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The environmental and social opportunities of reducing sugar intake

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Sugar is the largest agricultural crop by mass and has seen a rapid increase in consumption around the world. There are widespread public health efforts to curb sugar intake through targeted policies given its association with noncommunicable diseases. Although curbing sugar intake aligns with sustainable diets that meet essential environmental and health targets, such a shift may be challenging from a political economy perspective. Utilizing sugar for other purposes such as the production of microbial protein, biofuels, and bioplastics, or using sugar lands to grow other food items, or rewilding could provide health and environmental win–wins that could be more politically palatable. Here, we explore several potential scenarios to illustrate the option space from which national and international stakeholders could choose locally appropriate pathways for alternative utilization of sugar or its lands. While beneficial, such alternative pathways would require the integration of environmental, economic, and health policies to provide a smoother diet transition that reduces stakeholder tensions. Given the trade in sugar as a commodity crop, international approaches that compensate sugar producers for avoided production or incentivize them for redirecting sugars to other uses will be needed. Such approaches could borrow concepts from Just Transition Partnerships that have been applied to energy system transitions in ensuring a transition for major exporters of sugar cash crops across low- and middle-income nations.

sugar | food system | scenarios | environment | sustainability

Food Transitions Are Urgent

The current food system transgresses many planetary boundaries while failing to provide healthy foods to all. Without deep transformation, food system emissions alone could exceed 1.5 or even 2 °C targets (1, 2). As agriculture occupies approximately half of the habitable land, it also has far-reaching implications on targets for nature-based climate solutions and biodiversity recovery that require large areas of land to be effective (3). A Great Food Transformation consisting of dietary shifts, waste reduction, and production changes is urgently needed to safeguard planetary and human welfare (4, 5).

Given the adverse environmental and health implications of animal-based foods, discourse has focused on the much-needed transition to plant-rich diets. In contrast, the environmental implications of lowering consumption of other unhealthy foods, specifically added sugars, have been largely overlooked. This is partly due to the high caloric yield per land area of sugar production, which contributes a relatively small share (2%) of the food system's greenhouse gas emissions (6), emitted predominantly during production (including field burning before harvest) (7, 8). Given its lower carbon intensity coupled with poor nutritional consequences, reducing sugar intake has sometimes been represented as a potential environment-health tradeoff (9).

However, sugar cultivation has led to significant habitat fragmentation and biodiversity loss (10), resulting from massive land use changes, water uptake, and agrochemical runoffs. This is particularly pronounced for sugarcane, generally produced as a single, no-rotation, monoculture crop in biodiversity-rich tropical settings. Substantial water, soil, and air pollution from sugar mills into local environments have been reported in various locations including the United States of America, Australia, India, and Brazil (11). Reductions in sugar consumption as part of a Great Food Transformation would clearly impact food production, as well as the use of land, water, fertilizers, energy, and more (12, 13). Since sugarcane and sugar beet crops are the largest crops by mass, accounting for 25% of global output (14), reducing sugar intake and/or simply redirecting it to other uses could provide large environmental and health benefits.

Sugar's Role in Human Health

There is a clear rationale for reducing the intake of added sugar on the basis of human health impacts alone. Along with other factors, sugar has been linked to current obesity trends (15–17) and some estimate that half of the global

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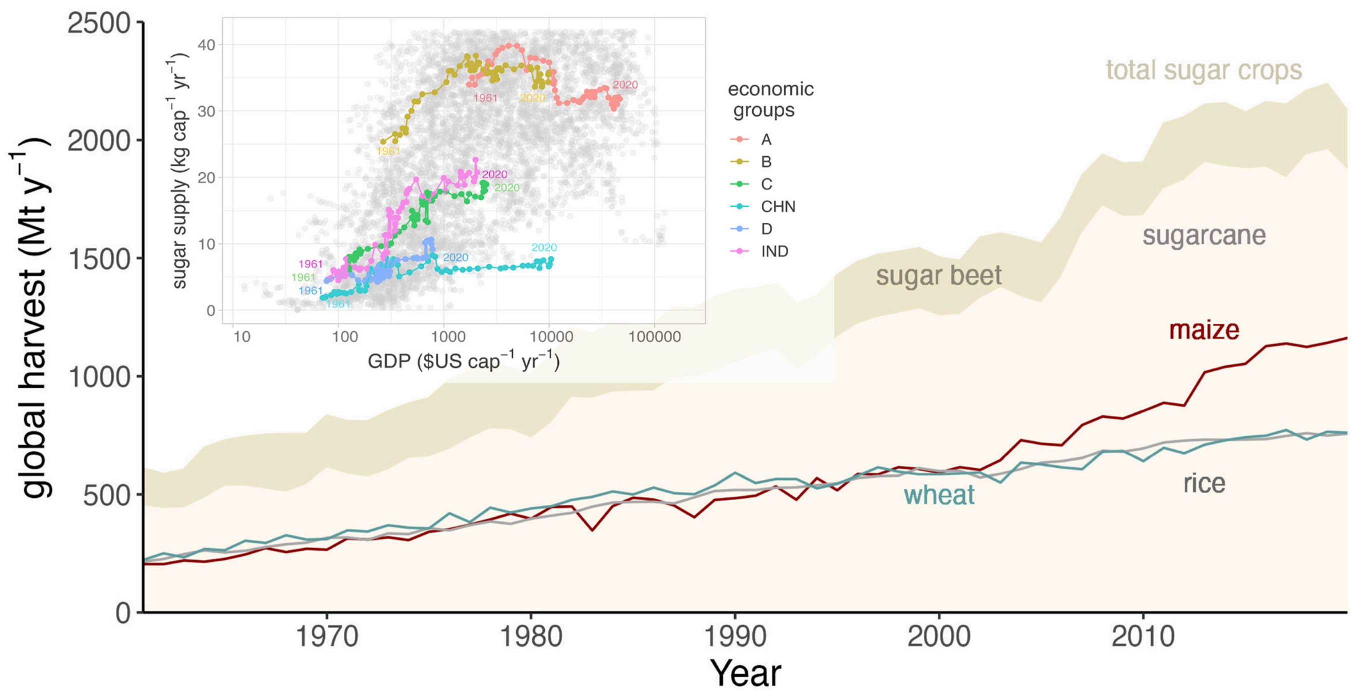

Fig. 1. Sugar production and supply. Global harvest of sugarcane and sugar beet (stacked and collectively referred to as "sugar crops") against major cereal crops and national supply per capita from 1960 to 2020 (*Inset*). Sugar crops contribute roughly 8% of all consumed calories (14, 19) while the presented cereals contribute over 50% (30). Due to their high water content, only around 8% of sugarcane's and 18% of sugar beet's harvested mass end up as raw sugar for supply (31). Countries' sugar supply across this period are presented against their respective GDPs per capita, with GDPs generally increasing with time. Values are based on data from the Food and Agriculture Organization of the UN's database (14) and World Bank. In the *Inset*, CHN stands for China; IND for India and economic groups are divided into high-income (*A*), upper-middle-income (*B*), lower-middle-income (*C*), and low-income countries (*D*).

population could be obese by 2035 (18). Added sugar is the third largest contributor to human caloric intake, accounting for roughly 8% of all calories consumed globally (14, 19) and its intake has quadrupled over the past 60 y (Fig. 1) as part of wider adoption of unhealthy western dietary patterns (20). Critically, added sugars are considered "empty calories" as their refined forms lack beneficial nutrients such as vitamins or fibers. As such, forgoing added sugar consumption will not compromise nutritional security. Current guidelines recommend restricting intake to under 5 to 10% of caloric intake (4, 21–24) as the (over-) consumption of added sugar has been linked to illnesses including diabetes, cardiovascular disease, and cancer, among others (25–28). This overconsumption has raised concern among health officials and policymakers, leading to a call for greater regulation and reduced sugar intake (29).

There is a moderate to strong relationship between national GDP and sugar supply, such that higher-income nations tend to have much higher supply compared to lower-income ones (Fig. 1, *Inset*). The ubiquity of sugar has led to serious nutrition and health issues across many middle- and high-income nations, and consumption is predicted to increase over the next decade due to rising incomes and urbanization, especially in Asia.

The Economic and Political Role of Sugar

In response, policymakers have considered several interventions, including sugar taxes. However, political contestation in countries like Israel has led to the suspension of policies or the elimination of existing taxes, actions that are expected to carry dire public health consequences (32). Some of the controversies surrounding sugar reduction interventions are driven by the economic importance of the sugar economy, estimated at $68 billion dollars annually (33) and its role in global markets with around 40% of sugar traded (34). Powerful sugar stakeholders are known to engage in political lobbying (35) and resulting social dynamics have led to a range of policies which incentivize and protect sugar production and consumption (36, 37).

Addressing these dynamics could be made much easier by providing a variety of different sugar transition options, that would give industries alternative pathways and make efforts to reduce sugar intake politically palatable. For example, reducing sugar consumption according to health recommendations to no more than 5% of dietary caloric intake would spare 483 Mt of sugarcane and 128 Mt of sugar beet (*SI Appendix*, section 1 and Dataset S1) opening up two sets of options. In the first set, sugar production at the field level could be reduced and the spared lands could be rewilded or used to grow other food crops. In the second set, sugar production could be maintained and the mass diverted from direct human consumption could be utilized for other purposes including the production of microbial protein, biofuel, bioplastic, and bioenergy carbon capture and storage (BECCS).

In the reduced production scenarios, the spared lands (predominantly in the tropics, Fig. 2*A*) could be shifted to other environmental or agricultural uses. For example, the saved land, totaling 6.9 Mha for sugarcane and 2.7 Mha for sugar beet, could be used to cultivate other locally significant crops such as vegetables or fruits in regions that suffer from high to moderate food insecurity (Fig. 2*B*) albeit at elevated environmental impacts (Dataset S1). Alternatively, spared lands could be reverted to natural vegetation, and sequester 8.9 Gt CO_2e over the long term. Assuming a linear sequestration

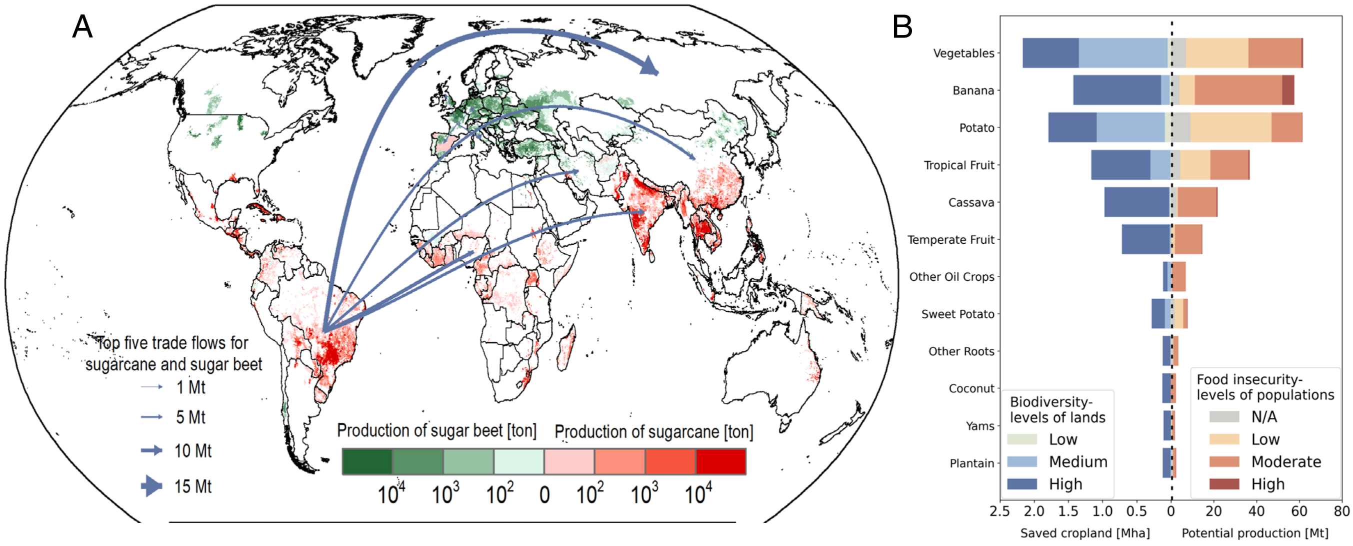

Fig. 2. Global production of sugar and crops produced on spared lands when sugar intake is reduced to 5% of energy intake. (*A*) The global distribution of sugarcane and sugar beet production in 2010. The green and red colors show the spatial distribution of sugar beet and sugarcane production, respectively, measured in metric tons per grid cell. The map is derived from IFPRI's Spatial Production Allocation Model (SPAM) (41). (*B*) Reducing sugar production to 5% of energy intake globally could result in land freed for other crops (left bars) and agricultural production (right bars) already locally produced in those regions. These lands are subdivided by their biodiversity importance (*Left*) and the food insecurity level of populations within them (*Right*).

rate, this equates to 99 Mt $CO_2e{\cdot}y^{-1}$ or around 2 Gt CO_2e over the first 20 y—likely an underestimate as the relationship is generally nonlinear with more sequestration happening in earlier years—while providing significant improvements in biodiversity and environmental impacts. Sparing land may also have other benefits including improved resilience to climate extremes such as floods since natural vegetation serves as a more effective buffer (38) and diversifying sugar crops with other nonsugar crops can improve productivity, maximize profits, and increase soil health (39). In some cases, growing other crops on high-quality spared sugar lands can avoid their cultivation elsewhere, increasing carbon efficiency through avoided expansion (40).

There are further opportunities for ambitious transitions that do not involve reducing sugar production. For example, sugar spared from human diets could be utilized to produce microbial proteins, providing an estimated 15 Mt of protein annually—enough to fulfill the needs of approximately 521 million adults. This protein could, for example, displace 190 $Mt{\cdot}y^{-1}$ of poultry and subsequently save 58 $Gm^3{\cdot}y^{-1}$ of water, approximately 0.71 Gt of $CO_2e{\cdot}y^{-1}$, 108 Mha of land (Table 1 and Dataset S1), and reduce associated water pollution, zoonotic spillover risk, antimicrobial resistance, and more. Naturally, if the protein were to displace beef the resulting environmental benefits would be even larger. Alternatively, the spared sugar could be used to produce 22 $Mt{\cdot}y^{-1}$ of low-density polyethylene (LDPE), around a fifth of global polyethylene production (42), and avoid 48 $MtCO_2e{\cdot}y^{-1}$. Another option is to use the spared sugar to produce approximately 198 million barrels of ethanol (in oil equivalents, or 1.1EJ annually), displace fossil fuel, and lower carbon emissions by roughly 89 $MtCO_2e{\cdot}y^{-1}$. In this biofuel scenario, fermentation emissions from ethanol (precombustion) could be captured, sequestering 35 $MtCO_2e{\cdot}y^{-1}$ (*SI Appendix*, section 1 and Dataset S1).

Reduced sugar production or reutilization of spared sugar would also help progress toward several Sustainable Development Goals (SDGs) (Table 1). For example, human health (SDG 3) is expected to improve across all scenarios. Others are more scenario-specific such as reducing water usage in agriculture (SD 6) or producing energy in the form of biofuel instead of fossil fuels (SDG 7).

National and International Policies

Transforming agri-food systems, and sugar in particular, is challenging given the complex and dynamic nature of supply chains, multiple stakeholders (e.g., governments, private sector, international institutions), and lock-ins manifested through profit-making, power, and existing policies. It can succeed only through a holistic approach that identifies and addresses political economic factors such as the incentives and values of the diverse stakeholders involved, the types of coalitions that can form and their underlying tactics, plausible policy designs, and the specific circumstances (e.g., political opportunities) that can facilitate change (43). In the context of sugar, this translates to the need to implement a range of multisectoral demand and supply policies, considering diverse stakeholders, including consumers, local and international sugar corporations, nongovernmental organizations, and various other institutions.

In recent years, efforts have been made to reduce sugar intake by expanding national sugar taxes and other demand-side policies (e.g., limiting advertisements to children or national awareness campaigns). If demand ultimately does decrease, it can potentially signal a reduction in production, yet this is rarely the case on a global scale as is evident by historical trends (Fig. 1). Sugar taxes cover approximately half of the global population (44) and their imposition has generally resulted in varying degrees of reduced purchases. However, evidence that this has resulted in reduced consumption overall is weak (45). The government of South Africa, for instance, has adopted a health promotion levy, which resulted in the food industry using other sweeteners instead. The reduction in local sugar production stimulated the local government to

Table 1. Scenarios for alternative utilization of spared sugar or spared sugar lands following a reduction in added sugar consumption to 5% of total caloric intake globally

	Scenarios	Harvested sugar mass ($Gt \cdot y^{-1}$)	Reutilization product	Avoided production	Estimated GHG impact	Assumptions	Contribution to SDGs
	Baseline	1.91		N/A	46 $MtCO_2e \cdot y^{-1}$ for production.		
Reduced Sugar production	Rewilding	1.3		0.6 $Gt \cdot y^{-1}$ of sugar crops.	99 $MtCO_2e \cdot y^{-1}$ on average of sequestration over the long term.	Spared land previously used to grow sugar crops is rewilded.	13 (climate), 15 (land), 3 (health), 6 (water)
	Crops	1.3	282 $Mt \cdot y^{-1}$ of crops.	0.6 $Gt \cdot y^{-1}$ of sugar crops.	374 $MtCO_2e \cdot y^{-1}$ for production.	Spared sugar crops land is used to grow other crops.	3 (health)
Reutilization	Bioplastic	1.91	22 $Mt \cdot y^{-1}$ of bioplastic.	22 $Mt \cdot y^{-1}$ of fossil fuel-based plastic.	48 $MtCO_2e \cdot y^{-1}$ avoided.	Bioplastic (LDPE) replaces virgin fossil-based plastics (at a 1:1 ratio) and leads to avoided production of conventional plastic.	13 (climate), 3 (health)
	Protein	1.91	23 $Mt \cdot y^{-1}$ of microbial biomass.	190 $Mt \cdot y^{-1}$ of poultry (live weight).	710 $MtCO_2e \cdot y^{-1}$ avoided.	Microbial protein replaces poultry protein (at a 1:1 ratio) and leads to avoided production of conventional poultry. Assuming 65% protein content in dry microbial biomass, and 20% protein content in the edible portion of poultry (which is 40% of live weight).	13 (climate), 15 (land), 3 (health), 6 (water)
	Biofuel	1.91	52 $Glit \cdot y^{-1}$ of ethanol.	198 million barrels of petroleum per year.	89 $MtCO_2e \cdot y^{-1}$ avoided.	Biofuels replace fossil-based fuels (at a 1:1 ratio) and lead to avoided production of conventional petroleum.	13 (climate), 3 (health), 7 (energy)
	BECCS	1.91			35 $MtCO_2e \cdot y^{-1}$ sequestered.	Assuming capture in the ethanol fermentation process.	13 (climate), 3 (health)

The "baseline" scenario depicts current production and consumption of sugar globally. Reduction scenarios include "rewilding" and crop production ("crops") on spared sugar lands. Reutilization scenarios, with no reduction in sugar production, include bioplastic production ("bioplastic"), alternative protein production ("protein"), biofuel production ("biofuel"), and "BECCS." Estimated positive environmental and social impacts for all scenarios are compared to the "baseline" and direct impacts on SDGs are assessed (*SI Appendix*, section 2).

initiate the Sugar Industry Value Chain Masterplan to increase local production and support local livelihood of smallholder sugar farmers (43). This implies that imposed taxes alone will likely not be sufficient to drive a reduction in production, demonstrating the need for encompassing policies across different domains. At the same time, other demand-side policies—such as restricting advertisement and food labeling—have been less successful due to their lower public visibility, lack of political will, and lower fiscal revenues for governments as well as weaker coalitions, leaving the industry to self-regulate itself (43).

We argue that the much-needed reduction in human sugar intake is likely to see greater political traction if public health policies are coupled with supply-side interventions that give the industry more options in transition pathways (36). Where sugar is redirected to other uses, sugar economies will be mostly left intact, but new sector-wide economic opportunities for energy (biofuels), food (protein), and carbon sequestration (in the form of employment, investments, research and development, etc.) will arise, increasing economic growth, especially in emerging economies where sugarcane is currently produced. These different utilization opportunities might lead to various economic rebounds in production and consumption that would have to be closely monitored. For example, substituting sugar with local crops will increase the price of sugar (and will likely reduce its consumption) but at the same time reduce the price of other healthier crops, which on the one hand provides better access to consumers but on the other hand reduces the revenue for farmers unless regulated.

The alternative pathways we discuss here are largely mutually exclusive; yet policymakers, in coordination with stakeholders, could choose combinations of these opportunities depending on local requirements. Moving forward, comprehensive Multi Criteria Decision Analysis could be conducted in specific locations and settings to help decision-makers realize the most suitable pathways across a wide range of environmental and social considerations.

Alternative sugar pathways offer multiple opportunities but will require concentrated international efforts due to sugar's heavily globalized supply chain spanning more than 100 countries and the millions that depend on its cultivation for livelihood (46). In addition, it is a highly regulated commodity, with national-level policies such as guaranteed minimum prices, production and import quotas, and subsidies, which together create obstacles for change on the one hand but also opportunities through these in-place measures on the other hand. A report of existing initiatives and coalitions to increase sustainable practices within the sugar industry (such as Bonsucro) identified several levers for transformation such as changing mindsets and perceptions, improving incentives, consistency in supporting policies, development of voluntary standards, and profitable business models that facilitate change (46). These on-the-ground initiatives have yet to mobilize a critical mass for change, but they shed light on the path forward for transition within the sugar industry as we envision here.

One approach could be to develop a Sugar Transition Partnership, inspired by Just Energy Transition Partnerships, initiated at COP26, where a consortium of donor countries support the just transition of heavy coal-dependent economies (such as South Africa and Indonesia) by supporting fair economic opportunities and ensuring inclusive participation (47). A Sugar Transition Partnership could be instrumental for major producing and processing sugarcane countries (e.g., Brazil, India, and Thailand) to facilitate a transition by encouraging local sugar industries to either reduce production or divert sugar into more beneficial uses. It can establish a fund to cover at least some of the costs of the transition through developing infrastructure, training, and R&D for various sectors which will be crucial to incentivize the change. In cases where sugar is phased out and livelihoods are compromised, the fund can offer compensations and facilitate the training of new skills. By setting specific standards, partnerships could also facilitate a positive change in labor conditions within the sugar sector through regulation and investments. Resources for this fund could even include redirected funds from high-income nations as a result of avoided sugar-related health expenditures [a limited 20% reduction in sugars is estimated to save $10.3 billion in the United States alone (48)], development banks, and development finance agencies, as well as the private sector. Employing diverse advisory groups with multiple perspectives will be important to developing regional and country-specific master plans that deliver optimal sugar solutions (49). Ultimately, only a multidimensional, full-system's approach can capture the cascading effects of phasing out, replacing, or better utilizing sugar while identifying strategies for global-scale sustainability interventions.

Data, Materials, and Software Availability. 1) Codes (for visualizing Fig. 1) can be found in Github at https://github.com/alonshepon/sugar (50); 2) The FABIO model data can be accessed in Zenodo at (51). All supporting material and data can be found in the supporting information. More details related to the FABIO modeling should be addressed to Z.S.

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