Voluntary sustainability standards could significantly reduce detrimental impacts of global agriculture

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Contributed by S. Polasky, July 12, 2018 (sent for review May 11, 2017; reviewed by Daniel C. Nepstad and Vivek Anand Voora)

Voluntary sustainability standards (VSS) are stakeholder-derived principles with measurable and enforceable criteria to promote sustainable production outcomes. While institutional commitments to use VSS to meet sustainable procurement policies have grown rapidly over the past decade, we still have relatively little understanding of the (*i*) direct environmental benefits of large-scale VSS adoption; (*ii*) potential perverse indirect impacts of adoption; and (*iii*) implementation pathways. Here, we illustrate and address these knowledge gaps using an ecosystem service modeling and scenario analysis of Bonsucro, the leading VSS for sugarcane. We find that global compliance with the Bonsucro environmental standards would reduce current sugarcane production area (−24%), net tonnage (−11%), irrigation water use (−65%), nutrient loading (−34%), and greenhouse gas emissions from cultivation (−51%). Under a scenario of doubled global sugarcane production, Bonsucro adoption would further limit water use and greenhouse gas emissions by preventing sugarcane expansion into water-stressed and high-carbon stock ecosystems. This outcome was achieved via expansion largely on existing agricultural lands. However, displacement of other crops could drive detrimental impacts from indirect land use. We find that over half of the potential direct environmental benefits of Bonsucro standards under the doubling scenario could be achieved by targeting adoption in just 10% of global sugarcane production areas. However, designing policy that generates the most environmentally beneficial Bonsucro adoption pathway requires a better understanding of the economic and social costs of VSS adoption. Finally, we suggest research directions to advance sustainable consumption and production.

sustainability standards | ecosystem services | agriculture | environmental policy | land use change

Increasing agricultural output to meet growing global demand for food, fiber, and fuel is a major driver of ecosystem degradation and biodiversity loss (1–4). Reducing detrimental environmental impacts while maintaining needed agricultural production can be achieved by increasing yields, improving input use efficiency, and targeting agricultural production to areas with lower environmental impact (1, 2, 5–10). While some opportunities for jointly increasing agricultural production and environmental outcomes exist (11), large-scale reductions in the environmental impact of agricultural production will likely require additional incentives for producers to adopt environmentally benign practices (12, 13). Such incentives may include social pressures (i.e., peer pressure to adopt certain practices), price premiums, market access, and/or government-promulgated rewards for adopting certain practices or penalties for not abiding by environmental laws and regulations.

Public policy has traditionally played a key role in driving large-scale transitions toward more sustainable land use (14). Governments have used both involuntary regulatory approaches and voluntary incentive-based regulatory programs to encourage more sustainable agriculture production. Some governments have used mandates via laws to regulate the environmental impact of commodity production (15, 16). However, involuntary mandates tend to be unpopular with agricultural producers, can be economically inefficient, and can be environmentally ineffective where government institutions are weak or political will is insufficient to enact and enforce legal regulations (16–18). For example, the 2012 Brazilian Forest Code seeks to legally protect the conversion of forests and savannas on Brazil's 394 Mha of privately owned lands. However, a recent analysis found that full compliance with the Forest Code offered few economic benefits to landowners (19). Full compliance with the law requires high restoration costs and large opportunity costs of foregone production. In addition, expected landowner costs are low for noncompliance due to poor code enforcement. While registered properties initially showed lower deforestation rates than unregistered ones, these differences diminished over time; moreover, only 6% of registered landowners reported taking steps to restore illegally cleared areas on their properties (19).

Significance

Voluntary sustainability standards (VSS) may be an effective way to reduce the negative impacts of agriculture at regional to global scales. Here, we present an approach that highlights the potential of VSS to reduce some of the negative externalities associated with agriculture production. To illustrate this potential, we show that VSS could reduce the global environmental impacts from growing sugarcane. Further, most of this environmental benefit comes from targeting just 10% of production area. To realize these environmental gains, incentives for VSS adoption need to be sufficient to cover the costs of criteria compliance. Determining these costs and public and private-sector mechanisms for efficiently transferring VSS-adoption subsidies to farmers and millers are key future research needs.

Author contributions: W.K.S., E.N., J.A.J., S.P., J.C.M., J.S.G., P.C.W., S.S., K.A.B., K.M.C., M.A., J.P.R., and D.N.P. designed research; W.K.S. and D.N.P. performed research; W.K.S. analyzed data; and W.K.S., E.N., J.A.J., S.P., J.C.M., J.S.G., P.C.W., S.S., K.A.B., K.M.C., M.A., J.P.R., and D.N.P. wrote the paper.

Reviewers: D.C.N., Earth Innovation Institute; and V.A.V., Central European University.

The authors declare no conflict of interest.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1707812116/-/DCSupplemental.

Incentive-based government policies that pay agricultural producers who voluntarily adopt certain practices or standards of production are much more common in the industrialized world. Examples include the Conservation Reserve Program in the United States (20, 21), the Sloping Lands Conversion Program in China (22, 23), and the European Union's (EU) reformed Common Agricultural Policy (CAP) for 2014 to 2020. The CAP allocates almost 40% of the EU's budget and influences farm management on half of its terrestrial area. EU members can use CAP to design national plans to protect farmland to ensure long-term provision of ecosystem services (24). Such payment programs are less common in the developing world because of the fiscal strain such programs put on government budgets and the lack of compliance efforts (25, 26). And even those payment programs that exist in the developing world are underfunded and fail to achieve the large-scale adoption of better practices that are needed to realize their environmental goals. These programs often receive additional financial subsidies from the private sector and other investment agencies (27–29).

Alternatively, landowners could be pressured by commodity buyers to voluntarily adopt sustainable agricultural production practices. For example, buyer-imposed requirements that the commodity be produced under certain sustainability standards could generate high levels of compliance if buyers enforce their own standards and market incentives meet or exceed a landowner's cost of compliance. Demand-led and/or market-based regulatory instruments may be the best way to achieve desired environmental goals when fiscal and/or political conditions for policy making and effective implementation of government regulations are limited or absent (24). Moreover, without international government-led environmental agreements defining sustainable production goals and criteria, globally consistent agricultural sustainability standards could offer an effective way to make progress on reducing the negative impact of agriculture on the environment at regional to global scales (13, 30–32). For example, achieving Brazil's zero illegal deforestation under a demand-led program would require an effective private–public partnership. The public sector could develop a land registry for standard monitoring and verification (19). In exchange, buyers would need to agree to exclusively purchase commodities grown under the standards. Presumably, enthusiasm for the program will be higher if farmers and millers gain financially from the program (or at least do not generate less in returns) and the program's environmental returns are strong. Any financial incentives provided to complying farms and mills would most likely come from the demand side (33, 34). Thus, a central question is determining how consumer- or buyer-led sustainability standards can contribute to driving large, landscape-scale environmental benefits via a credible set of codes of conduct that are compatible with public contributions to the program and farmer and miller incentives.

Buyer-led agricultural sustainability standards, often referred to as voluntary sustainability standards (VSS), are programs comprised of a system of principles along with measurable and enforceable criteria to promote sustainable outcomes from producing agricultural products. A VSS can be administered by a nongovernmental organization (NGO), government, or the affected industry. Sustainability standards can be defined broadly and can include environmental, labor, and social criteria that promise a road map for sustainable development. Compliance with standards is assessed through an assurance system of independent verification or certification (13). A producer's decision to enroll and comply with VSS is voluntary although demand-led pressure to adopt from some buyers could make a producer's choice less discretionary. A producer's rewards for adopting VSS range widely, including price premiums for production of certified products, greater market access, local norms and a culture of sustainability, and production training and support (35).

The growth of both government and private-sector commitments to supporting sustainable production by purchasing VSS-endorsed commodities illustrates the market potential for VSS to create more sustainable food production around the globe (e.g., www.supply-change.org). Many of these commitments are in response to pressure by consumers, civil society groups, and supply chain actors for more public transparency regarding an institution's efforts to be more sustainable. For example, PepsiCo and The Coca-Cola Company have faced boycotts by India's trade associations amid concerns the companies are using excessive amounts of water to produce their products (https://www.theguardian.com/world/2017/mar/01/indian-traders-boycott-coca-cola-for-straining-water-resources). In response, both companies have made public commitments to sustainably source 100% of their sugarcane procurement via the Bonsucro VSS, which addresses sustainable water use, and, in the case of The Coca-Cola Company, 80% of its global water footprint is associated with the production of sugar (www.bonsucro.com/members/pepsico-2/, www.bonsucro.com/members/the-coca-cola-company/). Achieving these two commitments would drive large-scale adoption of VSS as The Coca-Cola Company alone buys over 5% of the world's sugarcane (https://www.cokecce.com/system/file_resources/148/Sustainable_Agriculture.pdf). The 250 million euro European investment fund eco.business Fund uses VSS compliance as an eligibility criterion for loans (https://www.ecobusiness.fund/about-the-fund/). As for public institution examples, the United Kingdom government is working toward achieving 100% sourcing of credibly certified sustainable palm oil (https://rspo.org/certification/national-commitments), and Minnesota's (United States) state government validates the "sustainable management" requirement of its public forests through certification by the Forest Stewardship Council (FSC) (https://www.dnr.state.mn.us/forestry/certification/index.html). Overall, the volume of VSS-certified products has grown rapidly in recent years. For example, in 2012, the average annual growth rate of VSS-compliant production across all commodity sectors was 41%, an order of magnitude larger than growth in conventional commodity markets (13).

Despite these growing commitments to use VSS, its uptake is still not "mainstream." Uncertainty over and limited information on (*i*) the biophysical, environmental (12, 13), and economic impacts across different levels of VSSs adoption, (*ii*) the challenges of scaling adoption, including any perverse indirect impacts created by an expanding program, and (*iii*) effective pathways for inducing adoption of the standards may be limiting their adoption. If this is the case, shrinking these knowledge gaps could lead to increased uptake in VSS use by industries, producers, and governments.

Here, we present a method for generating a better understanding of the environmental ramifications of both incremental and universal adoption of individual and multiple sustainability standards. We modeled the global environmental impact of the world's sugarcane producers, adopting the environmental standards of the Bonsucro VSS. We focused on sugarcane because it is one of the fastest growing VSS commodity markets and on Bonsucro because it is the leading VSS for the sugarcane sector (13, 35). Bonsucro was established through a multistakeholder process informed by expert guidance, according to international norms set by the ISEAL Alliance, a global umbrella organization for VSS (36, 37). As of 2016, roughly 4.4% of global sugarcane production area had been certified under Bonsucro (36).

We considered environment-related criteria of the Bonsucro VSS that target yield, greenhouse gas emissions due to cultivation ($\mathrm{GHGE_{CULT}}$) and land use change ($\mathrm{GHGE_{LUC}}$), freshwater eutrophication potential, freshwater usage, and impacts on biodiversity via habitat loss (Table 1). Using a global production and ecosystem service modeling framework based on a previously developed yield

Table 1. Bonsucro VSS environmental requirements considered in the study and their expected environmental outcomes

Indicator	Standard	Impact on efficiency	Impact on expansion
Yield	>50th percentile of estimated yields in the year 2000 by climate zone	Increased sugarcane production per unit area	Reduced need for expansion to meet demand
Water quality (eutrophication potential)	<1.05 actual fertilizer inputs per estimated optimum fertilizer inputs*	Increased sugarcane production per unit eutrophication	NA
Water use	>90 kg sugarcane per mm irrigation water applied	Increased sugarcane production per unit irrigation	Reduced expansion into areas where irrigation water demands are high
$GHGE_{CULT}$	<40 kg CO_2eq per metric ton sugarcane	Increased sugarcane production per unit GHG emission	NA
$GHGE_{LUC}$	<50 kg CO_2eq per metric ton sugarcane	NA	Reduced expansion into areas of high carbon stocks

NA, not applicable.

*Fertilizer inputs defined to include nitrogen and phosphorus inputs.

gap approach (5, 6), we evaluated production and environmental impacts from the following VSS-adoption scenario comparisons: (*i*) universal adoption of Bonsucro environmental criteria over all current sugarcane production areas versus current sugarcane production; (*ii*) doubling of global sugarcane production under universal adoption of Bonsucro versus a business-as-usual (BAU) doubling scenario where there is no deliberate attempt to make new production Bonsucro compliant; and (*iii*) incremental adoption of the Bonsucro VSS to maximize its near-term global environmental benefits. We also explored the potential indirect effects, such as the displacement of existing land use, of large-scale uptake of Bonsucro VSS.

Results

Global Sugarcane Production Efficiency and Current Compliance with Bonsucro VSS. First, we assessed the extent of existing sugarcane cultivation that does not comply with Bonsucro's criteria for minimum yield (yield indicator; Table 1), maximum nutrient use (water quality and $GHGE_{CULT}$ indicators; Table 1), and water use (water use indicator; Table 1). We found that 63% of global sugarcane production areas are currently noncompliant with at least one of these criteria (Fig. 1 and *SI Appendix*, Table S1): 40% of global production areas are noncompliant with the yield standard, 44% are noncompliant with the water use standard, and 23% are noncompliant with the nutrient use standard. Patterns of compliance and noncompliance were clustered regionally (Fig. 1 and *SI Appendix*, Table S1). For instance, 52% of rain-fed sugarcane production in South America—a region accounting for 57% (26.7%) of global rain-fed (total) sugarcane production—are compliant with at least two of the three standards (Fig. 1 and *SI Appendix*, Fig. S5). By contrast, only 21% of sugarcane production in South Asia—a region accounting for 50% (26.9%) of global irrigated (total) sugarcane production—are compliant with at least two of the three standards (Fig. 1 and *SI Appendix*, Fig. S5).

Our models suggest that universal adoption of all Bonsucro environmental criteria would mean that 24.3% of current production area would need to be abandoned, resulting in a 10.6% reduction in sugarcane production, 65.3% reduction in water use, 33.4% reduction in nutrient loading, and 51.2% reduction in GHG_{cult} emissions relative to current conditions (*SI Appendix*, Table S1). These potential impacts are clustered regionally, with the largest potential water use and nutrient loading reductions found in South Asia (Fig. 1 and *SI Appendix*, Table S1); this region, currently the second largest in global sugarcane production, also shows the largest reductions in existing production area and production tonnage. By contrast, other regions, such as Central Africa, could potentially see large increases in production tonnage (+219.0%) by increasing nutrient application rates according to the Bonsucro environmental criteria, with the trade-off of potential increases in eutrophication potential (+104.9%) and GHG_{cult} emissions (+29.3%). This finding is generalizable to many regions in Africa that appear to be currently low yielding due to underapplication of nutrients N and P (*SI Appendix*, Figs. S3 and S4).

Global Sugarcane Expansion Potential and Compliance with Bonsucro VSS. We estimated the amount of current forest, savanna, grassland, and shrubland in climates suitable for sugarcane production ("available natural land") (*Methods*) that would be compliant with Bonsucro environmental criteria if converted to sugarcane. The relevant indicators in this case were total greenhouse gas emissions from land clearing ($GHGE_{LUC}$ indicator; Table 1) and irrigation

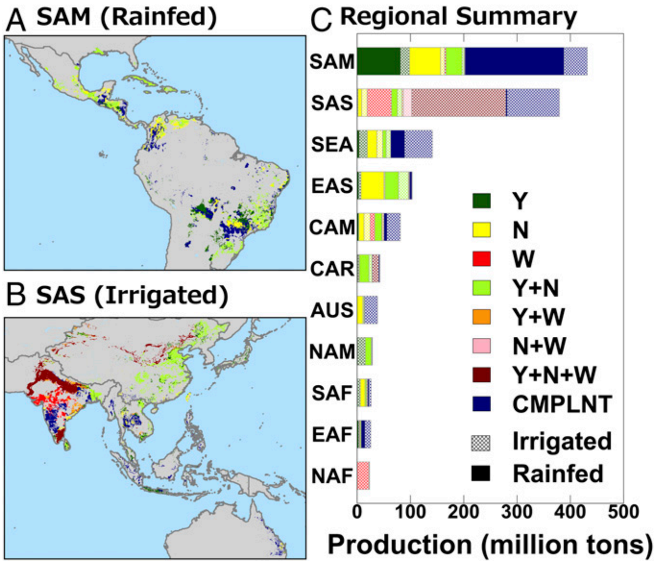

Fig. 1. Compliance with Bonsucro VSS environmental indicators affecting sugarcane production efficiency. Areas currently noncompliant with different combinations of yield (Y), water use (W), and nutrient application (N), as well as areas identified as fully compliant with these criteria (CMPLNT) (Table 1). (*A*) Spatial pattern of compliance across major rain-fed production areas in and around South America (SAM). (*B*) Spatial pattern of compliance across major irrigated production areas in and around South Asia (SAS). (*C*) Regional summary of compliance partitioned by irrigated and rain-fed production. Roughly 63% of global sugarcane production is noncompliant with at least one of the indicators considered. AUS, Australia; CAF, Central Africa; CAM, Central America; CAR, Caribbean; EAF, East Africa; EAS, East Asia; NAF, North Africa; NAM, North America; SAF, South Africa; SAM, South America; SAS, South Asia; SEA, Southeast Asia; WAF, West Africa.

water use per unit of sugarcane produced (water use indicator; Table 1). We found that only 5% of available natural land could be converted to sugarcane and comply with the $\mathrm{GHGE}_{\mathrm{LUC}}$ indicator (Fig. 2). High carbon density of available natural land is the main factor that would drive noncompliance with the $\mathrm{GHGE}_{\mathrm{LUC}}$ indicator (*SI Appendix*, Fig. S6) if available natural land was converted to sugarcane production. Areas that would be compliant with the $\mathrm{GHGE}_{\mathrm{LUC}}$ indicator are clustered in arid regions where carbon losses are low relative to sugarcane yields, especially in the case of irrigated sugarcane (*SI Appendix*, Fig. S6). When considering both the $\mathrm{GHGE}_{\mathrm{LUC}}$ and water use indicators, only 4% of available natural land would be compliant with Bonsucro, due to the high-water requirements of sugarcane production on drylands (Fig. 2 and *SI Appendix*, Fig. S6). The combination of these two indicators excluded all available natural forests from consideration for complaint production (*SI Appendix*, Tables S1 and S2). By contrast, 73.6% of land currently in agriculture other than sugarcane and in climates suitable for sugarcane production—termed "available managed land" (*Methods*)—would be compliant across both the $\mathrm{GHGE}_{\mathrm{LUC}}$ and water use indicators (*SI Appendix*, Fig. S7). Low carbon density of available managed land is why most of these lands would be compliant with the $\mathrm{GHGE}_{\mathrm{LUC}}$ indicator.

Potential Future Environmental Outcomes with Doubled Sugarcane Production. Next, we explored the potential environmental gains of large-scale adoption of the Bonsucro VSS under a doubling of global demand for sugarcane, a widely assumed future for the global sugarcane sector (38). We compared the environmental impacts of spatially allocating sugarcane production in such a way that the doubling of global sugarcane tonnage is fully compliant with the full Bonsucro environmental criteria (BON scenario) to the environmental impacts of a business-as-usual doubling where there is no deliberate attempt to make new production Bonsucro compliant (BAU scenario) (*Methods*).

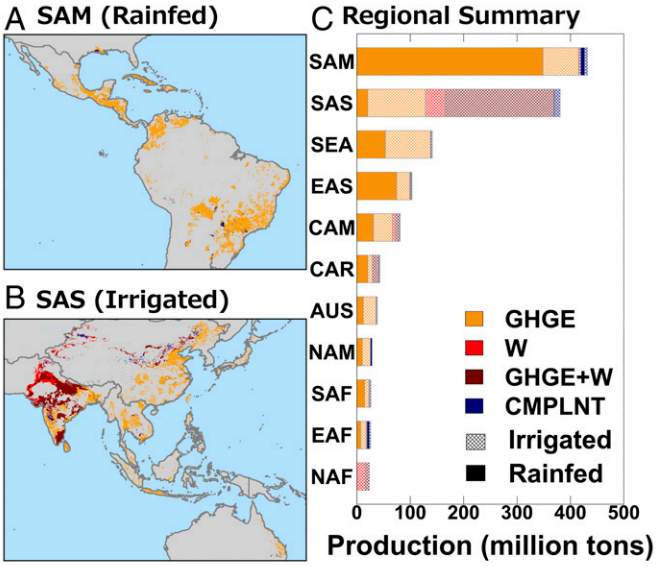

Fig. 2. Compliance with Bonsucro VSS environmental indicators affecting the expansion of sugarcane production into natural areas. Natural areas are defined to include relative wildlands outside crop and pasturelands (e.g., forests, grasslands, and savanna ecosystems) (*Methods*). Areas currently noncompliant with different combinations of $\mathrm{GHGE}_{\mathrm{LUC}}$ (GHGE) and water use (W), as well as areas identified as fully compliant with these criteria (CMPLNT) (Table 1). (*A*) Spatial patterns of compliance for expansion of rain-fed sugarcane production within South America. (*B*) Spatial patterns of compliance for expansion of irrigated sugarcane production within South Asia. (*C*) Regional summary of the total production within each of these categories for both irrigated and rain-fed sugarcane production areas. If sugarcane were expanded outward from existing production areas, roughly 96% of encountered natural areas would be noncompliant with at least one of the Bonsucro indicators affecting expansion. Same regional abbreviations are used here as in Fig. 1.

Eutrophication potential, water use, $\mathrm{GHGE}_{\mathrm{CULT}}$, $\mathrm{GHGE}_{\mathrm{LUC}}$, and available natural land conversion are reduced by 27 ± 11.6%, 47 ± 9.8%, 46 ± 11.7%, 99 ± 0.6%, and 96 ± 0.9%, respectively, in the BON scenario relative to BAU (Fig. 3 and *SI Appendix*, Tables S1 and S2). These environmental benefits are partially the result of an increase in available managed land conversion of 58 ± 26.5% in the BON scenario relative to BAU (Fig. 3 and *SI Appendix*, Tables S1 and S2). Water use in areas of high to severe water stress (*SI Appendix*, Fig. S8) (31) is 66 ± 8.6% lower in the BON scenario relative to BAU. Conversion of natural forest and savanna ecosystems in regions of high biodiversity (*SI Appendix*, Fig. S9) (32) is 95.8 ± 0.9% less in the BON scenario relative to BAU. Notably, this avoidance of available natural land areas in the BON scenario is mainly due to an 88 ± 40.4% increase in available managed land conversion in high biodiversity regions under the BON scenario relative to BAU.

We also measured the environmental tradeoffs of achieving each Bonsucro VSS environmental standard alone while doubling current production. Each of these single criteria complaint scenarios generated spatial patterns of sugarcane expansion different from the full compliance BON map. We conducted these analyses to better understand the potential unintended environmental consequences of partial adoption of Bonsucro criteria rather than the previously assumed adoption of all environmental criteria (*SI Appendix*, Fig. S10). We found that compliance with the yield standard alone, without changes in resource use efficiency, resulted in large increases in eutrophication potential (10 ± 2.3%), freshwater use (9 ± 1.3%), and $\mathrm{GHGE}_{\mathrm{CULT}}$ (13 ± 1.8%) relative to BAU. Adoption of only the water use standard results in disproportionate expansion into areas of high carbon stocks (27 ± 10.6%) and natural habitat (12 ± 5.3%) relative to BAU. Adoption of the GHG emissions associated with the land use change ($\mathrm{GHGE}_{\mathrm{LUC}}$) standard alone resulted in increased rates of managed land conversion and displacement of other crop and pasture production (93 ± 1.7%) relative to BAU.

Targeting Incremental Large-Scale Bonsucro VSS Adoption. Our previous scenario analyses estimated the global environmental benefits from the universal adoption of Bonsucro's environmental criteria; however, this degree of adoption is likely unrealistic, especially in the near-term. Therefore, we also explored potential practical pathways for incrementally targeting the future adoption of Bonsucro VSS in sugarcane production. A targeting algorithm's set of production areas it could choose from was defined by the BAU scenario's spatial pattern of doubled global sugarcane production. A targeting algorithm incrementally chooses which production areas to convert to Bonsucro VSS-compliant production. We considered two different targeting algorithms for incremental adoption: (*i*) Areas that are closest to complying based on their percent deviation from compliance with the Bonsucro VSS criteria are adopted first ("maximizing compliant production area strategy"), and (*ii*) areas that are furthest from complying with Bonsucro VSS criteria based on their percent deviation from compliance with the Bonsucro VSS criteria are adopted first ("maximizing additional direct environmental benefits strategy") (*Methods*). Under the maximizing compliant production area strategy, ∼37% of the global sugarcane production area is converted to Bonsucro compliant before any direct additional environmental benefits relative to BAU are realized. This outcome is explained by the fact that ∼37% of global sugarcane production was estimated to already be compliant with the Bonsucro environmental criteria (Fig. 4). In contrast, under the maximizing additional direct

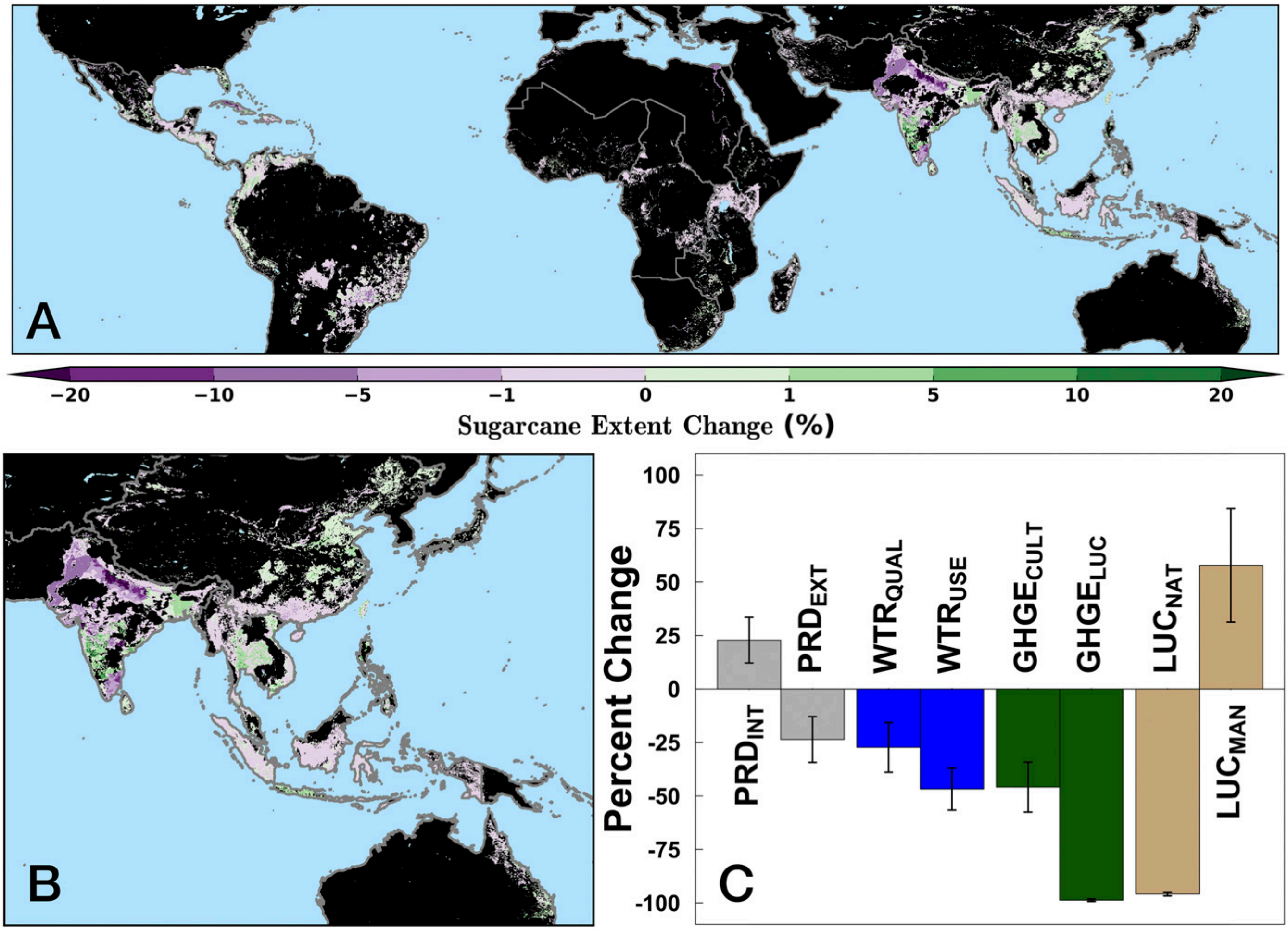

Fig. 3. The potential impact of global uptake of Bonsucro VSS environmental indicators under future doubled sugarcane production. The spatial difference between the Bonsucro (BON) and business-as-usual (BAU) scenarios for (*A*) global and (*B*) Southeast Asia production areas. Values indicate increased (green) or decreased (purple) sugarcane production areas under BON relative to BAU. (*C*) The relative change across environmental indicators under BON relative to BAU. Reported are the mean values across an ensemble of model runs that account for uncertainty in yield, nutrient demand, water demand, GHG emissions, and land use change. GHGE$_{CULT}$, greenhouse gas emissions associated with cultivation; GHGE$_{LUC}$, greenhouse gas emissions associated with land use change; LUC$_{MAN}$, conversion of managed land to sugarcane; LUC$_{NAT}$, conversion of natural land to sugarcane; PRD$_{EXT}$, extensified production; PRD$_{INT}$, intensified production; WTR$_{QUAL}$, water quality; WTR$_{USE}$, water use. Error bars represent 2 SDs of the mean.

environmental benefits strategy, converting only ∼10% of global sugarcane production area is required to achieve more than 50% of the potential environmental benefits realized under the full BON scenario (Fig. 4*A*). The large difference in incremental efficacy of these two targeting approaches demonstrates the importance of objective definition—maximizing compliant area versus maximizing environmental benefits per unit area—when targeting future VSS adoption.

Discussion

We find significant potential for environmental and production efficiency improvements across the global sugarcane sector. We also demonstrate that adoption of the environmental criteria in the Bonsucro VSS, whether incrementally targeted or universal, would greatly reduce the direct environmental damage caused by sugarcane production. We found that the potential environmental benefits of the Bonsucro VSS are driven largely through two major changes in current sugarcane production patterns. First, Bonsucro VSS adoption shifts production away from arid ecosystems where annual freshwater use exceeds the water use indicator (Fig. 3). The environmental benefit of this shift is most notable in areas identified as high to severely water-stressed (39). In these areas, under the doubling of sugarcane production scenario analysis, we found that Bonsucro VSS compliance (the BON scenario) reduces total annual water use by sugarcane by 66 ± 8.6% relative to BAU (*SI Appendix*, Fig. S8). Indeed, a third of the current sugarcane production area in India, the second largest producer of sugarcane globally, cannot comply with the water use indicator. Such shifts away from current major production areas highlights a significant challenge for those seeking to meet VSS commitments via 100% compliance with Bonsucro. Second, any level of sugarcane expansion under Bonsucro VSS adoption shifts expansion toward managed lands, thus sparing the direct conversion of high carbon density natural ecosystems (Fig. 3).

That expanded production under the Bonsucro VSS (the BON scenario) prevents the direct conversion of natural lands, including forest and savanna ecosystems, is especially important given the growing trend of “deforestation-free” or “land conversion-free” commitments by the private sector. In addition to meeting “conversion-free” policy goals, incremental or universal Bonsucro VSS adoption also promotes production intensification and improves water and climate mitigation outcomes, thus highlighting the value of multicriteria standards to help deliver multiple outcomes and the potential shortcomings of developing and

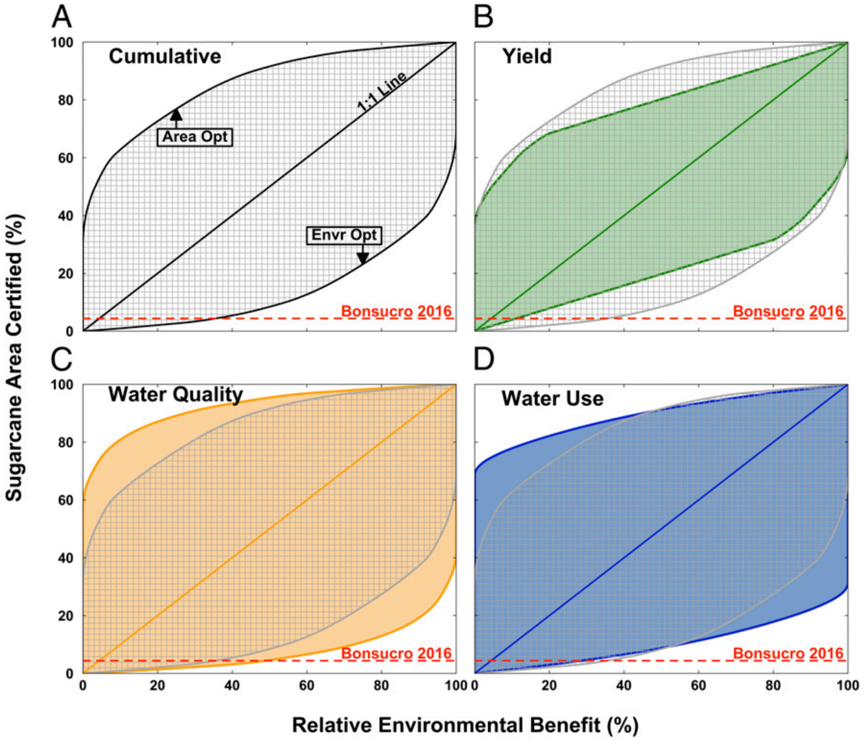

Fig. 4. Uptake of cumulative (*A*), yield (*B*), water quality (*C*), and water use (*D*) Bonsucro VSS environmental indicators and the associated range of potential environmental benefits. The hatched areas in all panels represent the integrated range of potential environmental benefits for a given level of Bonsucro VSS uptake whereas solid colored areas correspond to the range for each individual indicator. Because both the GHG_{CULT} indicator and the water quality indicator are largely driven by current nutrient application rates, we only report on the latter for simplicity. For comparison, current Bonsucro VSS uptake (Bonsucro 2016) is represented by the red dotted line. The range of potential environmental benefits with respect to Bonsucro VSS uptake are bounded by two scenarios of incremental adoption: (*i*) adoption designed to maximize total Bonsucro-compliant production area (Area Opt) and (*ii*) adoption designed to maximize additional environmental benefits (Envr Opt).

promoting single-criterion VSS (e.g., zero-deforestation) to achieve net environmental benefits over multicriteria VSS schemes, like Bonsucro.

However, the net environmental gain of implementing the Bonsucro environmental VSS criteria would surely be less than gross gains presented here due to the indirect land use change impacts of adopting and complying with the criteria. Expansion of sugarcane into existing managed lands would push some existing agricultural production into available natural lands. This trade-off is most notable in areas identified as biodiversity hotspots (40) where, under the doubling of sugarcane production scenario analysis, Bonsucro VSS compliance (the BON scenario) drives an 88 ± 40.4% increase in other crop and pasture land conversion relative to the BAU scenario in which expansion into high carbon density regions is not restricted (*SI Appendix*, Fig. S9 and Table S1). This potential displacement of other crop and pasture land could have a substantial environmental cost, particularly if these displaced land uses are not held to similarly rigorous VSS criteria (33, 41). Coordination across VSS for different commodities, in addition to the larger physical and policy landscape, will be important to minimize unintended consequences from unequal enforcement of standards. However, even without such coordination, leakage effects could be reduced if the Bonsucro VSS were to adopt a more aggressive yield indicator (e.g., yield gap closure to the 70th percentile by climate zone), thus increasing production on existing land and reducing the need for land expansion.

We also found that only complying with individual criteria of the Bonsucro VSS, rather than all environmental criteria, results in unintended detrimental environmental outcomes (*SI Appendix*, Fig. S10). For instance, under the doubling of sugarcane production scenario analysis, we found that compliance with the Bonsucro yield standard criterion alone, without also adopting the additional Bonsucro standards and criteria driving resource use efficiency, increases global eutrophication potential (10 ± 2.3%), freshwater use (9 ± 1.3%), and $GHGE_{CULT}$ (13 ± 1.8%), relative to BAU. On the other hand, we found that compliance with just the standard and criterion for reducing GHGE from land use change ($GHGE_{LUC}$) reduces expansion into high carbon natural areas relative to BAU, by funneling expansion into other crop and pasture production areas potentially driving detrimental indirect effects (93 ± 1.7%). Understanding the potential synergies and trade-offs across multiple environmental outcomes when producers only comply with select criteria should be a focus of future research and is an important consideration in the future improvement of VSS design and implementation. These issues are especially important for VSS such as Bonsucro that require less than 100% compliance for producer endorsement or certification (i.e., producers can choose a subset of environmental criteria to follow).

While we showed large potential benefits of the global adoption of the Bonsucro VSS, the rate of incremental gain in environmental benefits per unit of Bonsucro uptake varies widely depending on the targeting strategy (Fig. 4). We found that over half of the potential environmental benefits from the global universal adoption of Bonsucro VSS (the BON scenario) are achieved by targeting VSS adoption in just 10% of potential global sugarcane production area. This indicates that most of the environmental benefit generated under the Bonsucro-compliant doubling scenario is attributed to a relatively small amount of sugarcane production area. The efficiency of targeting land that generates the most benefit per unit area is a critical insight for those stakeholders who support adoption of VSS as an effective way to reduce the impact of agricultural production on the environment versus those who only base VSS impacts on market adoption. Many VSS supporters track progress based on the total area of production enrolled under VSS rather than a quality adjusted measure of uptake. For example, World Wildlife Fund for Nature (WWF), a founding member of Bonsucro, established a target whereby 25% of global sugarcane production area is enrolled under Bonsucro by 2020 (wwf.panda.org/our_work/markets/mti_solutions/certification/agriculture/sugarcane2/bonsucro/). Similar targets have been set by major corporate buyers of sugarcane. However, such production-based targets ignore the tendency for most early adaptors to be in places where VSS compliance is most readily achieved, not necessarily those that can generate the most environmental benefit per area. Since ~37% of global sugarcane production is currently compliant with Bonsucro environmental criteria (Fig. 1), 37% adoption of Bonsucro is needed before any additional environmental benefits are realized (Fig. 4). In other words, focusing on quantity of uptake rather than quality of uptake could mean much less new environmental benefit from incremental adoption of the standards. Therefore, environmentally effective incremental adoption of VSS requires targeting of production areas that are underperforming relative to the VSS criteria (33). To do this, incentives for VSS adoption (e.g., price premiums, public and private financial funds, technical information, market access) need to be sufficient to overcome the costs of compliance on land furthest from complying with Bonsucro VSS criteria (42–44). Determining these costs is a key future research priority that has implications for VSS and land-use policy, generally.

Finally, our analysis also highlights the uneven impact that widespread adoption of Bonsucro VSS could have on sugarcane producers' economic livelihoods. For example, we found large regional differences in the ability to comply with Bonsucro VSS criteria (Fig. 3). Reducing or eliminating sugarcane production in such noncomplaint regions (e.g., water-stressed areas in South Asia) is almost certain to cause socioeconomic hardships for people dependent on the regional sugarcane industry. How to meet environmental standards while not imposing undue social and economic burdens remains an important open question.

Conclusions

We demonstrate the potential of Bonsucro—one of the largest and fastest growing global voluntary sustainability standards (VSS)—to reduce eutrophication, water use, greenhouse gas emissions, and natural ecosystem conversion. A better understanding of the potential large-scale sustainability outcomes associated with VSS adoption is vital to determining the optimal contribution that VSS, as part of a portfolio of sustainability policy mechanisms, can make to national and global sustainability commitments and development goals (e.g., United Nation's Sustainable Development Goals) (45). VSS or other sustainability policies for commodity production can use the analytical framework presented here for design and assessment of specific indicators, identification of leverage points, exploration of incentives for widespread adoption, and insight into potential leakage and other indirect market effects. For example, this framework could be adapted to define goals for how much adoption or market penetration is needed to have impact beyond the local level. This approach also provides a logical framework for integrating the assessment of environmental standards with social and economic factors, a key next step and priority research area in sustainability science.

Our framework also presents the opportunity for the agriculture VSS community to rigorously reassess standard design in a more explicit outcome-based and forward-looking way. It is important to separate standards from their implementing mechanism. The standards (i.e., the principles, criteria, and indicators) define the "rules of the game" for producers. The implementation mechanism can be demand-led or market or governmental regulation. Therefore, standard design is paramount to defining what outcomes can be expected from a VSS certification or a law. Such information could improve standard efficacy and illustrate the potential value from supporting its adoption.

The Bonsucro VSS is unique among existing agriculture VSS schemes in that it uses a performance or metric-based approach to standard design that leverages basic agronomic and conservation principles that could be readily adapted to many commodity sectors. A more common approach to standard design, often described as practice-based, tends to have less explicit, more relative (to baseline conditions) and directional criteria and associated indicators. Moreover, Bonsucro strives to enhance both production intensification and reduced extensification by setting standards to promote production efficiency and reduce natural land conversion. Better understanding of how these design choices affect the environment and adoption patterns can inform the broader private and public-sector debate on the utility of VSS in driving the achievement of sustainable development goals (45).

VSS of the Bonsucro design potentially offer an effective mechanism to manage commodity supply reliability risks, reduce environmental impacts, and meet the growing consumer preference for sustainable products regardless of state actions to increase product sustainability. The results of this research inform long-term commodity sourcing strategies by assessing regional differences in producers' basic ability to meet VSS. These strategies can be adjusted to avoid increasing procurement from areas where complying with VSS will remain a challenge until best practices can be scaled and innovations introduced such that compliance is achievable. Commodity sourcing strategies can also seek to increase procurement in areas where compliance is readily achievable and may also drive greater productivity with a smaller environmental footprint. Moreover, we illustrate the need for VSS, or any land-use policy, to be evaluated within the context of the larger physical and policy landscape. VSS can ultimately only be effective if they complement other landscape-wide efforts.

Our results suggest that the realization of the potential environmental benefits of VSS schemes will depend on (*i*) accounting for and limiting indirect effects that could undermine direct environmental benefits and (*ii*) effective intervention to bring current production areas that are underperforming relative to the Bonsucro VSS environmental criteria. Thorough assessment of the costs of VSS adoption and the incentives is needed to drive adoption for farmers, buyers, and customers.

Future research is needed to improve understanding of the explicit economic cost (e.g., management related) and related barriers (e.g., market access) of targeting adoption of VSS in underperforming areas, which can increase the incremental environmental benefits of VSS. To attain such targeting may require leveraging diverse policy and incentive instruments, including public and private financing mechanisms, regulatory controls, and institutions to mitigate up-front economic barriers to compliance and increase benefits to producers and value chain actors of certification in these areas. This analysis provides a first step toward a more comprehensive understanding of the role of VSS in driving a global transition toward sustainable agriculture.

Methods

The spatially explicit sugarcane yield and extent data used in this analysis are originally based on data from ref. 46 and are available at www.earthstat.org/ as the "Harvested Area and Yield for 175 Crops" dataset. These data were computed with national, state, and county level agricultural census statistics from the period 1997 to 2003 and distributed to a 5-arc minute spatial resolution based on satellite observations of global cropland area. We used the reference time period of 1997 to 2003 since it predates the initiation of the Bonsucro sustainability standard and thus allowed an unbiased evaluation of the potential environmental benefits of standard implementation. Our yield maps give a multiyear average to account for differences between higher yielding first and lower yielding ratoon crop cycles (36). The multiyear average also reduces the impact of year-to-year variation due to weather. Yield data were partitioned into irrigated and rain-fed based on output from the Global Crop Water Model (GCWM) (47). These are the same yield data used by Bonsucro to define yield targets for global sugarcane production and thus enable a focus on the impacts of the policy (*SI Appendix, Text S1*).

Empirically derived yield models were developed for rain-fed and irrigated sugarcane production using a nonlinear least squares algorithm to fit climate-response curves to yield distributions by climate zone (*SI Appendix, Text S2*). We next developed nutrient-response curves that explicitly consider soil quality and current rates of nitrogen and phosphorus fertilization using a combination of the best available data to calculate actual, optimum, and excess nutrient application rates (*SI Appendix, Texts S3* and *S4*). We finally utilized the Liebig law of the minimum to estimate the combined effects of water, nitrogen, and phosphorus inputs on yield (*SI Appendix, Texts S3* and *S4*).

We utilized outputs from our global modeling to calculate a global map of sugarcane production in terms of percent deviation from compliance across the full set of environmental criteria considered (*SI Appendix, Text S5*). We evaluated the potential impacts of the Bonsucro sustainability standard by considering a hypothetical future of doubled sugarcane production. We then compared a business-as-usual (BAU) scenario against a Bonsucro (BON) scenario in which all sugarcane production shifts to compliant with the full Bonsucro environmental criteria considered (Table 1), allowing the evaluation of the direct potential environmental benefits of large-scale uptake of Bonsucro sustainability standards (*SI Appendix, Text S6*). We quantified the sensitivity of our global model to four key model inputs: (*i*) estimated sugarcane yields, (*ii*) estimated nutrient demand, (*iii*) estimated irrigation demand, and (*iv*) estimated carbon stocks. We assumed that these spatially explicit model inputs had a variation of ±10%, and their respective uncertainties were propagated by iteratively running the model for all combinations of minimum and maximum input values, resulting in 16 total model runs (*SI Appendix*, Table S3). We report the mean across the ensemble of model runs and represent uncertainty as 2 SDs of the mean (*SI Appendix, Text S7*).

ACKNOWLEDGMENTS. We gratefully acknowledge support for this research from the Luc Hoffmann Institute, The World Wildlife Fund, and The Coca-Cola Company Partnership, University of Minnesota's Carlson School of Management, the Belmont Forum/FACCE-JPI/NSF funded DEVIL project (Grant NE/M021327/1), NSF Award 1540195, the Gordon and Betty Moore Foundation, and the US Department of Agriculture National Institute of Food and Agriculture Hatch Project HAW01136-H managed by the College of Tropical Agriculture and Human Resources. The funders had no role in study design, data collection, or analysis, decision to publish, or preparation of the manuscript.

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