in order to obtain a single cost share for a hypothetic aggregated biopolymer. The split utility ensures that the global Social Accounting Matrix (SAM) derived from GTAP 9 remains balanced to maintain the equilibrium conditions in all the markets in the CGE context. It also guarantees that the newly generated entries for the three new sectors exhaust exactly the original SAM entries for the total chemical sector, including bilateral trade flows.

As a result, a new database with 59 sectors is obtained, completely consistent with the original one, which serves as a benchmark for the experiments proposed in section 2.3 of the main body text. Some adjustments are still made in the underlying GTAP structure in order to:

- Introduce land as a primary production factor in the production technology of the bioplastic sector, since it is not considered in the chemical sector from which it is derived.
- Reduce the cost share of both fossil plastics and bioplastics in agriculture and forestry, since the split utility replicates the use of chemicals such as fertilizers and plant-protection products.
- Allow for substitution between plastics and bioplastics in intermediate demand, which constitutes an improvement relative to the study of Lee (2016).

Section 2. Results

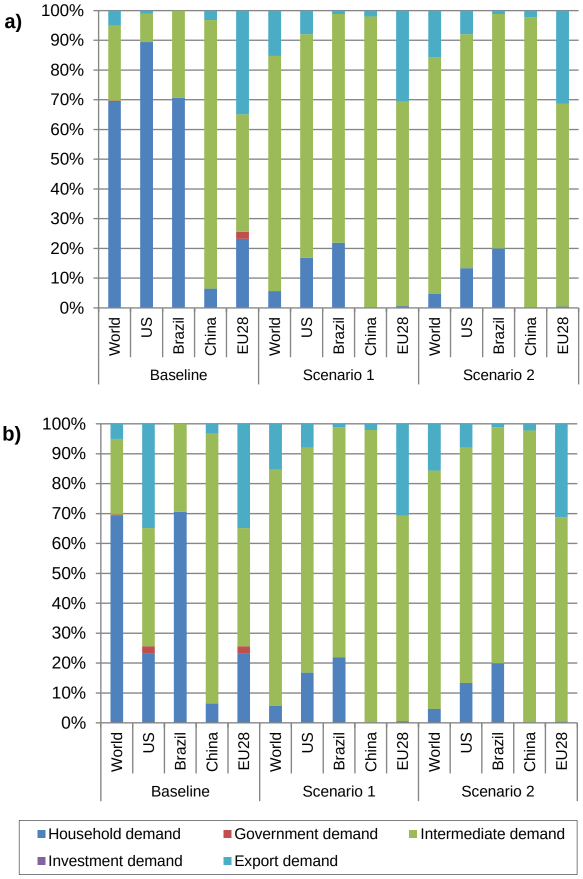

Figure A2. Share of agents’ demand for bioplastics (a) and fossil-based plastics (b), based on quantities in constant US$.

Table A2. Total intermediate demand for bioplastics (constant US$), broken down by sector (%).

	Scenario 1				Scenario 2			
	US	**Brazil**	**China**	**EU**	**US**	**Brazil**	**China**	**EU**
Total (constant US$)	9.99	2.75	15.5	16.02	10.46	2.81	15.5	16.03
PubAdmin, defence, health, education	40.74%	30.91%	14.39%	16.10%	40.63%	30.96%	14.45%	16.22%
Machinery and equipment nec*	7.91%	1.09%	12.97%	11.86%	7.93%	1.42%	13.10%	11.85%
Construction	7.51%	14.55%	6.52%	12.17%	7.46%	14.59%	6.45%	12.16%
Motor vehicles and parts	7.41%	14.18%	4.45%	9.18%	7.46%	14.23%	4.45%	9.17%
Trade	7.11%	1.45%	0.71%	6.24%	7.17%	1.42%	0.71%	6.30%
Paper products, publishing	4.00%	3.27%	4.77%	4.62%	4.02%	3.56%	4.77%	4.62%
Textiles	3.80%	1.09%	6.32%	3.25%	3.73%	1.07%	6.32%	3.18%
Business services nec	3.00%	1.09%	3.68%	7.43%	2.96%	1.07%	3.61%	7.42%
Electronic equipment	2.40%	3.27%	7.23%	0.00%	2.39%	3.20%	7.23%	0.00%
Metal products	1.70%	1.45%	2.19%	2.87%	1.72%	1.42%	2.26%	2.87%
Food products nec	1.70%	1.09%	1.94%	2.37%	1.72%	1.07%	2.00%	2.37%
Recreation and other services	1.40%	0.73%	2.32%	1.56%	1.43%	0.71%	2.32%	1.56%
Wood products	1.40%	0.73%	3.61%	1.25%	1.34%	0.71%	3.55%	1.25%
Manufactures nec	1.00%	1.09%	3.55%	2.12%	0.96%	1.07%	3.61%	2.12%
Mineral products nec	0.80%	1.09%	6.71%	1.81%	0.76%	1.07%	6.65%	1.81%
Transport equipment nec	0.80%	1.09%	1.87%	0.94%	0.76%	1.07%	1.87%	0.94%
Beverages and tobacco products	0.70%	1.09%	0.97%	1.62%	0.67%	1.07%	0.97%	1.62%
Metals nec	0.60%	1.09%	1.87%	1.37%	0.57%	1.07%	1.87%	1.37%
Transport nec	0.50%	1.09%	1.87%	1.12%	0.48%	1.07%	1.87%	1.12%
Petroleum, coal products	0.50%	1.09%	0.52%	0.69%	0.57%	1.07%	0.52%	0.69%
Dairy products	0.40%	0.73%	0.32%	0.94%	0.38%	1.07%	0.32%	0.94%
Ferrous metals	0.40%	1.09%	0.65%	0.87%	0.38%	1.07%	0.65%	0.87%
Wearing apparel	0.40%	0.00%	0.71%	0.69%	0.38%	0.00%	0.71%	0.69%
Meat: cattle, sheep, goats, horses	0.40%	1.09%	0.00%	0.44%	0.38%	1.07%	0.00%	0.44%
Oil	0.40%	1.09%	0.52%	0.37%	0.38%	1.07%	0.58%	0.37%
Water	0.30%	1.09%	0.32%	0.50%	0.38%	1.07%	0.32%	0.50%
Financial services nec	0.30%	0.00%	0.26%	0.50%	0.29%	0.00%	0.26%	0.50%
Coal	0.30%	0.36%	0.45%	0.31%	0.29%	0.36%	0.45%	0.31%
Leather products	0.20%	0.73%	2.97%	0.94%	0.19%	0.71%	2.90%	0.94%
Electricity	0.20%	0.00%	0.26%	0.69%	0.19%	0.00%	0.26%	0.69%
Meat products nec	0.20%	1.09%	0.19%	0.62%	0.19%	1.07%	0.19%	0.62%
Minerals nec	0.20%	1.09%	2.97%	0.56%	0.29%	1.07%	3.10%	0.56%
Communication	0.20%	1.09%	0.00%	0.56%	0.19%	1.07%	0.00%	0.56%
Insurance	0.20%	0.36%	0.00%	0.37%	0.19%	0.36%	0.00%	0.31%
Dwellings	0.20%	0.73%	0.52%	0.37%	0.19%	0.71%	0.52%	0.37%
Animal products nec	0.20%	1.09%	0.26%	0.31%	0.19%	1.07%	0.26%	0.31%
Cattle, sheep, goats, horses	0.10%	1.09%	0.00%	0.31%	0.10%	1.07%	0.00%	0.31%
Raw milk	0.10%	0.73%	0.00%	0.31%	0.10%	0.71%	0.00%	0.31%
Sea transport	0.10%	0.00%	0.32%	0.31%	0.10%	0.00%	0.32%	0.31%
Air transport	0.10%	0.36%	0.00%	0.25%	0.10%	0.36%	0.00%	0.25%
Gas manufacture, distribution	0.10%	0.36%	0.00%	0.19%	0.10%	0.36%	0.00%	0.12%
Gas	0.10%	0.36%	0.00%	0.06%	0.10%	0.36%	0.00%	0.06%
Processed rice	0.10%	0.73%	0.13%	0.06%	0.10%	0.71%	0.13%	0.06%
Vegetable oils and fats	0.00%	0.73%	0.19%	0.44%	0.00%	0.71%	0.19%	0.37%
Sugar	0.00%	1.09%	0.00%	0.31%	0.00%	1.07%	0.00%	0.31%
Fishing	0.00%	0.36%	0.26%	0.19%	0.00%	0.36%	0.26%	0.19%
Wool, silk-worm cocoons	0.00%	0.73%	0.06%	0.00%	0.00%	0.71%	0.06%	0.00%

**nec: not elsewhere classified.*

Table A3. Changes in factor prices (tax inclusive) in land-based sectors, together with bioplastics and fossil-based plastics, as a % change relative to the baseline.

	Scenario 1: subsidy on bioplastics				Scenario 2: tax on fossil-based plastics			
	Land	**Capital**	**Uns. Labor**	**Sk. Labor**	**Land**	**Capital**	**Uns. Labor**	**Sk. Labor**
Total	0.90%	-0.02%	0.01%	-0.02%	0.52%	0.00%	-0.16%	0.09%
Bioplastics		-0.05%	0.05%	0.03%		-0.91%	-1.03%	-0.58%
Fossil-based plastics		-0.04%	-0.06%	-0.11%		0.20%	-0.29%	-0.46%
Other chemicals		-0.03%	-0.02%	-0.01%		-0.26%	-0.39%	-0.09%
Paddy rice	0.14%	0.26%	0.31%	0.52%	-0.06%	0.15%	0.07%	-0.25%
Wheat	1.68%	0.25%	0.35%	0.62%	1.47%	0.32%	0.31%	0.52%
Cereal grains	9.39%	0.39%	0.10%	0.59%	8.95%	0.38%	-0.06%	0.50%
Vegetables, fruit, nuts	0.29%	0.32%	0.32%	0.57%	-0.13%	0.27%	0.10%	0.16%
Oilseeds	0.26%	0.45%	0.30%	0.64%	-0.11%	0.42%	0.18%	0.55%
Sugar cane, sugar beet	1.13%	0.40%	0.35%	0.52%	1.13%	0.36%	0.37%	0.40%
Plant-based fibers	0.11%	0.37%	0.29%	0.75%	0.29%	0.44%	0.27%	0.49%
Other crops	0.19%	0.32%	0.21%	0.45%	0.27%	0.45%	0.41%	0.52%
Forestry	0.27%	-0.03%	-0.02%	-0.04%	-0.68%	-0.04%	-0.40%	-0.46%
Cattle, sheep, goats	0.12%	0.40%	0.39%	0.54%	-0.70%	0.30%	0.08%	0.33%
Other animal products	0.18%	0.45%	0.51%	0.59%	-0.97%	0.06%	-0.16%	-0.03%
Raw milk	0.11%	0.27%	0.23%	0.42%	0.46%	0.45%	0.41%	0.42%
Wool, silk-worm cocoons	-0.36%	0.41%	0.53%	0.51%	-0.68%	0.11%	-0.16%	-0.17%

Table A4. Changes in agricultural sectors' output (constant US$), relative to the baseline (%).

	Scenario 1: subsidy on bioplastics					Scenario 2: tax on fossil-based plastics				
	World	**China**	**US**	**Brazil**	**EU28**	**World**	**China**	**US**	**Brazil**	**EU28**
Paddy rice	-0.05%	-0.16%	-0.41%	-0.11%	-0.31%	-0.05%	-0.17%	-0.51%	0.06%	0.27%
Wheat	0.77%	0.71%	-0.16%	0.02%	2.64%	0.73%	0.63%	-0.18%	0.72%	2.78%
Cereal grains	3.51%	11.13%	5.00%	0.06%	1.88%	3.47%	11.00%	5.03%	0.13%	1.85%
Vegetables, fruit, nuts	-0.06%	-0.22%	-0.23%	-0.10%	-0.08%	-0.06%	-0.08%	-0.29%	0.06%	0.02%
Oilseeds	-0.06%	-0.45%	-0.37%	-0.07%	0.06%	-0.22%	0.52%	-0.93%	-0.16%	-0.06%
Sugarcane, sugar beet	0.55%	-0.24%	-0.20%	1.71%	0.08%	0.53%	0.22%	-0.13%	1.68%	-0.01%
Plant-based fibers	-0.10%	-0.44%	-0.47%	-0.18%	-0.24%	-0.04%	-0.16%	-0.67%	0.07%	-0.03%
Other crops	-0.02%	-0.56%	-0.69%	-0.15%	-0.05%	-0.10%	1.21%	-0.83%	0.04%	-0.12%
Forestry	-0.03%	-0.11%	-0.02%	0.04%	-0.02%	-0.24%	-1.04%	-0.16%	-0.07%	-0.09%
Cattle, sheep, goats	-0.13%	-0.36%	-0.50%	-0.04%	-0.03%	-0.29%	-1.06%	-0.55%	-0.16%	-0.20%
Other animal products	-0.14%	-0.26%	-0.15%	-0.13%	-0.10%	-0.37%	-0.69%	-0.37%	-0.61%	-0.24%
Raw milk	-0.10%	-0.44%	-0.42%	-0.05%	-0.09%	-0.09%	-0.15%	-0.40%	-0.16%	-0.24%
Wool, silk-worm cocoons	-0.13%	-0.82%		0.19%	0.32%	-0.35%	0.05%		-0.54%	-1.88%

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