King, Lewis Carl; van den Bergh, Jeroen C. J. M. «Sugar taxation for climate and sustainability goals». Nature sustainability, Vol. 5, issue 10 (Oct. 2022), p. 899–905. DOI 10.1038/s41893-022-00934-4

Sugar taxation for climate and sustainability goals

Author list

Lewis C. King [1,*] and Jeroen van den Bergh [1,2,3]

Affiliations

[1] Institute of Environmental Science and Technology, Universitat Autònoma de Barcelona, Spain

[2] ICREA, Barcelona, Spain

[3] Institute for Environmental Studies & Faculty of Economics and Business Administration, VU University Amsterdam, The Netherlands

[*] Corresponding author: lewiscarl.king@uab.cat; phone +34-93-586-8773; address: UAB campus, Edifici Z, 08193 Bellaterra (Barcelona), Spain.

Abstract

Meeting environmental sustainability goals while simultaneously recovering from the health and economic crises arising from the coronavirus pandemic requires creative policy solutions. Sugar taxation presents one such policy as sugar crops are arguably the least efficient to consume from a health perspective, but the most efficient for biofuel production. Here, we analyse the sustainability co-benefits of reducing sugar consumption through redirecting existing sugar cropland to alternative uses. Emissions could fall 20.9–54.3 $MtCO_2e\ yr^{-1}$, if the EU were to reduce its sugar consumption in line with health guidelines and the excess Brazilian sugarcane redirected to ethanol. These savings would be around four times higher than an alternative strategy of afforesting existing EU sugar beet cropland and double those from producing sugar beet ethanol in the EU. Achieving this through policies aimed at behavioural change, with a serious role for sugar taxation, would not only reduce the environmental impacts of biofuels but also provide health and economic benefits.

Main text

COVID-19 has presented a challenge in the sense that policies aimed at recovering from the pandemic in both economic[1] and public health[2,3] terms must be aligned with environmental sustainability objectives[4,5]. The EU's 'Recovery Plan for Europe' leans towards this direction by trying to achieve its green priorities alongside the post-pandemic economic recovery through "advancing climate action and promoting environmental and biodiversity protection"[6]. Meeting these simultaneous and competing goals is an unprecedented challenge that requires devising creative policy instruments that can contribute to multiple goals without shifting problems or posing hard trade-offs.

One policy with the potential to simultaneously contribute to economic, environmental, and public-health goals is the taxation of sugar. The overconsumption of sugar has been linked to multiple health issues including diabetes and obesity, which have both been indicated as significant risk factors for severe COVID-19 outcomes[7]. In recent years, levies have been introduced on sugar-sweetened beverages in countries including the UK and Mexico, and early signs suggest they are successful in encouraging a reduction in sugar consumption[8,9].

Although sugar taxation is usually considered for delivering health and economic benefits[10], it has recently been suggested that environmental co-benefits could be achieved by switching sugar consumption to (bio)ethanol production, which could reduce GHG emissions by displacing petroleum[11]. Converting this already existing cropland to ethanol feedstock production would limit the negative effects on sustainability usually associated with biofuel production, such as land-use change (LUC) and food security[12,13]. However, the level of these co-benefits has not yet been quantitatively assessed, so it remains uncertain whether the co-benefits would be significant enough to be worth pursuing.

Here, we aim to further the literatures on both climate policy and sugar taxation by quantitively assessing the emission reductions that could be achieved through regulating sugar consumption. This involves evaluating which particular strategy could maximise the co-benefits. Using the EU as a case in a scenario analysis, we assess the theoretical maximum co-benefits to society from three scenarios of alternative use of sugar cropland that could be achieved by the EU reducing its sugar consumption in line with World Health Organization (WHO) guidelines. We then discuss the potential for the emission reductions to be realised through a policy of sugar taxation across the continent.

The sustainability challenges of biofuels

The complex nature of sustainability is typified by the UN's sustainable development goals, which comprise 17 individual goals with 169 specific targets covering a variety of economic, environmental, and social issues. The connections and synergies between these goals make it particularly challenging to design policies that can help in some areas without exacerbating other problems[14]. Biofuels are a quintessential example of this challenge. Although biofuels may play a necessary role in meeting our climate change goals, they often pressure other targets including food security, biodiversity, and the supply of affordable and reliable energy. It has been estimated that globally achieving not only basic needs, such as food and electricity, but also qualitative goals, like improving healthy life expectancy, would require a resource use 2–6 times beyond the level of the planetary boundaries[15]. Converting sugar consumption to biofuel production would offer a more efficient use of resources that will help reduce the pressure on the key planetary boundaries of climate change, LUC, and biodiversity loss.

Transitioning to renewable energy will be a fundamental part of achieving the Paris climate goals, but moving away from our dependency on fossil fuels while also continuing to supply enough net energy to main current lifestyles is not without its challenges[16]. Nuclear power has become politically unpopular since the Fukushima disaster[17] and the most reliable renewable sources of baseload electricity, hydroelectric and geothermal, are limited by suitable geographical locations[18]. Other renewable electricity sources, particularly solar, wind, and tidal will therefore have to grow at rapid rates over the coming decades. However, for them to completely displace fossil fuels, the additional challenge of mass electrification will need to be addressed.

Liquid biofuels have an advantage over renewable electricity sources as they can directly displace petroleum, particularly for transport uses where electrification will be a slow process. Nevertheless, several challenges need to be overcome to be fully aligned with all sustainable development goals[19,20]. Firstly, there is considerable debate around the level of net energy that biofuels provide to society. This is typically calculated through the concept of energy return on investment (EROI), which is the ratio of useful energy output to society over the energy input to produce it[16]. Corn-based ethanol, the main feedstock used for ethanol in the US, is likely to have a very low EROI of 1.25:1; meaning a positive but small net energy gain[21].

EROI estimates for ethanol produced from sugarcane vary from 3:1 to 10:1, meaning much greater net energy potential even at the less optimistic end of the range[19]. A recent study found that final stage petroleum may have an EROI of around 8:1, which is much lower than typically suggested when viewed at the primary energy stage[22]. Sugarcane ethanol, therefore, offers a fairly competitive replacement for petroleum from a net energy perspective. Ethanol obtained from sugar beet likely has a lower EROI of around 3, but this is still higher than most estimates for corn ethanol and around the minimal level arguably considered necessary to be useful to society[23,24]. There may also be potential for reasonable EROIs to be achieved with organic farming, which would further decrease our reliance on fossil fuels[25].

Biodiversity loss, and associated harm to biosphere integrity, is one of the most pressing sustainability issues. The current rate of loss of genetic, species and ecosystem diversity is considered beyond the zone of uncertainty to cause irreparable changes to the Earth system[26]. Although biofuels may help reduce GHG emissions if they displace fossil fuel use, the LUC associated with them – especially in the tropics – has contributed to serious biodiversity loss[27] and created a “biofuel carbon debt” from LUC emissions[28]. Ethanol production is likely to drive an expansion of the Brazilian sugarcane area 14–58% above

2018 land use, depending upon the level of future ethanol demand[29]. The repeal of the Brazilian agroecological zoning policy for sugarcane in 2019 has exposed ecosystems within the Amazon, Pantanal, and Upper Paraguay River basin to this sugarcane expansion, foretelling further biodiversity loss[30]. Reducing sugar demand can help limit the expansion of sugarcane cropland, resulting in reduced pressure on biodiversity and carbon debt from LUC.

Food security is another concern as biofuel crops must compete with food crops for the limited availability of arable land[13]. Refined sugar, however, is essentially a pure carbohydrate that contains no protein or essential micronutrients, which may lead to a dilution effect on nutrient intake[31]. These empty calories supplied by sugar should not be a priority in a global food system that already supplies sufficient calories but is deficient in protein and micronutrients[32], especially as sugar has been associated with the simultaneous global pandemics of undernutrition and obesity[33]. Converting sugar consumption to ethanol production presents an opportunity that could minimise all of the sustainability issues typically associated with biofuels.

Overview of the sugar industry

Sugar production primarily comes from two crops: sugarcane, which grows in tropical and subtropical zones, and sugar beet, which grows exclusively in temperate zones. The combined sugar crops have accounted for a fairly consistent 24% of total global crop production over the past 20 years, roughly double the vegetable crop[34]. Sugar cane is the largest individual crop, accounting for 21% of total global crop production by weight. Nevertheless, from a land-use perspective, sugar crops are far more efficient than cereals or oil crops and account for only 2% of the global harvested area of primary crops.

In 2019, sugarcane comprised 87.5% of annual sugar production at 1,950 Mt with sugar beet providing the remaining 278 Mt[35]. Figure 1 provides a summary of global sugar crop production by the ten highest producing countries globally and the ten highest within the EU.

Brazil is the largest individual producer, accounting for 34% of the total sugar crop, which is exclusively from sugar cane. With production of 113 Mt yr^{-1}, the EU is the largest producer of sugar beet, accounting for 40.6% of the total global sugar beet crop and 5.1% of all sugar crops. France (33.6% of total EU production), Germany (26.3%) and Poland (12.2%) are the most significant producer countries in the EU.

Sugar crops go through a process of juice extraction, followed by purification, evaporation, crystallisation, and centrifugation to produce raw sugar crystals[36]. Figure 2 shows production (in raw sugar equivalents) and human consumption of centrifugal (after processing in a centrifuge) sugar of the ten highest sugar crop producers, along with human consumption per capita[37]. It should be noted that this data does not include alternative sweeteners such as isoglucose (also known as high-fructose corn syrup), the consumption of which varies significantly across countries.

Brazil is the largest producer of centrifugal sugar and, despite its high consumption per capita, exports around two-thirds of its production, particularly to Asia and the Middle East[38]. Brazil also typically uses 50–60% of its sugarcane crop for ethanol. In 2020/21 Brazil produced 32.2 Gl of sugarcane ethanol[38], around 26% of global ethanol production[39]. The proportion of the crop used for ethanol largely depends on the relative prices of sugar as Brazilian sugar-ethanol mills can switch production between ethanol and sugar.

The EU is largely self-sufficient regarding its sugar consumption, importing around 20% of its sugar supply, often in raw form to be processed in the EU, and exporting around 10% of its production[40]. Around 10% of the sugar beet crop is used for industrial uses, including ethanol production. In 2020, around 2 Gl of ethanol were produced from sugar beet, roughly a quarter of the total production from all feedstocks[41]. The EU average per capita consumption of sugar is 37.3 kg yr^{-1}, which is considerably higher than the global average of 21.3 kg yr^{-1}. Isoglucose is uncommon in the EU, only amounting to 3% of its total sweetener consumption[42].

EU sugar consumption translates to 102.1 grams per person per day. The WHO recommends limiting the intake of sugar to less than 10% of calories and suggests a further reduction to 5%, or roughly 25 grams per day, could have additional benefits[43]. The EU should therefore be aiming for a 75.5% reduction in its sugar consumption to limit the health impacts of sugar consumption.

Environmental co-benefits of reducing EU sugar consumption

If the EU were to reduce its sugar consumption by 75.5% to align with WHO guidelines, it would create an excess production of 12.54 Mt of sugar each year. Sustainability co-benefits could be realised from this excess production. Here, we analyse these potential co-benefits in terms of GHG emissions under three policy scenarios aimed at reducing human sugar consumption and environmental impacts of sugar production: (1) The EU afforests its excess sugar beet cropland, (2) The EU uses its excess sugar beet production for ethanol purposes, (3) the EU exports its excess sugar production, displacing Brazilian sugar exports, and imports an equivalent amount of sugarcane ethanol from Brazil. To simplify the analysis, we assume that isoglucose consumption also falls by 75.5%. However, given the low level of isoglucose consumption in the EU at 3% of total sweeteners, we do not quantify the environmental co-benefits of this reduction.

EU afforestation scenario

In the EU afforestation scenario, we assume that all freed-up EU cropland is afforested to offset GHG emissions. According to USDA data, the EU currently uses 1.50 Mha of land for sugar beet cultivation[40]. A 78% reduction in EU human sugar consumption could shrink EU27 sugar beet production by 87.8%, as the remainder is made up of imports. This would free up 1.32 Mha for other uses – the one with arguably the greatest carbon mitigation potential is afforestation. GHG emissions would be reduced directly from the lower lifecycle emissions in the sugar industry and indirectly, in the category of Land Use, Land Use Change and Forestry (LULUFC), through forest carbon sequestration. Forestation of agricultural lands can also improve biodiversity, nutrient cycling, and water cycling[44].

EU ethanol scenario

In the EU sugar beet ethanol scenario, we assume that the EU switches the excess sugar beet production of 12.54 Mt yr^{-1} to ethanol. The EU could expect to produce 3.26–6.52 (mean 4.89) Mtoe of ethanol from the extra 1.32 Mha dedicated to its production. In this case, direct lifecycle emissions from sugar production will decrease in line with the EU afforestation scenario, but these will be offset by the lifecycle emissions associated with ethanol production. However, indirect emission reductions will also be realised through displaced petroleum demand and its associated lifecycle emissions. No LULUCF emission changes are assumed as the same quantity of cropland would still be in use.

Brazil ethanol scenario

In the Brazil ethanol scenario, the EU keeps its level of sugar production but exports the 12.54 Mt excess instead of consuming it domestically. As a result of the lower global demand, Brazil reduces its sugar production by 12.54 Mt and instead uses this freed-up land to produce ethanol. In total, 1.06–1.31 (mean 1.18) Mha could be freed up – similar to the level in the EU ethanol scenario – which could yield 2.93–7.21 (mean 4.87) Mtoe of ethanol. This level of production is slightly higher than the EU ethanol scenario due to the higher yield per hectare of ethanol from sugarcane[45].

Brazilian GHG emissions from sugar production will fall but, as with the EU ethanol, these will be offset by those associated with the increased ethanol production. There will also be an indirect decline in GHG lifecycle emissions from displaced petroleum. We also assume that the lower global demand for sugar will lessen pressure on sugar cane LUC in Brazil, which is expected to expand 1.2–5 Mha by 2030 and will likely result in LUC in the Amazon rainforest and Cerrado[29]. Indirect benefits may therefore be realised in terms of Brazilian LULUCF emissions by a 1.06–1.31 (mean 1.18) Mha reduction of LUC in Brazil.

The results of the analysis for the three scenarios are presented in Figure 3. The EU Afforestation scenario would result in a mean net reduction of 9.74 (range 4.95–15.43) $MtCO_2e\ yr^{-1}$, which is 0.27% (0.14–0.43%) of the EU's total 3,615 $MtCO_2e$ emissions in 2019[46]. Using existing EU cropland for ethanol production instead of afforestation would result in a higher reduction of 20.11 (range 13.87–27.00) $MtCO_2e\ yr^{-1}$, meaning this approach would be about twice as effective at abating emissions. This level of reduction translates to 2.4% (range 1.7–3.2% of EU transport emissions of 838 $MtCO_2e$ in 2019 [46], which would provide a significant contribution to the EU's goal of a 55% reduction in net emissions by 2030. These emission savings are particularly significant as they mostly relate to reductions in petroleum use, which are challenging to achieve as replacing liquid fuels with renewable electricity sources would require widespread electrification.

The scenario of Brazil producing ethanol instead of the EU was roughly twice as effective at reducing emissions – presenting a strategy to maximise the environmental co-benefits. Reductions in emissions related to petroleum displacement would be 9% higher due to the higher yield and lower energy input of sugarcane over sugar beet. Lower LULUFC emissions in Brazil of 17.53 (range -8.77–28.14 $MtCO_2e$) yr^{-1} would also greatly reduce the effectiveness of reducing emissions on a global scale. Although some of these savings would be indirect, total emission reductions would represent 4.3% (range 2.5–6.5%) of the EU transport sector.

The Brazil ethanol scenario would also produce greater co-benefits in other aspects of sustainability than the other scenarios. As sugarcane ethanol requires far less energy input than sugar beet, this scenario would be much more desirable from a net energy perspective. Assuming a mid-range EROI estimate of 5:1 for sugarcane ethanol as suggested by de Castro et al.[21], 3.9 (range 2.3–5.8) Mtoe of net energy could be supplied to society in the Brazil ethanol scenario. This is approximately 20% higher than the 3.3 (range 2.2–4.3) Mtoe supplied in the EU ethanol scenario, assuming an EROI of 3:1 for sugar beet[23]. Brazilian sugarcane is also one of the most efficient crops for ethanol production in terms of water and nitrogen use as well as there being considerable potential to vastly increase yields[47].

Although the EU afforestation strategy would provide some other environmental benefits such as biodiversity, preserving existing ecosystems in Brazil would provide far greater benefits in terms of biodiversity and ecosystem services.

The analysis above provides indicative values of the potential benefits that could be achieved. A limitation of the study is that not all possible costs, such as transition costs, have been taken into account. These are likely to be lower for the Brazil ethanol scenario due to Brazil already possessing a mature ethanol industry, and hence the ability to switch between ethanol and sugar production. A further limitation is that we did not calculate the emissions related to any increase in alternative sweeteners, such as stevia, which manufacturers and consumers may use as a substitute for sugar. However, this would not affect the relative results as it would be constant across scenarios.

Effectiveness of sugar taxation

Despite continual public health messages about the dangers of excess sugar consumption, EU sugar consumption per capita has remained remarkably flat since 1980, as shown in Figure 4. Over the same period, tobacco consumption – another public health risk – has fallen considerably. EU countries for which data are available show a 51.5% reduction in tobacco consumption from 1980 to 2014 and have been following a steady downward trend since 2000. Ireland has even achieved a tobacco reduction of 75.6% from its per capita peak in 1974, which is in line with the sugar reduction discussed in this paper. This has been achieved through Pigouvian taxes on consumption that correct for the negative health externalities generated from tobacco as well as educational and health policies aimed at behavioural change. This suggests a similar approach could achieve equivalent reductions in sugar consumption.

Over 45 countries have already introduced some form of a sugar tax, typically on sugar-sweetened beverages (SSBs), including the United Kingdom, France, Spain (Catalonia), and Poland[48]. The UK Soft Drinks Industry Levy (SDIL) introduced in April

2018 is one of the most studied of these, and findings suggest sugar consumption in beverages was reduced by 10% one year after implementation[9]. Moreover, the quantity of sugar being consumed per capita had already fallen by 30% between 2015 and 2018 in anticipation of the SDIL[49]. This change came both from producers reformulating their products and consumers shifting their preferences towards low- or zero-sugar alternatives. This suggests that reducing sugar consumption may potentially be easier to achieve than tobacco consumption due to greater substitutability and the incentive for food and drink manufacturers to focus on lower sugar alternatives. There is, therefore, a response on both the supply and demand sides.

A meta-analysis of global SSB taxes found that a 10% tax on the price of an SSB reduced consumption by an average of 10%, suggesting a -1 price elasticity of demand[50]. This is consistent with other studies suggesting a price elasticity of -0.8 to -1.0 for all soft drinks[51]. Sugar taxes would also clearly need to be implemented across other categories of processed foods to achieve the full effect, such as that implemented in Norway on unprocessed sugar and sugar products[52]. The elasticity of -1 applies to a marginal change, and would be unlikely to remain constant across the level of reduction considered. Nonetheless, incrementally increasing and high taxation rates can play a role in achieving the reduction goal, combined with additional policies aimed at achieving widespread behavioural change such as information campaigns, regulation of advertising, or product labels. To illustrate, Chile introduced regulation in 2016 that restricts advertising, mandates warning labels, and prohibits sales in schools for food products high in sugar, calories, sodium, or saturated fat. The first phase of Chile's implementation of the policy has already achieved a 10.2% reduction in sugar consumption and there is an expectation that the following two phases may result in greater changes[53].

In high-income countries, a similar approach for tobacco involving taxation at rates higher than 100% of the price before tax[54], has not only been effective at reducing consumption, raising tax revenue, and reducing health externalities but has also received widespread support from the public. Somewhat surprisingly, there appears to be considerable public support for and perceived effectiveness of sugar taxation. In a UK survey, 70% of respondents supported the SDIL and 71% expected it to be effective[55], which is higher levels of support typically seen for conventional climate mitigation policies such as a carbon tax[56]. A sugar tax could therefore be an alternative route to emission reductions with greater support and fewer political obstacles. On top of this, it would provide a source of tax revenue that governments could invest in other green projects.

Discussion

For sustainability policies to be both efficient and effective, we must consider the full impact across the three – environmental, social, and economic – pillars. Changing how we use sugar crops presents an appealing strategy from this perspective as sugar is arguably the least efficient crop to consume as food from a health perspective, and the most efficient crop for biofuel from a net energy perspective – potentially competitive with petroleum products. Taxation and other regulatory policies as well as educational and health policies aimed at nudging producers and consumers away from sugar consumption have proved to be effective. Although the 75.5% target analysed in this paper would be a great challenge likely requiring the levels of pricing, regulation, and education implemented against tobacco use, it is one the EU should be aiming for purely from a health perspective. Additionally realizing important climate and environmental co-benefits as discussed here makes it a particularly attractive policy tool to support a sustainability transition.

Our analysis confirms that an EU-Brazil agreement with the EU focusing on sugar production from sugar beet and Brazil producing ethanol from sugarcane would provide the greatest environmental benefits to society. Sugarcane ethanol production has also proved to be an economically viable alternative to sugar in Brazil[57]. The economic impact on farmers in both the EU and Brazil would therefore be minimal, resulting in an equitable specialisation across countries that provides welfare gains through reducing negative externalities. It provides a clear example of how broad collaboration can help direct society in a more cohesively sustainable direction. This could be achieved through market mechanisms alone given Brazil's already developed ethanol industry and its ability to switch between sugar and ethanol depending on market conditions. Ideally, an EU-Brazil treaty could help reinforce this to get a stronger and more certain effect.

Tackling climate change indirectly through linking it to health concerns that have widespread public and political support may present an effective complement to traditional instruments, which still face political hurdles. Framing climate change around public health has also been shown to contribute to the public support for and political feasibility of proposed policies[58]. Sugar taxation offers a concrete and practical example of how this can be achieved with careful policy design.

Methods

All data used in the calculations are for the EU27, without the United Kingdom, except for the historic data presented in Figure 4. Sugar crop quantities in Figure 1 are based on production data by the FAO[35]. Figure 2 is based on centrifugal sugar production and human domestic consumption data from the USDA[37], with per capita values calculated by using UN population data[59]. Sugar consumption per capita trends in Figure 4 are based on food supply quantity data by the FAO for the EU28 (including the United Kingdom)[35], with per capita values calculated by using UN population data[59]. Tobacco consumption per capita trends in Figure 4 are presented for a weighted average by population for 16 of the EU28 countries that had complete data for the years 1980–2014 in the cigarette consumption dataset by Hoffman et al. (Austria, Belgium, Bulgaria, Denmark, France, Germany, Greece, Hungary, Ireland, Italy, Netherlands, Poland, Portugal, Romania, Spain, Sweden)[60] .

The three scenarios are based on modelling a reduction in EU sugar consumption to align with WHO recommendations of 25 g per person per day. EU human sugar consumption in 2020/21 was 16.6 Mt based on USDA data and 2020 population is estimated at 445.25 million based on UN data. This gives an EU sugar consumption per capita of 102.14 g per day. The 77.14 g reduction per person per day to meet WHO recommendations would therefore require a 12.54 Mt decrease in total annual EU sugar consumption, which is a 75.5% reduction on current levels of 16.6 Mt.

Net energy quantities are calculated with equation (1):

$$Net\ Energy = Gross\ Energy\left(1 - \frac{1}{EROI}\right) \quad (1)$$

EU afforestation scenario

In the EU afforestation scenario, the 12.54 Mt decrease in sugar consumption is assumed to no longer be produced in the EU. Direct GHG emission reductions from the fall in EU sugar production are calculated using a lifecycle emission range of 0.300–0.643 (mean 0.472) $kgCO_2e\ t^{-1}$ of sugar, based on the preferred substitution method for co-product accounting from Klenk et al.[61].

The EU used 1.50 Mha of land to produce 14.72 Mt of sugar in 2020/21 according to USDA data[40]. The 75.5% reduction in EU human sugar consumption of 12.54 Mt could shrink EU sugar beet production by 85.2% (12.55/14.72). The difference in percentages between consumption and production is due to the remainder being made up by imports. An 85.2% decrease in sugar beet production would therefore result in 1.28 Mha of current cropland being freed up. Reductions in EU LULUCF emissions were calculated using IPCC average rate of carbon uptake values for afforestation in a temperate climate region of 1.5–4.5 (mean 3.0) tC ha^{-1}, applied to the 1.28 Mha of freed up EU cropland[62].

EU ethanol scenario

In the EU ethanol scenario, the freed-up EU cropland is now assumed to be used for ethanol production. Potential EU ethanol production was calculated with an ethanol yield of sugar beet of 5.0—10 (mean 7.5) m^3 ha^{-1} from Manochio et al.[45]. The freed-up 1.28 Mha of EU cropland could therefore produce approximately 6.39–12.78 (mean 9.58) million m^3 of ethanol, which in oil equivalent translates to 3.26–6.52 (mean 4.89) Mtoe with a conversion rate of 1 m^3 of ethanol = 0.51 toe, as used by the European Union[63].

Direct emissions related to ethanol production were calculated with a total lifecycle emission rate of 0.41 $kgCO_2e$ L^{-1} ethanol from Manochio et al.[45] for the 6.39–12.78 (mean 9.58) million m^3 produced. Indirect emission reductions from petroleum displacement were calculated using the EEA lifecycle well-to-wheel GHG intensity value of 93.3 gCO_2e MJ^{-1} for petrol[64]. The intensity value was applied to the quantities of ethanol converted for oil equivalent energy (3.26–6.52 Mtoe) at a rate of 1 toe =41,868 MJ. Emission reduction from the fall in EU sugar production followed the same methodology as Scenario 1.

Brazil ethanol scenario

In the Brazil ethanol scenario, the EU continues producing sugar and sugarcane cropland is now freed up in Brazil for ethanol production. The amount of freed up Brazilian sugarcane agricultural land was calculated assuming an estimated sugarcane agricultural yield of 72–82 (mean 77) t ha^{-1} based on Bordonal et al.[47] and an industrial yield of 0.133–0.144 (mean

0.138) tonnes of total reduced sugars per tonne of sugarcane, based on the past six years of USDA/ATO/Sao Paulo data[38]. Using these assumptions, a reduction in sugar demand of 12.54 Mt would free up 1.06–1.31 (mean 1.18) Mha of cropland (reduced sugar demand/industrial yield/agricultural yield).

Reductions in emissions from Brazilian sugar production were modelled with a 12.54 Mt decrease in sugar production to match the same level of fall in global sugar demand. Reductions were calculated using estimates of lifecycle emissions for refined sugar from Brazilian sugarcane production to be around 0.241–0.307 (mean 0.274) kgCO_2e per tonne of sugar in the literature[65, 66].

Potential Brazilian ethanol production was calculated with an ethanol yield of 5.4—10.8 (mean 8.1) m^3 ha^{-1} from Manochio et al.[45]. With these yields, 5.75–14.13 (mean 9.55) million m^3 of ethanol could be produced from the 1.06–1.31 (mean 1.18) Mha of freed up Brazilian cropland, which in oil equivalent translates to 2.93–7.21 (mean 4.87) Mtoe with a conversion rate of 1 m^3 of ethanol = 0.51 toe[63].

Direct emissions related to ethanol production were calculated with a total lifecycle emission rate of 0.25 kgCO_2e L^{-1} ethanol from Manochio et al.[71]. for the 5.75–14.13 (mean 9.55) million m^3 produced. Indirect emission reductions from petroleum displacement were calculated using the EEA lifecycle well-to-wheel GHG intensity value of 93.3 gCO_2e MJ^{-1} for petrol[67]. The intensity value was applied to the quantities of ethanol converted for oil equivalent energy (3.64–7.27 Mtoe) at a rate of 1 toe = 41,868 MJ.

Brazilian LULUCF emissions were calculated following the 2006 IPCC Guidelines for National GHG Inventories[68]. The tier 1 method for ‘land converted to cropland’ (section 5.3) was adopted using default values for a tropical wet climate region to measure the impact on biomass, dead organic matter, and soils. The uncertainty range in calculations result from the uncertainty ranges given alongside the IPCC assumptions. An annual area of land converted to cropland of 106,000–131,000 (mean 118,000) ha was assumed, which is the total area of 1.06–1.31 (mean 1.18) Mha of freed up cropland divided by ten years (assuming reductions are spread over a ten year period until 2032).

Data availability

The agricultural production data that support these findings are publicly available in the FAOSTAT repository https://www.fao.org/faostat and the USDA Foreign Agricultural Service repository https://www.fas.usda.gov/data.

Additional information

Correspondance and requests for materials should be addressed to L.C.K.

Acknowledgements

The research received financial support from the Spanish Ministry of Science and Innovation through the "María de Maeztu" Programme for Units of Excellence (CEX2019-000940-M) as well as from the European Union through an Advanced ERC Grant under the EU's Horizon 2020 program (grant agreement Nr. 741087).

Author contributions statement

L.C.K. and J. v.d.B. jointly designed the study and wrote the paper. L.C.K. performed the analysis.

Competing interest statement

The authors declare no competing interests.

Figure legends/captions

Fig. 1. Sugar crop production. **a,** Global sugarcane and sugar beet production in 2019. **b,** EU sugar beet production in 2019

Fig. 2 Centrifugal sugar production and consumption. Data for the ten highest global producers of centrifugal sugar production in 2019/20.

Fig. 3. Changes in GHG emissions for the three scenarios. Box plots show the mean and ranges of total change in emissions for the three scenarios analysed, and whisker plots for constituent sectors of each scenario. Result ranges derive from uncertainty ranges in the carbon footprints and yields of sugar and ethanol per hectare of cropland. Full details of underlying assumptions are provided in the Methods.

Fig. 4. EU sugar and tobacco consumption per capita. Sugar consumption per capita is presented for the EU28 countries (including the United Kingdom) and tobacco consumption per capita for the 16 of the EU27 countries that had complete data for the years 1980–2014 in the dataset used (see Methods).

References (main text)

[1] Bai H.M., Zaid A., Catrin S., Ahmed K., & Ahmed A.J. The socio-economic implications of the coronavirus pandemic (COVID-19): A review. International Journal of Surgery 8, 8–17 (2020).

[2] Iacobucci G. Covid-19: Public health must be "at the core" of global recovery plans, say doctors. *BMJ* ; **369,** m2077 (2020).

[3] Lynch J. Health equity, social policy, and promoting recovery from COVID-19. *Journal of Health Politics, Policy and Law* **45**, 983–95 (2020).

[4] Belesova, K., Heymann, D. L. & Haines, A. Integrating climate action for health into covid-19 recovery plans. *BMJ* **370,** m3169 (2020).

[5] McNeely, J. A. Nature and COVID-19: The pandemic, the environment, and the way ahead. *Ambio* **50,** 767–781 (2021).

[6] The European Council. *European Council conclusions, 17-21 July 2020*. (2020). Available at: https://www.consilium.europa.eu/en/press/press-releases/2020/07/21/european-council-conclusions-17-21-july-2020/

[7] Van de Graaf, R. C. & Hofstra, L. Obesity and covid-19: the role of the food industry. *BMJ* ***370****,* m2813 (2020).

[8] Sánchez-Romero, L. M. *et al*. Association between tax on sugar sweetened beverages and soft drink consumption in adults in Mexico: open cohort longitudinal analysis of Health Workers Cohort Study. *BMJ* **369,** m1311 (2020). doi:10.1136/bmj.m1311

[9] Pell, D. *et al*. Changes in soft drinks purchased by British households associated with the UK soft drinks industry levy: controlled interrupted time series analysis. *BMJ* **372,** n254 (2021).

[10] Brownell, K.D. *et al*. The Public Health and Economic Benefits of Taxing Sugar-Sweetened Beverages. *New England Journal of Medicine* **362,** 1250–1250 (2010).

[11] de Andrade, M. A., Watson, J. E. & Maxwell, S. L. Unveiling the environmental benefits of reducing sugar. *The Lancet Planetary Health* **4,** E497-E498 (2020).

[12] Searchinger, T. *et al*. Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. *Science* **319,** 1238–1240 (2008).

[13] Renzaho, A. M. N., Kamara, J. K. & Toole, M. Biofuel production and its impact on food security in low and middle income countries: Implications for the post-2015 sustainable development goals. *Renewable and Sustainable Energy Reviews* **78,** 503–516 (2017).

[14] Lu, Y., Nakicenovic, N., Visbeck, M. & Stevance, A.-S. Policy: Five priorities for the UN Sustainable Development Goals. *Nature* **520,** 432–433 (2015).

[15] O'Neill, D. W., Fanning, A. L., Lamb, W. F. & Steinberger, J. K. A good life for all within planetary boundaries. *Nature Sustainability* **1**, 88–95 (2018).

[16] King, L. C. & van den Bergh, J. C. J. M. Implications of net energy-return-on-investment for a low-carbon energy transition. *Nature Energy* **3,** 334–340 (2018).

[17] Bernardi L, Morales L, Lühiste M, & Bischof D. The effects of the Fukushima disaster on nuclear energy debates and policies: a two-step comparative examination. *Environmental Politics*. **27,** 42–68 (2018).

[18] Moriarty, P. & Honnery, D. What is the global potential for renewable energy? *Renew. Sustain. Energy Rev.* **16**, 244–252 (2012).

[19] Solomon, B. D. Biofuels and sustainability. *Annals of the New York Academy of Sciences* **1185,** 119–134 (2010).

[20] Nazari, M. T., Mazutti, J., Basso, L. G., *et al*. Biofuels and their connections with the sustainable development goals: a bibliometric and systematic review. *Environ Dev* Sustain **23**, 11139–11156 (2021).

[21] de Castro, C., Carpintero, Ó., Frechoso, F., Mediavilla, M. & de Miguel, L. J. A top-down approach to assess physical and ecological limits of biofuels. *Energy* **64**, 506–512 (2014).

[22] Brockway, P. E., Owen, A., Brand-Correa, L. I. & Hardt, L. Estimation of global final-stage energy-return-on-investment for fossil fuels with comparison to renewable energy sources. *Nature Energy* **4,** 612–621 (2019).

[23] Garofalo, P., Mastrorilli, M., Ventrella, D., Vonella, A. V. & Campi, P. Modelling the suitability of energy crops through a fuzzy-based system approach: The case of sugar beet in the bioethanol supply chain. *Energy* **196,** 117160 (2020).

[24] Hall, C., Balogh, S. & Murphy, D. What is the Minimum EROI that a Sustainable Society Must Have? *Energies* **2,** 25–47 (2009).

[25] Atlason, R. S. *et al*. Energy return on investment of Austrian sugar beet: A small-scale comparison between organic and conventional production. *Biomass and Bioenergy* **75,** 267–271 (2015).

[26] Steffen, W. et al. Planetary boundaries: Guiding human development on a changing planet. *Science* **347,** 1259855–1259855 (2015).

[27] Koh, L. P. & Ghazoul, J. Biofuels, biodiversity, and people: Understanding the conflicts and finding opportunities. Biological Conservation **141**, 2450–2460 (2008).

[28] Fargione, J., Hill, J., Tilman, D., Polasky, S. & Hawthorne, P. Land Clearing and the Biofuel Carbon Debt. Science **319**, 1235–1238 (2008).

[29] de Andrade Junior, M. A. U., Valin, H., Soterroni, A. C., Ramos, F. M. & Halog, A. Exploring future scenarios of ethanol demand in Brazil and their land-use implications. Energy Policy **134**, 110958 (2019).

[30] Andrade Junior, M. A., Maxwell, S. L. & Watson, J. E. Renewed threats to Brazilian biodiversity from sugarcane. Frontiers in Ecology and the Environment **18**, 178–180 (2020).

[31] Wong, T. H. T., Mok, A., Ahmad, R., Rangan, A. & Louie, J. C. Y. Intake of free sugar and micronutrient dilution in Australian children and adolescents. *European Journal of Nutrition* **58**, 2485–2495 (2018).

[32] Schmidhuber, J. et al. The Global Nutrient Database: availability of macronutrients and micronutrients in 195 countries from 1980 to 2013. *The Lancet Planetary Health* **2**, (2018).

[33] Mendenhall, E. & Singer, M. The global syndemic of obesity, undernutrition, and climate change. *The Lancet* **393**, 741 (2019).

[34] FAO. World Food and Agriculture - Statistical Yearbook 2020. Rome: Food and Agriculture Organization of the United Nations. (2020). https://doi.org/10.4060/cb1329en

[35] Food and Agriculture Organization of the United Nations. *FAOSTAT*. (2020). https://fao.org/faostat/

[36] Delgado, A. V. & de, A. C. C. *Sugar processing and by-products of the sugar industry*. FAO (2001).

[37] USDA Foreign Agricultural Service. *Sugar: world markets and trade*. (2021). https://www.fas.usda.gov/data/sugar-world-markets-and-trade

[38] USDA Foreign Agricultural Service. *Brazil: Sugar Annual*. (2021). https://www.fas.usda.gov/data/brazil-sugar-annual-7

[39] OECD/FAO. *OECD-FAO Agricultural Outlook 2020-2029,* (OECD Publishing, 2020). https://doi.org/10.1787/1112c23b-en

[40] USDA Foreign Agricultural Service. *European Union: Sugar Annual*. (2021). https://www.fas.usda.gov/data/european-union-sugar-annual-1

[41] European Commission. *EU Agricultural Outlook for markets and income 2018-2030*. (2018). https://ec.europa.eu/info/sites/default/files/food-farming-fisheries/farming/documents/medium-term-outlook-2018-report_en.pdf

[42] European Commission. *EU Sugar Balance 25 February 2021 update*. (2012). https://ec.europa.eu/info/sites/default/files/food-farming-fisheries/farming/documents/sugar-balance-sheet-presentation_en.pdf

[43] World Health Organization. *Guideline: Sugars intake for adults and children*. (2015). https://www.who.int/publications/i/item/9789241549028

[44] Cunningham, S. C. et al. Balancing the environmental benefits of reforestation in agricultural regions. *Perspectives in Plant Ecology, Evolution and Systematics* **17**, 301–317 (2015).

[45] Manochio, C., Andrade, B. R., Rodriguez, R. P. & Moraes, B. S. Ethanol from biomass: A comparative overview. *Renewable and Sustainable Energy Reviews* **80,** 743–755 (2017).

[46] European Environment Agency. *Approximated estimates for greenhouse gas emissions*. (2020). *https://www.eea.europa.eu/data-and-maps/data/approximated-estimates-for-greenhouse-gas-emissions-2*

[47] Bordonal, R. de O. *et al*. Sustainability of sugarcane production in Brazil. A review. *Agronomy for Sustainable Development* **38**, (2018).

[48] Popkin, B. M. & Ng, S. W. Sugar-sweetened beverage taxes: Lessons to date and the future of taxation. *PLOS Medicine* **18,** (2021).

[49] Bandy, L. K., Scarborough, P., Harrington, R. A., Rayner, M. & Jebb, S. A. Reductions in SUGAR sales from soft drinks in the UK from 2015 to 2018. *BMC Medicine* **18,** (2020).

[50] Teng, A. M. *et al.* Impact of sugar-sweetened beverage taxes on purchases and dietary intake: Systematic review and meta-analysis. *Obesity Reviews* **20,** 1187–1204 (2019).

[51] Andreyeva, T., Long, M. W. & Brownell, K. D. The impact of food prices on consumption: A systematic review of research on the price elasticity of demand for food. *American Journal of Public Health* **100,** 216–222 (2010).

[52] Pfinder, M. *et al.* Taxation of unprocessed sugar or sugar-added foods for reducing their consumption and preventing obesity or other adverse health outcomes. *Cochrane Database of Systematic Reviews* (2016). doi:10.1002/14651858.cd012333

[53] Taillie, L. S. *et al*. Changes in food purchases after the Chilean policies on food labelling, marketing, and sales in schools: a before and after study. *The Lancet Planetary Health* **5**, e526–e533 (2021).

[54] World Health Organization. *WHO report on the global tobacco epidemic, 2017*. (2017).

[55] Pell, D. *et al.* Support for, and perceived effectiveness of, the UK soft drinks industry levy among UK adults: cross-sectional analysis of the International Food Policy Study. *BMJ Open* **9**, (2019).

[56] Drews, S. & van den Bergh, J. C. J. M. What explains public support for climate policies? A review of empirical and experimental studies. *Climate Policy* **16,** 855–876 (2015).

[57] Outlaw, J. L. *et al.* Economics of Sugar-Based ethanol production and related policy issues. *Journal of Agricultural and Applied Economics* **39,** 357–363 (2007).

[58] Pillay, C., & van den Bergh, J. C. M. Human Health Impacts of Climate Change as a Catalyst for Public Engagement. *International Journal of Climate Change Strategies and Management* **8**, 578–96 (2016).

References (Methods)

[59] United Nations. *World Population Prospects 2019*. Department of Economic and Social Affairs, United Nations. (2019). https://population.un.org/wpp/

[60] Hoffman, S. J. *et al.* Cigarette consumption estimates for 71 countries from 1970 to 2015: systematic collection of comparable data to facilitate quasi-experimental evaluations of national and global tobacco control interventions. *BMJ* **365** (2019) doi:10.1136/bmj.l2231.

[61] Klenk, I., Landquist, B. & de Imana, O. R. The Product Carbon Footprint of EU beet sugar (Part I). Sugar Industry **137**, 169–177 (2012).

[62] IPCC. IPCC special report land use, land use change, and forestry. (Cambridge University Press, 2000).

[63] European Commission. Review of EU biofuels directive. Energy and Transport Directorate-General, European Commission. (2006). http://ec.europa.eu/energy/res/legislation/doc/biofuels/2006_05_05_consultation_en.pdf

[64] EEA. Quality and greenhouse gas intensities of transport fuels in the EU in 2017. European Environmental Agency. (2019). https://www.eea.europa.eu/publications/quality-and-greenhouse-gas-intensities-1

[65] de Figueiredo, E. B., Panosso, A. R., Romão, R. & La Scala, N., Jr. Greenhouse gas emission associated with sugar production in southern Brazil. *Carbon Balance and Management* **5**, (2010).

[66] Rein, P. W. The carbon footprint of sugar. *Sugar Industry* **135,** 427–434 (2010).

[67] European Environmental Agency. *Quality and greenhouse gas intensities of transport fuels in the EU in 2017*. (2019). https://www.eea.europa.eu/publications/quality-and-greenhouse-gas-intensities-1

[68] IPCC. 2006 IPCC guidelines for national greenhouse gas inventories. (IGES, 2006).