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Deforestation-Free Commodity Supply Chains: Myth or Reality?

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Abstract

Since the early 2000s, many private companies, public-private coalitions, and governments have committed to remove deforestation from commodity supply chains. Despite these zero-deforestation commitments (ZDCs), high rates of deforestation persist and may even be increasing. On the upside, a few region- and commodity-specific ZDCs have contributed to reductions by up to hundreds of thousands of hectares of deforestation, with mixed evidence on associated leakage. ZDCs have also spurred progress in monitoring, traceability, and awareness of deforestation. On the downside, as currently implemented, supply chain initiatives only cover a small share of tropical deforestation. Government- and company-led ZDCs are just two components of broader policy mixes aimed at reducing deforestation. To be more impactful, ZDCs needs to cover entire biomes, supply bases of companies, and export and domestic markets, with special attention not to exclude marginal producers.

Contents

1. INTRODUCTION

The conversion and degradation of forests have major impacts on the terrestrial carbon cycle (1), water and energy balance (2), biodiversity, and the livelihood of forest communities, including Indigenous groups. Most losses of tropical forests are associated with agriculture (3). Among agricultural commodities, cattle ranching is by far the leading direct cause of deforestation, followed by palm oil and soy, and a few non-staple (cocoa, coffee, plantation rubber) and staple (rice, maize, cassava) crops (4, 5).

Nongovernmental organizations (NGOs) have campaigned to end tropical deforestation (6), which led to numerous pledges by public and private actors to address the issue, collectively referred to as zero-deforestation commitments (ZDCs). In 2010, the Consumer Goods Forum pledged that its members would mobilize their collective resources to help achieve zero net deforestation by 2020. In 2012, the Tropical Forest Alliance was created as a multistakeholder partnership to support the implementation of private-sector commitments to remove deforestation from commodity supply chains (**https://www.tropicalforestalliance.org**). This alliance includes companies, government entities, civil society, Indigenous peoples, local communities, and international organizations. Members of the financial sector followed suit in 2013 with the Banking Environment Initiative's "Soft Commodities" Compact pledge to help achieve zero net deforestation by 2020.

Zero-deforestation commitments (ZDCs): in this article, also refers to all actions and initiatives adopted to implement these commitments

In 2014, the New York Declaration on Forests called for global action to halt natural forest loss by 2030, restore degraded landscapes and forestlands, improve governance, increase forest finance, and reduce emissions from deforestation and forest degradation (**https://forestdeclaration.org**). In 2015, the Amsterdam Declarations on Deforestation and Palm Oil included nine European countries that aimed to cooperate with private sector and producer country actors to achieve

deforestation-free commodities. In 2021, the Glasgow Leaders' Declaration on Forests and Land Use was signed at the 26th UN Climate Change Conference. More than 140 countries—who jointly cover 90.9% of the world's forests—committed to working collectively to halt and reverse forest loss and land degradation by 2030 while delivering sustainable development and promoting an inclusive rural transformation.

In parallel, national-level pledges have been made to align forest conservation with climate goals, such as Colombia's National Zero Deforestation Agreements that are public-private partnerships in several commodity sectors (7). Moreover, hundreds of companies have made public pledges to eliminate deforestation from their operations by a target date, either associated with specific commodities and/or regions or across entire supply chains (8). While some of these pledges are vaguely formulated, others led to company codes of conduct with specific actions (8). Some company commitments are consolidated as precompetitive pledges, e.g., the Cocoa and Forests Initiative to end deforestation associated with cocoa production (9, 10; see also **https://www.worldcocoafoundation.org/initiative/cocoa-forests-initiative/**).

Today's banner of zero-deforestation governance thus encompasses policy domains that include individual and collective commitments made by companies and governments, and the multistakeholder apparatus and public policies in place to support their implementation. It is not yet known to what extent ZDCs meet their objectives of eliminating deforestation among suppliers of specific supply chains and whether, together, they reduce overall deforestation regionally or globally (11). Here we address three questions: (*a*) Have ZDCs been effective at reducing deforestation overall and in specific supply chains? (*b*) Which conditions need to be met for ZDCs to be effective at eliminating global deforestation? (*c*) What are the main challenges ZDCs need to overcome to contribute to sustainable land use? We build on recent studies published since previous reviews on this topic (8, 11).

2. EFFECTIVENESS OF ZERO-DEFORESTATION COMMITMENTS

We evaluate, first, whether global deforestation has decreased and, second, whether ZDCs have been effective at reducing deforestation in specific supply chains. For the former, we analyze data on forest cover change and agricultural production in key forest countries with active forest frontiers. For the latter, we rely on impact evaluations of ZDCs for specific commodities and regions. We then review ex ante evaluations on the adoption of ZDCs by private sector actors—noting that adoption is only a prerequisite for success.

2.1. Trends in Overall Deforestation

The latest Global Forest Watch, based on annual updates of Hansen et al.'s (2013) data (12, 13), shows that the tropics lost 11.1 million hectares of tree cover in 2021, including 3.75 million hectares within tropical primary rainforests. Rates of tropical forest loss seem to be on an upward trend over the past decade—of course caution is required when analyzing multidecadal trends in tree cover loss due to methodological challenges (14). Other studies also measured a marked increase in deforestation and degradation of tropical forests after 2010 (1, 15).

In a few countries, most notably Indonesia and Malaysia, primary forest loss has declined since 2016 despite an expansion of oil palm plantations, one of the leading regional causes of forest loss (16, 17). By contrast, the rate of primary forest loss in Brazil due to agricultural expansion increased by 9% from 2020 to 2021. Bolivia and the Democratic Republic of Congo also experienced rapidly increasing rates of deforestation since 2010 (13). In sum, tropical deforestation persists at high, increasing rates despite more than a decade of ZDCs. These trends do not necessarily mean ZDCs were ineffective, given a lack of counterfactual: Recent deforestation could have been even greater without ZDCs. However, ZDCs have thus far failed to reverse global deforestation.

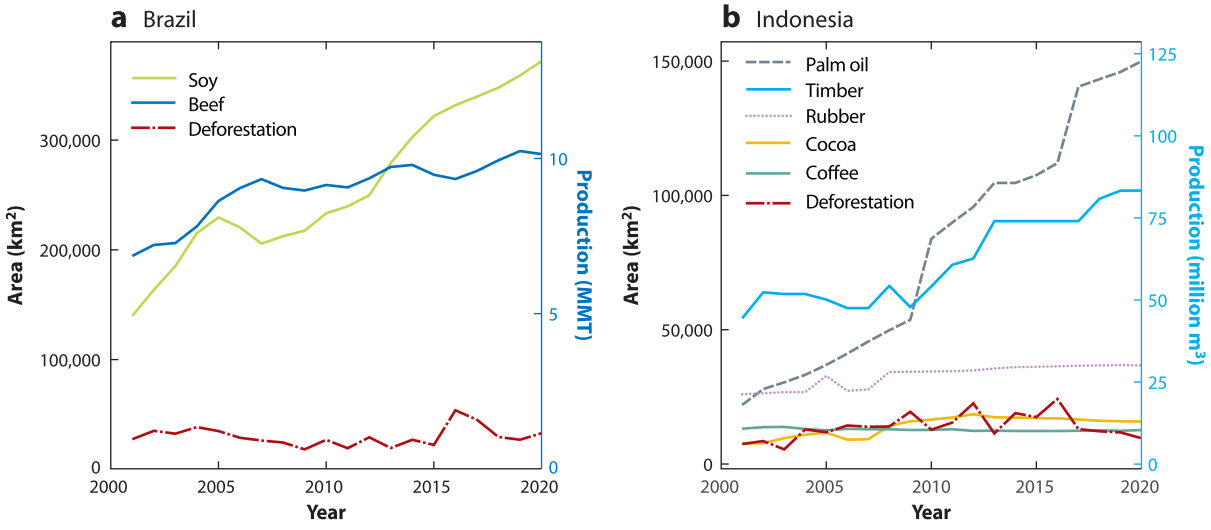

Figure 1

Deforested area and areas under cultivation for forest-risk commodities in two commodity powerhouses: (*a*) Brazil: tree cover loss (in km^2), soy (in km^2), and beef [in million metric tons (MMT)]; (*b*) Indonesia: tree cover loss (in km^2), palm oil (in km^2), rubber (in km^2), coffee (in km^2), cocoa (in km^2), and timber (in million m^3). For beef and timber, we show volumes of production because national statistics on areas under exploitation are unreliable. Only industrial roundwood is reported for timber. Data based on 2022 FAOSTAT (**https://www.fao.org/faostat/en/#home**) and UN Comtrade (**https://comtrade.un.org/**) data. The quality of FAOSTAT crop data varies across countries.

Supplemental Material >

Forest-risk commodities: main commodities, such as beef, soy, palm oil, cocoa, coffee, rubber, and timber/pulp, whose expansion contributes to deforestation

Amazon Soy Moratorium (ASM): signed in 2006 by the Brazilian Association of Vegetable Oil Industries and National Association of Grain Exporters, whereby these traders agreed not to purchase soy from newly deforested areas in the Brazilian Amazon biome

High-resolution remote sensing data revealed that, from 2001 to 2015, 27% of global forest loss was attributed to deforestation through permanent land use change for commodity production (18). National-scale data on cropland area for the main forest-risk commodities in the top producing countries show that commodity crop expansion was correlated with—although not necessarily a direct cause of—deforestation in several countries (**Figure 1**, **Supplemental Figure 1**). **Figure 1** also suggests that agricultural expansion in some countries and for some commodities is not associated with forest cover change. In these countries, most cropland expansion occurs on land already cleared for other uses or in nonforest regions, and other crops contribute to deforestation, including staple crops.

As most of **Figure 1** and **Supplemental Figure 1**'s graphs show, the area of forest conversion is much smaller than the area of expansion of forest-risk commodities. Oil palm and soy have caused massive forest conversion in the past decades, but their contribution to direct forest loss decreased recently. For beef production and timber extraction, total production shows a clear upward trend over the past decade. Land clearing for some of these commodities is still expanding in several countries.

2.2. Evidence on Impact of Zero-Deforestation Commitments in Specific Supply Chains

For a few regions and commodities, multiple studies have evaluated the effectiveness of ZDCs at reducing deforestation. These are reviewed below.

2.2.1. Brazilian Amazon Soy Moratorium: a success. Brazil represents more than one-third of global soy production. In 2006, Brazilian producer associations signed the Amazon Soy Moratorium (ASM) after a naming-and-shaming NGO campaign linking major traders and some of their

consumer-facing clients to deforestation in the Brazilian Amazon. These traders were responsible for 90% of the trade in soy produced in the Amazon. With the ASM, they agreed not to purchase soy from newly deforested areas in the Amazon biome. The ASM was initially signed for 2 years and then renewed year-by-year until 2016, when it was renewed indefinitely. The ASM became the first formal commitment for a deforestation-free supply chain involving multiple industry actors.

Leakage: occurs when an intervention to promote sustainable land use by restricting production in one region displaces unsustainable agricultural practices to another region

Between 2006 and 2014, only 1% of new forest clearing in the Brazilian Amazon biome was associated with soy expansion (19). Most soy expansion in the Amazon took place on pastures that had been cleared before the ASM cut-off date. A study evaluated deforestation trends before and after the ASM in the state of Mato Grosso, which accounts for approximately 85% of the soy grown in the Amazon biome (20). Based on MODIS satellite data, a sharp reduction in annual deforestation rate was observed immediately after implementation of the ASM, as well as a decrease in forest conversion to soy cultivation. Many cropland areas under soy that were cleared before the ASM had undergone intensification in the form of double cropping (20).

A study isolated the impact of the ASM from that of simultaneous policy and macroeconomic changes (21). A counterfactual analysis was created by comparing changes in deforestation rates on soy-suitable portions of the Amazon biome and on locations not suitable for soy in the same biome and in forests in the Cerrado biome. The study concluded that the ASM had a substantial effect on deforestation rates in the Amazon, preventing 18,000 ± 9,000 km^2 during 2006–2016. The ASM contributed to reinforce public policies that were already leading to a decline of deforestation in Brazil before the ASM was signed. The ASM only contributed one-quarter of this decline (21). A study based on a general equilibrium model found that the ASM led to 82 kha of gross avoided deforestation per year during 2011–2016 (22), an estimate on the lower bound of Heilmayr et al. (21). A subsequent study exploited variations in market shares of ASM companies across municipalities (23). It estimated that the ASM only reduced deforestation for soy expansion by 57% in municipalities where most soy was sourced by the signatories to the ASM. Overall, the ASM reduced total deforestation in the Amazon by 1.6% during 2006–2015 compared to a counterfactual with no ZDC. Incomplete market coverage of the ASM left more than 50% of soy-suitable remaining forests outside the reach of ZDCs (23).

With the implementation of the ASM, soy farmers in the Amazon biome suffered from relatively few immediate restrictions beyond those already imposed by the Brazilian Forest Code and by biophysical limitations on the agroecological suitability for soy cultivation. Only 1% of the existing soy farms in the Amazon biome had soy-suitable, forested areas that could be deforested lawfully at the time of ASM (24). Moreover, the biome had a large stock of land that was already cleared before the ASM cut-off date and was suitable for soy expansion (19). Thus, the ASM was a market-based mechanism for the enforcement of existing land use policies by soy traders. Its success was made possible by government policies that expanded protected areas, increased enforcement efforts on public land and private properties, supported a satellite-based forest monitoring system, and created the Rural Environmental Registry (25). Moreover, the neighboring Cerrado biome had a great potential for cropland expansion and had already benefited from large agricultural investments. High rates of deforestation in the Cerrado biome led to calls to implement a Cerrado soy moratorium (26, 23), which met opposition by producers' associations.

Indirect deforestation, mostly in the form of a displacement of deforestation between soybean and cattle production, was found to be responsible for more than half of the deforestation associated with soybean expansion in the state of Mato Grosso after ASM implementation, both at the level of properties (27) and municipalities (28). We discuss leakage associated with the ASM in Section 4.5, below.

Recently, the conversion of forest to soybean has increased from the 2008–2009 to the 2019–2020 periods, and soybean cultivation that is noncompliant with the ASM went from less than

0.07% in 2008 to more than 6% in 2019 (29). This trend was associated with a reduction of resources for enforcement of land use regulations by Bolsonaro's government and its public support for critics of the ASM.

Cattle agreements (CA): beef and leather retailers and meatpacking companies sourcing from the Brazilian Amazon signed in 2009 legally binding Terms of Adjustment of Conduct agreements to stop purchasing cattle from properties with illegal deforestation; the largest meatpacking companies operating in Brazil signed in the same year a zero-deforestation agreement with Greenpeace whereby they committed to block sales from properties that were unregistered or had experienced deforestation after 2009

2.2.2. Brazil's cattle agreements: low effectiveness but significant impact. Cattle production is the main cause of deforestation in Brazil. Two-thirds of the land that has been cleared in the Amazon and Cerrado biomes has been converted to cattle pasture (30). In response to pressures from the Federal Public Prosecutor's Office in the state of Pará in Brazil, the beef and leather retailers and meatpacking companies signed in 2009 legally binding Terms of Adjustment of Conduct agreements (referred to as the MPF-TAC agreements) to stop purchasing cattle from properties with illegal deforestation. Similar agreements were subsequently signed in the main states of the Brazilian Amazon. Together, these cattle agreements (CA) covered 75% of the major slaughterhouses (31). In the same year, the largest meatpacking companies operating in Brazil signed a zero-deforestation agreement with Greenpeace (referred to as the G4 agreement) after a naming-and-shaming campaign linking retailers and brands in the leather and meat sectors with deforestation in the Amazon. Meatpacking companies committed to block sales from properties that were unregistered or had experienced deforestation after 2009. The MPF-TAC agreements target illegal deforestation as defined by the Brazilian Forest Code—i.e., forest clearing that reduces native vegetation cover below 80% on properties in the Amazon biome. The G4 agreement prohibits any forest clearing, whether legal or not.

Only direct suppliers—i.e., selling directly to slaughterhouses—are concerned by these CA. Indirect supplying properties, such as calving and breeding ranches, are largely left off the hook, even though they are mentioned in both CA (32). Both CA were conceived to mimic the soy moratorium, despite differences between the two sectors. Supply chains in the cattle sector are more complex and less concentrated than in the soy sector (33), with more than 130 slaughterhouses just in the Legal Amazon. Unlike soybeans, cattle are highly mobile over their lifetime and move between three farms on average prior to slaughter (34). They can be bred or fattened on multiple ranches with deforestation not in compliance with the CA, and then sold to slaughterhouses from a ranch in compliance. This facilitates cattle "laundering" to intentionally escape CA rules. Due to cattle movements, monitoring forest clearing associated with a cattle herd cannot be performed reliably by satellite remote sensing alone.

Data on daily cattle purchases by slaughterhouses before and after the CA show that slaughterhouses reduced purchases from recently deforested properties in the Amazonian state of Pará. Moreover, properties selling their cattle directly to slaughterhouses had lower deforestation rates after the CA, in part because they had little forest left given higher pre-agreement deforestation rates (35). Deforestation was three times more likely on properties that were entirely outside the reach of the CA slaughterhouses. This does not imply a causal link as forest clearing could have been displaced to unmonitored segments of cattle supply chains (34).

One study exploited variations in the policy's rollout and the gradual acquisition of slaughterhouses by the CA's signatories to conduct a counterfactual analysis. It measured deforestation trends before and after the policy was applied in slaughterhouse supply zones that were eventually affected by the CA (36). On average, there was no impact of the CA on forest cover across the supply zones surrounding slaughterhouses. However, properties that were monitored by the slaughterhouses for compliance with the agreement—because they registered their boundaries earlier in a government-led rural environmental registry (known as CAR by its Portuguese acronym)—had less deforestation relative to those that registered later. The properties registered earlier were more likely to be influenced by the CA because they were publicly transparent and fully traceable, suggesting the CA also served as an enforcement mechanism for public land use

policies. However, cattle laundering occurred by frequently moving cattle between multiple properties prior to final sale, especially from early to late CAR registrants (36). Interviews with a large sample of ranchers and personnel from slaughterhouses and ranchers' associations from Pará identified multiple pathways for noncompliant properties to still sell their cattle to slaughterhouses, thus avoiding the no-deforestation requirement of the CA (37).

Based on cattle location data from the Brazil-wide vaccination campaign against foot-and-mouth disease, a study showed that, in southwestern Pará in 2014, hundreds of thousands of cattle, representing 57% of the total cattle herd, continued to graze on areas that should have been off limits per the CA (33). Cattle herds were grazing on properties that were illegally or recently deforested, under official property embargoes, or not registered in the CAR, thus severely undermining the effectiveness of the CA (33). Across the Brazilian Amazon, cattle production continued inside protected areas, including Indigenous reserves, where it is prohibited by the CA (31).

A more recent study exploited variations in market shares of signatory firms of the G4 across municipalities. Based on panel models and using a counterfactual, it concluded that the G4 led to a 15% reduction in pasture-driven deforestation in the Amazon biome portion of Mato Grosso, Pará, and Rondônia (38). Forest clearing for pastures persisted, however, as a large segment of the cattle sector was not covered by the CA. Deforestation also rebounded several years after CA implementation (38). Nevertheless, the amount of forest avoided by the CA was approximately 700 kha (38), nearly three times that avoided by the ASM (approximately 253 kha based on a similar method) (23). Thus, despite the CA's lower effectiveness within the beef supply chain, it had greater regional impact in reducing deforestation than the ASM, in part due to the pervasiveness of ranching compared to soy farming.

2.2.3. Indonesian forest moratorium: a small success. In 2011, the Indonesian government agreed to suspend the granting of new concession licenses for logging, oil palm, and timber plantations within certain areas as part of the REDD+ Readiness program supported by Norway (39). These concessions had been proven to increase deforestation (40). After multiple revisions, approximately 35% of Indonesia's terrestrial area was affected by this moratorium, including peatlands and primary dryland forests unprotected before 2011 and forests already legally protected before the agreement (41). Thus, the moratorium both expanded legally protected areas and strengthened law enforcement on some existing protected areas. All existing concession licenses were exempt. The moratorium was initially established for two years, then extended until 2021. By contrast to the ASM, it is not a supply chain ZDC but rather a government, area-based policy that prevents allocation of development rights to companies in designated areas to limit deforestation.

After the moratorium, the rate of forest loss decreased for Indonesia as a whole, due to several interacting political, macroeconomic, and climatic factors. Land concessions outside forests covered by the moratorium experienced much higher rates of forest loss than in land concessions affected by the moratorium with comparable landscape attributes (42). The impact of the moratorium was variable per province, depending on their area of potentially suitable land for oil palm that is not forested (43).

A study evaluated the effectiveness of the moratorium during 2011–2018 using a counterfactual, by applying a matched triple difference strategy to a panel dataset (44). For dryland forests, the moratorium allowed forests inside moratorium areas to retain at most 0.65% higher forest cover compared to forests outside the moratorium. For peatland forests, the moratorium had no statistically significant impact, suggesting that compliance with the moratorium was low (44).

2.2.4. Roundtable on Sustainable Palm Oil certification in Indonesia: negligible gross impact. Many companies with ZDCs in the palm oil sector rely on sustainability certification to implement their pledge. Roundtable on Sustainable Palm Oil (RSPO) certification is the scheme

Roundtable on Sustainable Palm Oil (RSPO): developed a certification scheme to meet sustainable sourcing commitments of palm oil

most commonly used to meet sustainable sourcing commitments. Based on a large sample of RSPO-certified and noncertified oil palm plantations in Indonesia, a study evaluated the impact of certification on deforestation using a panel model and propensity score matching to control for precertification differences between certified and noncertified plantations (45). Certified oil palm plantations were associated with a 33% reduction of deforestation compared to the counterfactual in some provinces. However, most RSPO-certified plantations had little residual forest when they received certification, containing less than 1% of forests remaining within all Indonesian oil palm plantations (46). Certification had no causal impact on forest fires and forest loss in peatlands, which contain large belowground carbon stocks (45). Other studies analyzed fire incidence in RSPO-certified versus noncertified concessions (46, 47). However, fire incidence is not a reliable indicator of deforestation, not least because fires can occur in nonforested lands.

2.2.5. Blind spots in other high deforestation regions. Other tropical regions that are experiencing high rates of commodity-driven deforestation either have ZDCs that have not yet been rigorously evaluated or lack credible ZDCs. In 2009, Colombia's government pledged to eliminate deforestation in the Colombian Amazon by 2020 and nationally by 2030 as part of REDD+ commitments to attract multilateral funding (7). The Amazon Vision program emerged as a regional zero-deforestation strategy to address legal and illegal forest land uses (48). It relies on measures to strengthen protected areas and policy incentives for deforestation-free commodities in remote frontiers. The program features a ZDC model led by the government and administered through conservation agreements with smallholders that provide in-kind support in exchange for a ZDC. It also stimulates supply chain infrastructure to connect producers of deforestation-free commodities with urban markets.

By contrast, Paraguay, despite having experienced very high rates of deforestation for beef and soy production until 2017, was not influenced by any ZDC for these commodities. By 2018, not a single company exporting beef from Paraguay had a ZDC covering these exports (49). The cattle sector in Paraguay has so far largely escaped demand-side pressures from importing countries (in 2018, mostly Russia and Chile), by contrast to the Brazilian Amazon. The Green Chaco and Green Production Landscapes projects do seek, however, to improve land use practices, regulations, and enforcement capacity in Paraguay.

2.3. Ex Ante Evaluations of Corporate Pledges: Progress Too Slow

Other studies have analyzed the adoption of ZDCs by private sector actors, which only provides an ex ante evaluation of the effectiveness of ZDCs.

2.3.1. Private actors exposed to deforestation risk. The Forest 500 project assesses the ZDCs of companies and financial institutions exposed to tropical deforestation risk. It showed that 72% of the 350 companies surveyed in 2021 did not have a ZDC for all the forest-risk commodities in their supply chains and 33% of these companies had no ZDC at all (50). Many companies with ZDCs did not provide evidence on their implementation strategies. The majority of financial institutions who are financing companies in forest-risk supply chains did not have a deforestation policy covering their investments (50).

A study evaluated 52 ZDCs made by the companies tracked by Forest 500 (51). Criteria to evaluate the expected effectiveness of ZDCs were defined within a company supply chain, regionally, and globally. This ex ante policy evaluation showed that ZDCs displayed a moderate convergence with effectiveness criteria but were lacking in a few areas. In particular, few companies adopted zero-gross deforestation targets and few ZDCs included biome-wide implementation mechanisms. Key design elements of ZDCs to increase their impact on global

forest conservation are the inclusion of targets with immediate deadlines, clear sanction-based implementation mechanisms, and traceability to indirect suppliers (51).

Indirect suppliers: suppliers who are more than one tier removed from the company that is buying their production

2.3.2. Zero-deforestation commitments in the cocoa sector. A study tracking progress of ZDCs in the cocoa sector highlighted that in 2020 more than half of companies in this sector had at least one commitment to source sustainably produced cocoa, but less than 20% of companies made a commitment that included time-bound targets to achieve zero deforestation in their supply chains. Over half of the companies were implementing traceability systems, which is required for ZDCs (52). In 2019, more than 55% of cocoa produced in Côte d'Ivoire remained untraced (53). Another study analyzed the action plans from all corporate signatories to the Cocoa and Forests Initiative. Unexpectedly, consumer-facing and high brand value firms generally had weaker ZDCs than traders or manufacturers. Many commitments lacked specificity (54).

2.3.3. Zero-deforestation commitments in the coffee sector. As of 2021, there was no sector-wide ZDC in coffee that involved a large share of key industrial actors. A study analyzed how the coffee sector approached sustainability by examining the sustainability efforts of a random sample of 513 companies (55). One-third of companies reported no commitment to sustainability, while another third only reported vague commitments, and the final third reported tangible commitments. Only 2.7% of the companies reported having an internal policy explicitly addressing deforestation, although restrictions on deforestation are included in Rainforest Alliance or UTZ certifications (which have now merged), which was adopted by 29% and 17% of companies, respectively. Company characteristics affected the scope and type of sustainability strategy chosen. Large, risk-aware companies tended to adopt internal sustainability practices along their value chain. Small, consumer-facing companies and producers, on the other hand, adopted external voluntary sustainability standards (55).

3. CONDITIONS FOR EFFECTIVE ZERO-DEFORESTATION COMMITMENTS

3.1. Theories of Change

Eliminating deforestation from commodity supply chains can be pursued in different ways. Governments' ZDCs are implemented by restricting land access, via the allocation of concessions to private companies that operate on public lands (e.g., moratorium in Indonesia), thus with a theory of change similar to that of land use zoning. A government can also collaborate with commodity sectors to incentivize or mandate private actors to voluntarily implement ZDCs.

Companies' ZDCs are implemented via their supply chains by restricting market access to providers responsible for deforestation (e.g., ASM in Brazil). There is no definitive theory of change of supply chain ZDCs because interventions evolve with changing policy and economic contexts, in a learning-by-doing approach.

3.2. Conditions

Below, we discuss conditions that need to be met for supply chain ZDCs to be effective at eliminating regional or global deforestation. We show that they are only partially met.

3.2.1. Condition 1: Agricultural expansion directly causes most tropical deforestation. A recent study distinguishes between agriculture-driven deforestation and deforestation resulting in agricultural production (14). The vast majority of deforestation (90–99%) is associated with agricultural activities as it occurs in landscapes where agriculture is the main driver of tree cover loss. However, only approximately half of deforestation (45–65%) is directly attributed to the

expansion of actively managed cropland, pasture, or tree crops. Large areas have been cleared but never cultivated or have been abandoned after a few years due to land speculation, inadequate land management, poor agroecological suitability, other land uses, land use conflicts, or uncontrolled fires initiated by agricultural activities (5, 14). Thus, only approximately half of all deforestation is associated with active actors in agriculture whose land use decisions can be influenced by supply chain interventions. Forest conversion for extensive ranching as land speculation, for example, can be influenced by government-led ZDCs but not by supply chain approaches with a focus on actual commodity production.

3.2.2. Condition 2: Agricultural commodities for export markets account for most of the agricultural expansion causing deforestation. Demand for deforestation-free commodities comes from governments, NGOs, and (notionally) consumers from importing countries. However, a large share of agricultural production on recently cleared land is destined for domestic markets, definitely in the case of staple crops (rice, maize, cassava, vegetables, fruits) but also in the case of some non-staple crops. Trade flows of the main forest-risk commodities show that, in 2020, the average share of production consumed domestically in major producing countries was 39% for palm oil, 24% for soy, 51% for rubber, 14% for cocoa, 36% for coffee, and 83% for beef (**Figure 2**, **Supplemental Figure 2**). Most beef production, the main direct cause of deforestation in Latin America, is sold on domestic markets (**Figure 2*d***).

Supplemental Material >

Domestic consumption of commodities in the major forest countries has increased over the past two decades, particularly for palm oil (14% increase in 2010–2020) and rubber (30% increase) (**Supplemental Figure 3**). This trend will likely continue, e.g., with Indonesia increasingly using its palm oil production for its biodiesel and oleochemical industry. For most commodities, the major exporting firms are also active in domestic markets. Thus, their ZDCs will only be effective if their sustainable sourcing policies to address demands from international customers are also implemented for domestic markets. Export market requirements often drive improvements across an entire sector, e.g., for sanitary standards (30).

3.2.3. Condition 3: Traded commodities primarily go to markets with demand for deforestation-free production. The preference for commodities that meet sustainability criteria largely originate from Europe and North America (56), which only represent a small—and decreasing—share of international markets for forest-risk commodities. The shares of production from the major producing countries that were exported to Europe and North America during 2016–2020 were 11% for palm oil, 13% for soy, 18% for rubber, 56% for cocoa, 46% for coffee, and 3% for beef (**Figure 2**, **Supplemental Figure 2**)—not accounting for re-exports after processing. In other export markets, demand for deforestation-free production is still limited. In 2020, India and China were the largest importers of palm oil, accounting for 15% and 14% of global imports, respectively (see 2022 FAOSTAT data: **https://www.fao.org/faostat/en/#home**). China was the largest importer of Brazilian beef, offal, and live cattle during 2015–2017, representing 30% of Brazil's exports (30). By contrast, the European Union and United States only represented 7.1% and 2.3%, respectively, of Brazil's beef exports by volume (30).

Demand from emerging markets prioritizes cheap and reliable imports with little attention to sustainability standards at the place of production, with some nuances between countries (57). Indonesia, India, and China purchase Indonesian palm oil with a 2.4 times greater deforestation risk per ton compared to palm oil imported by the EU (58). Nonetheless, where the cost of segregating supply chains is high, the highest production standards are expected to be implemented across the entire supply base of a company (59). Some Asian agribusiness companies operating internationally are starting to adopt sustainable sourcing policies as stringent as those of their Western competitors.

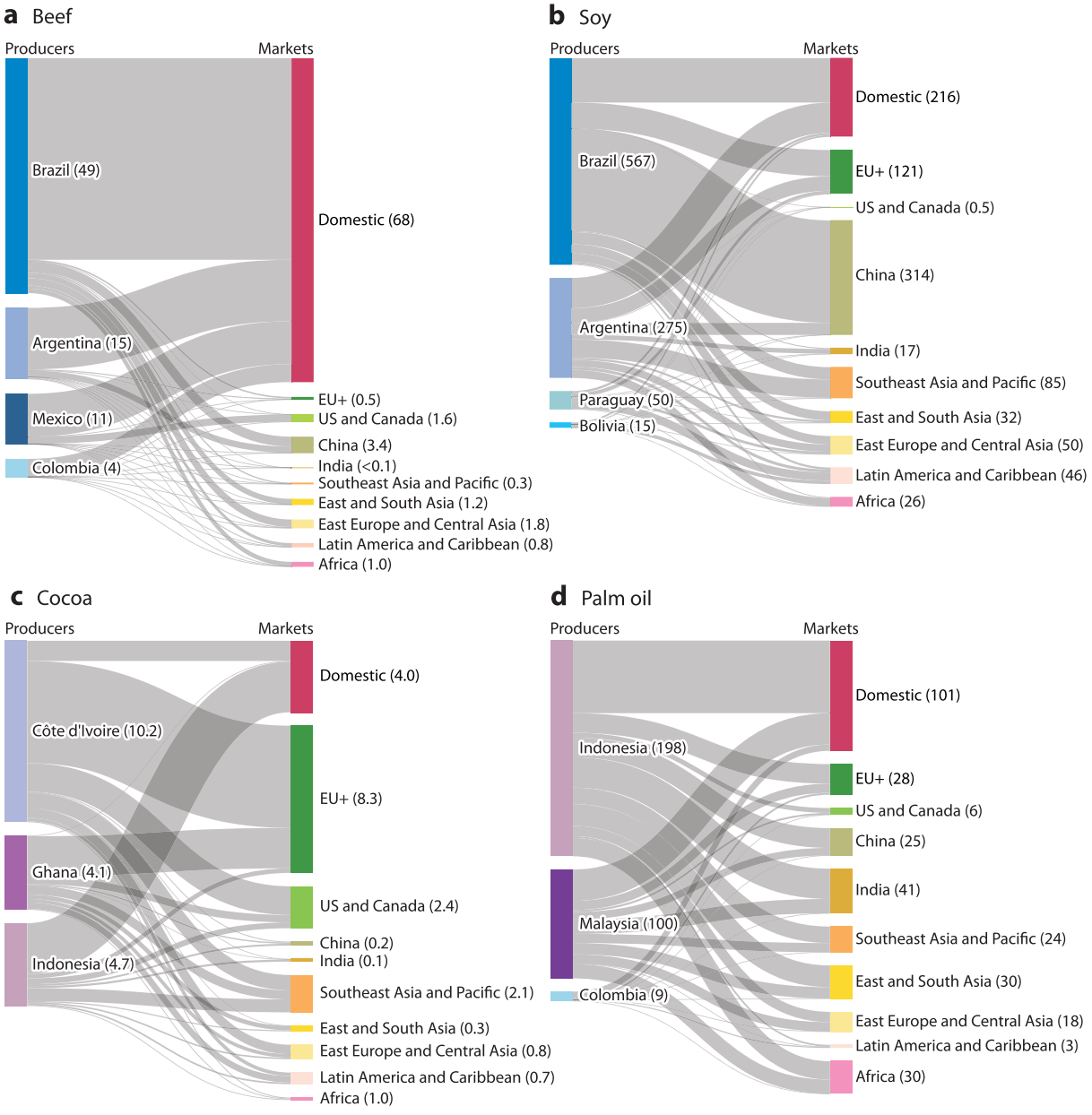

Figure 2

Global trade in the main forest-risk commodities from main producer countries (*left column*). EU+ includes EU countries plus Iceland, Norway, Switzerland, and the Faroe Islands. Trade data are aggregated over the 2016–2020 period for (*a*) beef, (*b*) soy, (*c*) cocoa, and (*d*) palm oil. Data based on 2022 FAOSTAT (**https://www.fao.org/faostat/en/#home**) and UN Comtrade (**https://comtrade.un.org/**) data. Numbers in parentheses indicate trade volumes in million metric tons (MMT).

3.2.4. Condition 4: Traders are able to transmit the market demand for deforestation-free goods to producers through supply chains. Transmission to producers of demands for deforestation-free commodities requires that traders (*a*) know the producers they are sourcing from and (*b*) establish a long-term relationship with them to be able to influence their practices. On the first point, the prevalence of indirect sourcing weakens the ability of large traders to implement ZDCs. Direct suppliers are the actors who sell to the company and indirect suppliers are more than one tier removed from the company, as they sell to brokers, aggregators, storage companies, or so-called pisteurs or coyotes who act as middlemen. Many of these intermediaries are opportunistic, do not sign long-term procurement contracts, and are less demanding in terms of product quality, legality, and sustainability than large traders. Most ZDCs focus on direct sourcing, but indirect sourcing makes up a large share of supply chains. For major traders, indirect suppliers represent 12–42% of soy sourcing, 15–90% of palm oil sourcing, 94–99% of live cattle exports, and up to 100% of cocoa sourcing (60).

Indirect sourcing obscures traceability and blurs information on products' origin and conditions of production, thus creating a blind spot in ZDC implementation (60). It is more difficult for companies with ZDCs to engage with indirect suppliers, promote the adoption of sustainable practices, and take responsibility for their actions, as indirect suppliers are neither identified nor under a contractual relationship. Moreover, deforestation risk is often higher among indirect than direct suppliers (60). Networks of indirect sourcing also facilitate leakage from producers under the direct influence of buyers' ZDCs (34).

Traders need to establish a long-term relationship with their producers to influence their practices. Some trading relationships tend to persist and display inertia—i.e., agricultural markets do exhibit "stickiness" (59). These traders develop social networks in producing regions and invest in supply chain infrastructure such as storage and transportation facilities (61), which allows them to promote and require sustainability standards among their producers (62). By contrast, traders with volatile geographic sourcing patterns have weaker connections, credibility, and engagement with farmers and thus a lower capacity to enforce zero-deforestation requirements (62). Markets with low stickiness allow traders with ZDCs to shift from regions with high to low deforestation risks to minimize their exposure. Thus, they meet their commitment by neither upgrading land use practices of their suppliers nor contributing to decrease overall deforestation (62).

The main factors influencing the persistence of trading relationships over time in Brazilian soy supply chains include surplus capacity in soy processing infrastructure, volatility in market demand, export-oriented production, land prices, and land-tenure security (63). The relative importance of these factors varies with geographic context and power relationships among supply chain actors.

3.2.5. Condition 5: Governments in importing and exporting countries support and reinforce zero-deforestation commitments. With the rise of supply chain initiatives and the authority gained by nonstate actors, national and subnational governments are increasingly engaging with and trying to regain partial control of private environmental governance initiatives (64). Governments in exporting countries facilitate compliance through enabling measures such as a functioning legal system, including contract and property laws, functioning markets, physical infrastructure to facilitate trade, collection and disclosure of information on economic activities and their social and environmental impacts, and redistribution policies to avoid the marginalization of weak actors, e.g., extension services to help all farmers meet sustainability standards (64). Governments in importing countries reinforce these standards, through due diligence regulations (65) that mandate compliance with sustainability criteria such as deforestation-free.

Coalitions formed between governments, civil society, and companies who align their interests in common causes are key to upscale sustainability initiatives such as ZDCs. There are great benefits from all actors acting synergistically to reinforce each other's actions for a common goal (66), in particular at the scale of subnational jurisdictions (67). Central governments are well-positioned to orchestrate transnational actors such that disparate initiatives contribute to national targets and are compatible with domestic legal and institutional frameworks (68). Governments' buy-in on ZDCs often comes through climate commitments under REDD+. Successful supply chain ZDCs rely on government information systems for monitoring compliance. With the ability to monitor property-level forest cover, incentives such as performance-based payments allow reinforcement of command-and-control measures. These policy interactions create mutual benefits: Firms increase compliance to public policies that support implementation of their own ZDCs.

Roundtable for Responsible Soy (RTRS): developed a certification scheme to meet sustainable sourcing commitments of soy

3.2.6. Condition 6: The market coverage of forest-risk commodities produced under fully implemented zero-deforestation commitments is large. ZDC market coverage can be estimated based on the commodity production (*a*) in countries or regions covered by a ZDC, (*b*) traded by companies with an active ZDC, or (*c*) under a certification scheme that includes zero-deforestation criteria. The first two methods overestimate actual market coverage as some ZDCs are weakly or not at all implemented. The third method is also unreliable, as not all ZDCs rely on certification schemes and not all certified producers are covered by a ZDC supply chain.

The share of Brazil's soy and cattle production taking place in the Amazon biome, a large fraction of which falls under the ASM and CA, is 13.9% for soy and 41.5% for cattle (69). In 2017, companies with ZDCs for soy had a 90% market share in the Amazon (70) and a 45% market share in the Cerrado (23). In 2018, the market share of the two CA were 33–34% each (38). Brazil's cattle exports from the Amazon biome covered by the CA were much higher: 83% and 70%, respectively (30). In Indonesia, more than 85% of palm oil exports were traded during 2018–2020 by companies with formal ZDCs. Supply chains governed by ZDCs generally had a lower rate of deforestation, with 70% of the deforestation risk compared to other traders (58). Companies handling 85% of the world's chocolate participate in the Cocoa and Forests Initiative, which covers Côte d'Ivoire and Ghana who export approximately 60% of global cocoa.

The market shares of forest-risk commodities under eco-certification schemes that restrict deforestation were low in 2019: 1.5% for Roundtable for Responsible Soy (RTRS)-certified soy, 10.9% for RSPO-certified palm oil, 16.1% for coffee, and 22.7% for cocoa [based on the certified planted area of each crop globally, not volumes of certified production or trade (71)]. The percent area under certification may be lower than the percent production under certification (e.g., 19% of palm oil production was RSPO certified in 2021). Overall, the market coverage of ZDCs for exports of forest-risk commodities is high, but their lower coverage of the total production in key forest regions combined with their partial implementation is insufficient to drastically reduce deforestation.

Combining the six above conditions suggests that only a few percent of global deforestation could potentially be eliminated by ZDCs as they are currently implemented (**Figure 3**, although note that **Figure 3** provides coarse estimates). Even if all exported forest-risk commodities were covered by a ZDC, it would still represent only approximately 11% of total deforestation risk. If ZDCs would cover traders' entire supply base—thus including both export and domestic markets—with a high level of compliance, their potential impact on deforestation would go up to approximately one-third of total deforestation risk (**Figure 3**). This highlights the imperative to also apply ZDCs to production for domestic markets.

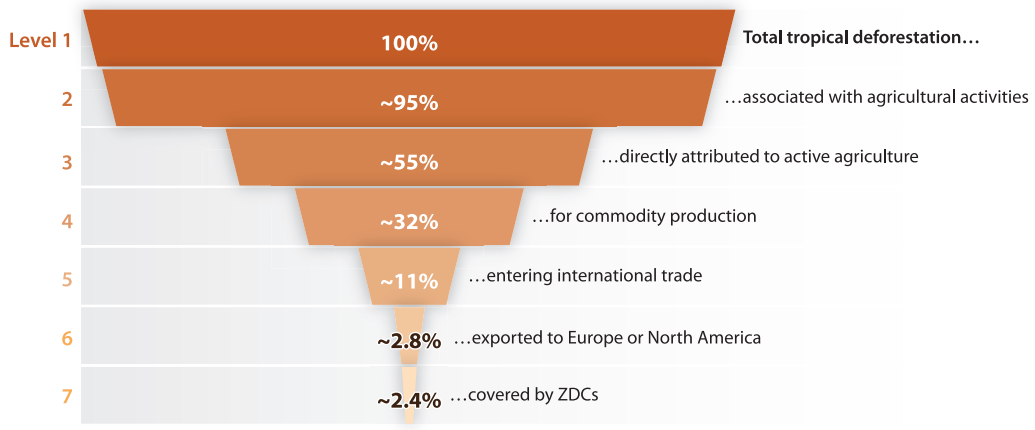

Figure 3

The zero-deforestation commitments (ZDCs) funnel: conceptual diagram with rough estimates of the share of total deforestation covered by ZDCs. Data are from the following sources: (*top* to *bottom*) Levels 2 and 3 are from Pendrill et al. (14); Level 4 is from Goldman et al. (4); Levels 5 and 6 are averages of trade data by commodity from 2022 FAOSTAT (**https://www.fao.org/faostat/en/#home**) and UN Comtrade (**https://comtrade.un.org/**) data weighted by percent contribution of each commodity to agriculture-linked deforestation from Goldman et al. (4); Level 7 is based on ZDC market coverage data reviewed in this article. The figure ignores knock-on effects from sustainable markets to domestic and other export markets (leading to an underestimate) and also the low effectiveness of ZDCs due to indirect sourcing, low compliance, and leakage (leading to an overestimate).

4. CHALLENGES WITH IMPLEMENTATION OF ZERO-DEFORESTATION COMMITMENTS

4.1. Challenges Faced by Companies with Zero-Deforestation Commitments

It is important to understand how companies perceive the challenges associated with ZDCs as they are implementing their commitments in daily operations. Two studies explored this question based on interviews with company and NGO representatives (72, 73).

The main barriers impeding implementation of ZDCs in the palm oil sector included the complexity across its supply chain, which restricts traceability and the ability of manufacturers and retailers to control their suppliers (72). Other barriers are a lack of consensus on definitions of deforestation, lack of government support to private companies' ZDCs, the reluctance of consumers to pay a price premium for sustainable palm oil, and the persistence of leakage markets in Asia for unsustainable palm oil (72).

Interviewees from all sectors in forest-risk commodities also highlighted that ZDC implementation requires significant financial, human, and technical resources with costs uncompensated by the market (73). Many companies find it challenging to engage their stakeholders, especially smallholders. Companies often rely on service providers to help implement their ZDCs. These external actors extend the reach of companies that lack in-house expertise, bring local knowledge on specific regions or commodities, or ensure buy-in and legitimacy across their supply chains by connecting businesses to stakeholders, such as consumers and local governments (73). Progressive companies acknowledge that eco-certification alone is insufficient for implementing their ZDCs and is merely a stepping stone for further action (73).

Some companies identify internal tensions between sustainability departments, who set ZDC strategies, and procurement departments, who are expected to implement them (72, 73). They also emphasize the need for greater traceability all the way to producers and for precompetitive

collaborations across supply chains. No company believes it can eliminate deforestation on its own. Progressive companies also call for regulations by governments in producer countries to create a level playing field. For successful ZDC implementation, internally, companies need to better adjust their organizational structures with their sustainability commitments; externally, they need to secure stakeholder buy-in from producers to consumers (72, 73). Below, we examine some of the challenges faced by companies.

4.2. Definitions of Forests

Stakeholders often lack a clear and agreed upon definition of forests. On one hand, broad definitions that encompass timber and tree crop plantations mean that the conversion of natural primary forests into an oil palm plantation, for example, does not count as deforestation (74). On the other hand, restrictive definitions of forests allow for the conversion of wooded landscapes or logged forests with conservation value. The RSPO standard includes provisions for the protection of primary forests but not of secondary and degraded forests. The RTRS standard prohibits conversion of both primary and secondary forests, but its definition of forest excludes vegetation under 10 m high, thus most savanna vegetation. Some certification schemes rely on the High Conservation Value (HCV) and High Carbon Stock (HCS) approaches as part of their requirements. These standards are not intended to prevent all deforestation but to maintain important environmental and social values. The HCV designation protects rare species and habitats, even in areas with limited canopy cover. Even though most eco-certification schemes do not exclude all forms of forest loss and despite a lack of evidence that they help reverse deforestation (75), many companies consider eco-certified procurement as sufficient proof of zero deforestation (76).

Between 34% and 74% of global forests qualify as HCV, HCS, or forests on tropical peatland (77). Many ZDCs in the palm oil sector in Southeast Asia cover forests on tropical peatlands as part of No Deforestation, No Peat and No Exploitation pledges (78). Of these forests most likely to be covered by ZDCs, approximately one-third have already been legally designated as protected areas, including Indigenous lands. Large forest areas remain that are suitable for agricultural development and are not covered by ZDCs. Avoidance of forests designated as HCV, HCS, and tropical peatlands to comply with ZDCs could displace agricultural pressure to these unprotected forests (77).

4.3. Definitions of Deforestation

ZDCs pledge to eliminate either gross or net deforestation (79). Under a gross deforestation definition, all deforestation should be eliminated, which limits options for a geographic adjustment of land use to land quality and accessibility. Under a net deforestation definition, forest conversion needs to be compensated by reforestation elsewhere, in the same biome or not. Replacing natural primary forests by eucalyptus or pine plantations elsewhere is highly problematic, as plantations are much less diverse, store less carbon, and provide fewer ecosystem services than natural forests even in the same biome (80).

The Glasgow Declaration on Forests to halt and reverse forest loss does not specify whether signatory countries committed to end net or gross deforestation. Model simulations show that, when summed globally, ending gross forest loss would sequester twice as much carbon as ending net forest loss (approximately 143 versus 68 Gt CO_2) and would prevent the replacement of primary forests by monoculture plantations (81).

The Accountability Framework initiative started by several NGOs provides guidance to companies to help them implement their commitments, including by standardizing definitions of key terms (82). Persistent inconsistencies in definitions and data decrease transparency, weaken forest governance, and facilitate greenwashing by companies.

4.4. Beyond Legal Compliance

Since the early 2000s, forest governance to achieve forest conservation has been reframed from a "sustainability" to a "legality" objective (83). Illegal deforestation could be largely reduced by better forest law enforcement (84). Some ZDCs, including some demand-side due diligence measures, are merely a zero-illegal deforestation commitment, which aligns companies' activities with government regulations (51). As few jurisdictions fully prohibit deforestation, complying with forest countries' land use laws sets a minimum sustainability requirement but is insufficient to eliminate deforestation. Under Brazil's current environmental legislation, large areas of natural ecosystems can be converted legally (85). Brazil has approximately 3.25 Mha of natural forests and native vegetation at a high risk of legal deforestation until 2025, mostly on private land (86).

Stringent ZDCs allow much less deforestation than is allowed legally in producing countries. Producer associations in these countries argue that it is illegitimate and a violation of national sovereignty for international companies to impose production standards that go beyond legal compliance in their country, especially under a threat of market exclusion. Producers claim that any requirement beyond legal compliance should be compensated by a price premium to reward adoption of sustainable land use practices. Historically, most traders have been reluctant to pay such a price premium. A payment for environmental services is being considered in the Brazilian Cerrado, for example, to add a financial incentive for achieving zero deforestation in soy supply chains (87).

4.5. Spillovers and Leakage

Leakage occurs when an intervention to promote sustainable land use by restricting production in one region displaces unsustainable agricultural practices to another region (8, 88). It decreases the overall impact of an intervention.

4.5.1. Brazilian Amazon Soy Moratorium and cattle agreements. Notwithstanding the success of the ASM, soy expansion remained a major driver of land conversion in Brazil's biodiversity-rich Cerrado biome, both in Mato Grosso and the states of Maranhão, Tocantins, Piauí, and Bahia (Matopiba), where land use is less strictly regulated (89). Supply chain data show that many companies with a ZDC—including the signatories of the ASM—are still exposed to soy-associated deforestation in the Cerrado, especially in municipalities where they have invested in supply chain infrastructure (70). Studies have attempted to quantify whether the soy expansion in the Cerrado is a spatial spillover from the ASM. They concluded that leakage of soy cultivation from the Amazon to Cerrado biome has occurred primarily on previously cleared land, such as pastures adjacent to the Amazon, and thus has not led to a significant increase in deforestation (21, 90). Another study using an applied general equilibrium model (22) estimated that approximately half of the avoided deforestation in the Amazon biome thanks to the ASM was offset by increases in deforestation in the Cerrado. Estimates of cross-border leakage to forest frontiers in Bolivia, Argentina, and Paraguay were negligible (22).

4.5.2. Indonesian forest moratorium and Roundtable on Sustainable Palm Oil certification. There is also mixed evidence on spillovers associated with the 2011 Indonesian forest moratorium. One study found that the moratorium induced deforestation in areas immediately around protected forests (91) while another study found no evidence of leakage to surrounding areas, even within some considerable distance from moratorium areas (44). In Kalimantan, deforestation spillovers from oil palm RSPO certification were shown to have reduced forest clearing within

government-designated forests while having induced additional deforestation outside these forest estates, thus offsetting conservation gains. The net impact of RSPO certification on deforestation was thus insignificant (92).

Supply- and demand-side restrictions on palm oil production have multiple market-mediated impacts at a global scale, as demonstrated for Malaysia and Indonesia with a computable general equilibrium model. Medium-run impacts include a shift to other agricultural commodities that can cause deforestation and rising consumer prices for vegetable oils (93). Model simulations also show that a European ban on high-deforestation palm oil would have only led to a meager 1.6% less deforestation in Indonesia during 2000–2015 relative to what occurred, due in part to a leakage of high-deforestation palm oil to non-European (including domestic) markets (94).

4.6. Monitoring and Traceability

Implementing ZDCs requires adequate forest mapping and monitoring tools and traceability data that link places of production to suppliers (95). These are essential components of Measurement, Reporting and Verification systems. Complex supply chains, indirect sourcing, and stakeholder demand for transparency created a need for traders to invest in traceability as a first implementation step of ZDCs. Innovative platforms were created by NGOs to facilitate and standardize forest monitoring and traceability (82). These include Global Forest Watch, an open-access satellite-based forest monitoring system; the HCS approach, a toolkit to support vegetation mapping within planned development areas; Transparency for Sustainable Economies (Trase), an open-access platform that maps trade flows of forest-risk commodities and links production landscapes to traders and ports of import; and the Accountability Framework initiative, with guidelines to measure progress toward corporate ZDCs. These tools provide clear metrics to support decision making related to deforestation and to build capacity for data collection and transparent monitoring and reporting mechanisms.

A study investigating the impact of the availability of information on deforestation showed that free, high-resolution and high-frequency deforestation alerts provided through Global Forest Watch reduced deforestation in protected areas and logging concessions in Africa—a continent where most countries lacked a national deforestation monitoring system (90).

Several studies used Trase data that link traders and international markets to deforestation caused by commodity crop expansion at the scale of subnational jurisdictions. A study showed how the sourcing patterns of different consumer countries and traders lead to different impacts on biodiversity caused by land conversion for commodity trade (96). Trase data also increase the transparency of ZDCs, showing, for example, that they had mixed impacts until 2017 in the Brazilian soy sector, especially in the Cerrado biome (70). Another study on Brazil's cattle sector combined official per-shipment trade records, slaughterhouse export licenses, subnational agricultural statistics, and data on the origin of cattle per slaughterhouse to map flows of cattle from thousands of municipalities to more than a hundred importing countries via traders and exporting slaughterhouses (30). This detailed supply chain mapping was then linked to spatially explicit data on deforestation for pastures. A large proportion of cattle exports from the Amazon biome were covered by the CA (70–80%), and yet the deforestation risk of these supply chains remained considerable due to a limited implementation and narrow geographical scope of these ZDCs (30).

Despite recent progress, traceability to the farm level remains a challenge, especially in smallholder-dominated systems as for cocoa and palm oil. Independent monitoring and verification of standard compliance at a scale above the farm may be sufficient in some cases, e.g., for jurisdictional-, landscape- or cooperative-level ZDCs.

4.7. Social Sustainability of Zero-Deforestation Commitments

Given that forests are socioecological systems, a challenge for ZDCs is to avoid an exclusive focus on forest cover at the expense of social sustainability. On paper, most ZDCs include social criteria aimed at enhancing the welfare of Indigenous and other forest-dependent populations affected by commodity production. These include small independent producers and sellers, small producers part of a larger commercial supply base that may or may not have a contract, and laborers working for companies. These social criteria cover issues of land rights, labor standards, and community consultation and inclusion (78).

The implementation of ZDCs risks excluding from international markets small producers with a limited capacity to comply with sustainability requirements. This can be for financial and educational reasons (97), or because they lack organizational capacity, do not have access to legal documents, and suffer from low traceability given their reliance on intermediary traders (98). Such an exclusion has adverse livelihood outcomes for smallholders.

The design and implementation of ZDCs have considerable influence on equity, i.e., the opportunity for various actors to engage with and participate in interventions to reduce deforestation. For example, RSPO certification in Indonesia encounters challenges with Indigenous and small, local producers (98), despite the simplified requirements in the 2019 RSPO independent smallholder standard. Key remediation actions include awareness raising, capacity building, and differentiated compliance enforcement for smallholders who are unable rather than unwilling to participate (97). Cooperative models of enforcement of ZDCs, for which targets for compliance are flexible and negotiated with suppliers, are in theory more likely to achieve compliance by producers with lower capabilities, thus minimizing effectiveness-equity trade-offs (99). Lack of equity may undermine ZDC effectiveness if excluded producers continue to clear forest.

A study compared village-level well-being across Indonesia from before oil palm plantations were first established to several years after plantations were certified (100). Certification was associated with marginally lower poverty in villages dominated by market-based livelihoods, but not in those oriented toward subsistence agriculture before adopting oil palm. This highlighted that blanket industry standards do not deliver social sustainability to all producer types (100). RSPO certification occurs mostly in villages with large-scale industrial plantations, which are associated with more conflicts, low-wage agricultural laborers, loss of social power by community leaders, and water and air pollution (100).

A political ecology analysis of forest governance (101) reveals how physical targets such as zero deforestation may have perverse effects on local forest users. It argues for moving beyond mainstreaming equity into forest conservation strategies by promoting equitable access, representation, and fairness in interventions for sustainable land use. Empowering local communities to set goals based on local priorities offers more diverse livelihood and land use options (101).

5. DISCUSSION AND CONCLUSION

Commitments to eliminate deforestation associated with commodity production have so far had only a rather small impact. This originates from a lack of market uptake, loopholes leading to partial implementation (75), low compliance, and their limited scope. For example, RSPO in Indonesia has strong uptake but failed to reach plantations with most remaining forests, whereas the CA in Brazil have wide market coverage but suffer from low compliance. A few region- and commodity-specific ZDCs have contributed to reductions by up to hundreds of thousands of hectares of deforestation, most notably the ASM. However, these rare success stories are undermined by leakage and vulnerability to subsequent political regime changes.

ZDCs have nonetheless led to incremental steps toward deforestation-free commodities thanks to better monitoring and traceability systems (102), and convergence of interest around reversing deforestation by public, private, and civil society actors. Companies are learning by doing within the limits of what they can do in rapidly changing global policy and food systems. Success will only come if ZDCs are fully implemented by companies across their entire supply base and not just to meet demands for sustainable commodities by rich-country markets.

We showed that current supply chain initiatives can only have a limited impact on global deforestation because the conditions for these initiatives to be effective at eliminating deforestation are only partially met. In short, the current scope of supply chain ZDCs is limited to forest clearing for agricultural production of commodities whose suppliers are traceable and that are exported by traders with credible ZDCs to countries where governments and civil society express a strong preference for sustainable consumer goods and with regulations requiring deforestation-free imports. Moreover, producing country governments need to create and maintain enabling conditions for ZDCs to be effective, and market coverage of commodity production under ZDCs needs to be large. The forest frontiers meeting all these conditions represent only a few percent of all deforestation. If firms adopt ZDCs across their entire supply base, including export and domestic markets, with a high level of compliance, their potential impact on deforestation could increase to approximately one-third of all deforestation, a much more significant contribution (**Figure 3**). While supply chain ZDCs can only restrict market access for some commodity traders, government-led ZDCs are able to restrict land access for all commodity producers.

ZDCs are just one component of a multistakeholder, multilevel governance system made of domestic public policies, international financial mechanisms, and initiatives by private actors (7, 103). The effectiveness of ZDCs depends on pre-existing public policies that set an agenda for forest protection, address underlying causes of deforestation at the local, national, and international levels, and create an enabling context (8).

ZDCs should be evaluated in the context of policy mixes where each intervention can generate greater impact through policy synergies. The right mix of policies depends on local conditions (e.g., specific deforestation drivers, institutional capacity) but ultimately relies on a combination of command-and-control measures that deter forest clearing, supply chain initiatives that incentivize alternative models of production, and enabling measures that increase coordination across instruments. The sequencing of interventions matters as governance systems navigate different stages of forest cover change dynamics (104). Command-and-control measures like protected areas and increased law enforcement play a greater role in new forest frontiers, whereas incentive-based measures are more relevant in established agricultural frontiers where most remaining forest is on private properties. Often, the main contribution of ZDCs by private companies is to enforce existing public land use policies by adding incentives to producers and increasing transparency. As such, supply-chain initiatives tend to enter at a later stage in these policy sequences (104). Integration of various interventions to reduce deforestation in a jurisdiction also depends on how they are perceived and thus adapted by the diverse actors involved locally (105).

Notwithstanding today's modest role of ZDCs, accelerating their adoption across all supply chains and biomes could greatly strengthen their role in policy mixes. They are the main institution that controls the access of forest-risk commodities to global markets, whose sustainability standards escape national jurisdictions. New business and financing models are needed to upscale ZDCs (106, 107). This requires further strengthening policy linkages between climate policies and the role of forests as carbon sinks through carbon markets and forest-based offsets (108) to increase private forest finance (e.g., the Lowering Emissions by Accelerating Forest finance Coalition). Climate commitments by rich and emerging economies as part of the United Nations

Framework Convention on Climate Change (UNFCCC) process create new opportunities for tropical forest finance.

The success of the zero-deforestation policy agenda will depend on the ability to create and maintain multistakeholder coalitions, at both the global scale (e.g., Tropical Forest Alliance, Good Growth Partnership, Cocoa and Forests Initiative) and the local scale, through jurisdictional approaches to sustainable land use (67). Effective demand-side initiatives are needed to complement supply-side approaches that currently dominate forest policies. These include due diligence requirements that restrict the import of products with embedded deforestation (109, 110) and nonprice mechanisms like shifting consumption away from forest-risk commodities (94).

Zero deforestation has been used as a short-hand expression for more sustainable land use practices in forest frontiers. On-the-ground realities are more complex, as ecological and social contexts vary between regions and commodities, which each require their own mix of solutions and trade-offs between the various dimensions of sustainability. Being in most cases defined by actors external to forest regions, ZDCs have suffered from an implementation gap largely caused by an inadequate understanding of land use complexities. Reaching sustainable land use can only be achieved by engaging all stakeholders, local and distant, through a diversity of public and private interventions.

SUMMARY POINTS

1. The past decade has seen a rise in zero-deforestation commitments (ZDCs) by coalitions of public and private actors.
2. Despite these commitments, high rates of deforestation persist and may even be increasing.
3. A few region- and commodity-specific ZDCs have contributed to small reductions in deforestation, with mixed evidence on associated leakage.
4. ZDCs have spurred progress in monitoring, traceability, and awareness of deforestation.
5. Implementation of supply chain ZDCs across their entire supply base and with greater market coverage, including domestic markets, would greatly increase their impact on global deforestation.
6. Government-led ZDCs restrict land access for all commodity producers while supply chain ZDCs restrict market access only for some commodity traders.
7. Zero-deforestation initiatives are just one component of broader policy mixes of public and private interventions to reduce deforestation.
8. Implementation of ZDCs risks excluding marginal producers, with negative impacts on equity and social sustainability.

FUTURE ISSUES

1. Various loopholes in the implementation of ZDCs need to be better understood to improve the design of land use interventions.
2. Incentives to maintain all actors engaged and committed to multistakeholder coalitions to eliminate deforestation need to be identified.

3. Demand-side initiatives that complement supply-side approaches in forest policies need to be more widely implemented, for both export and domestic markets.
4. Research is needed on how to steer consumption away from forest-risk commodities in different national contexts, including in producing countries.
5. Effective forest conservation strategies that also promote equitable access and fairness in interventions to avoid excluding marginal stakeholders need to be identified.
6. Research is needed on the design, implementation and evaluation of optimal policy mixes in specific jurisdictions, including frontier settings where ZDCs have limited influence.
7. Improved orchestration and coordination mechanisms are needed across various zero-deforestation initiatives that are implemented independently at different scales.
8. The governance architecture of a more deliberate polycentric forest governance that enhances instrument synergies needs to be designed.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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