Gaps in adoption and implementation limit the current and potential effectiveness of zero-deforestation supply chain policies for soy

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Abstract

Tropical deforestation continues despite global efforts to curb forest loss. Corporate zero-deforestation supply chain commitments (ZDCs) have the potential to address this deforestation, especially if strong state-led forest governance is absent. Yet, because ZDC adoption is limited to particular locations and supply chains, these commitments may fall short at reducing regional deforestation and protecting biodiverse ecosystems. Here, we leverage timeseries of spatially explicit corporate commodity sourcing data and ZDCs to assess the current and potential effect of ZDCs within soybean supply chains on forest loss and biodiversity. We focus on the Brazilian Amazon, where the first ZDC (soy moratorium (SoyM)) was implemented, and the Cerrado, where companies have adopted but not implemented ZDCs. We found that in the Amazon, SoyM signatories that controlled the market caused a 57% reduction in direct deforestation for soy from 2006 to 2015. In the Cerrado, if companies had implemented their ZDCs with the same relative effectiveness as in the Amazon, deforestation for soy could have been reduced by 46%. Thus, ZDC implementation in the Cerrado via stringent monitoring and enforcement could contribute substantially to forest and habitat conservation. Yet, incomplete ZDC adoption leaves >50% of soy-suitable forests and the biodiversity that they harbor outside the reach of ZDCs. To protect these forests, it is vital to incentivize more companies—including smaller, less publicly exposed traders—to make and implement ZDCs, while also promoting forest governance through public policy.

1. Introduction

Agricultural commodity expansion is a leading cause of tropical deforestation (Curtis et al 2018). Deforestation drives regional biodiversity loss and is the second-largest contributor to global greenhouse gas emissions after fossil fuel use (van der Werf et al 2009, Gibbs et al 2010). Locally, deforestation-induced ecosystem service losses may lead to reductions in agricultural productivity, threaten the livelihoods of indigenous and other forest-dependent groups, and increase inequality and conflicts (Henders et al 2015, de Vos 2016, Alroy 2017, Leclère et al 2020, Leite-Filho et al 2021, Russo Lopes et al 2021).

The main commodities causing deforestation are highly concentrated in the hands of a few multinational companies (Hoffmann 2013, Zu Ermgassen et al 2020). Increased public awareness of the corporate influence on commodity production has spurred civil society to demand that such companies improve the sustainability of their supply chains (Gefi and Mayer 2004, Latapí Agudelo et al 2019). By 2021, at least 94 companies had adopted zero-deforestation supply chain commitments (ZDCs), public pledges of intention to eliminate deforestation from their supply chains (Rothrock et al 2022). The large volume of agricultural commodity production handled by these companies positions voluntary supply chain
governance as a potentially important tool for conserving forests. However, ZDC adoption has no direct effect on forests without implementation. Implementation includes disseminating policy requirements to stakeholders, developing and/or applying deforestation monitoring and verification systems, and enforcing new requirements (Garrett et al. 2019, Austin et al. 2021, Grabs et al. 2021).

The Brazilian soybean sector has long been a focus of zero-deforestation initiatives due to the substantial deforestation attributed to soy in the Amazon and Cerrado biomes (figure 1) (Kastens et al. 2017, Gollnow et al. 2018, Rausch et al. 2019). While cattle ranching remains the main direct cause of deforestation in Brazil, in the mid-2000s soy expansion into forests caused around 30% of all deforestation in the Amazon and 18% in the Cerrado (Gibbs et al. 2015, Rausch et al. 2019). Deforestation for soy declined to 1% of Brazilian Amazon deforestation by 2014, but increased to 22% of Cerrado forest loss by 2011 (Gibbs et al. 2015, Rausch et al. 2019).

This reduction in direct deforestation for soy (hereafter, ‘soy-deforestation’) in the Brazilian Amazon has been partially attributed to the soy moratorium (SoyM) (Rudorff et al. 2011, Macedo et al. 2012, Gibbs et al. 2015, Costa et al. 2017, Kastens et al. 2017, Gollnow et al. 2018, Heilmayr et al. 2020). The SoyM was the first industry-specific voluntary ZDC in the tropics (Greenpeace 2006, Gibbs et al. 2015). Companies that signed the SoyM implemented their agreements to not purchase soybeans produced on lands deforested after 2006, a cut-off date later moved to 2008 (Gibbs et al. 2015).

Previous research on the SoyM’s impacts assumed complete and homogenous implementation across all soy companies and producing regions in the Brazilian Amazon (Gibbs et al. 2015, Kastens et al. 2017, Heilmayr et al. 2020). SoyM signatories handled around 90% of exports from the Amazon in 2017 (Zu Ermgassen et al. 2020). Because these companies preferentially source from certain municipalities, levels of ZDC implementation vary across space (Leijten et al. 2022). This heterogeneity is relevant because the collective local market share of companies implementing ZDCs may influence supplier decisions regarding forest clearance. Specifically, in locations where SoyM signatories dominate the market, suppliers may be less likely to deforest because they cannot easily sell to actors without ZDCs (Mayer and Gefi 2010, Garrett et al. 2019). Evaluating how deforestation is affected by the local degree of SoyM implementation, measured as ZDC market share, would provide insight into the mechanisms underpinning ZDC effectiveness.

Although ZDC implementation in Brazil has occurred largely in the Amazon, most Brazilian soy is produced in the Cerrado, a biome rich in biodiversity but subject to comparatively lax native vegetation protection requirements (NVP 2012, Strassburg et al. 2017). In 2018, 48% of Brazil’s soybean production was located in the Cerrado, compared to only 14% in the Amazon (IBGE 2020). Yet only 20% of remaining native Cerrado vegetation is undisturbed and just 8% of the biome is covered by protected areas compared to 46% in the Amazon (Strassburg et al. 2017, Rausch et al. 2019). The recent adoption of ZDCs by several companies that source from the Cerrado promises to increase conservation in the biome, protecting additional forest and associated habitats. A previous ex-ante assessment of potential ZDC impacts in the Cerrado used a best case but unrealistic scenario in which all companies sourcing from the Cerrado adopted and implemented ZDCs (Soterroni et al. 2019). To inform corporate and advocacy organizations strategies regarding ZDCs in the Cerrado, a more realistic appraisal that incorporates the level and distribution of current pledges is needed.

Finally, ascertaining the future potential of ZDCs relies partially on a better understanding of which companies adopt ZDCs. Existing research suggests no significant differences in soy-deforestation risk between firms with and without ZDC, and that traders with geographically stable sourcing areas are more likely to adopt a ZDC (Zu Ermgassen et al. 2020, Leijten et al. 2022). However, it remains unclear how other factors condition ZDC adoption in soybean supply chains.

Given the potential of ZDCs to address tropical deforestation and biodiversity loss, we aim to more accurately measure how the spatial and temporal heterogeneity of ZDC adoption and implementation across companies, biomes, and localities affects soy-driven deforestation in the Brazilian Amazon, and how ZDCs might reduce deforestation if current commitments were implemented in the Cerrado. Specifically, we ask:

(a) What are the attributes of companies that have adopted soy ZDCs in the Amazon and Cerrado?
(b) To what degree do adopted or implemented ZDCs cover forests suitable for soy expansion, and how much of the habitat of threatened, forest-dependent species falls within those soy-suitable forests?
(c) What was the effect of SoyM implementation on direct soy-deforestation in the Amazon?
(d) How much direct soy-deforestation in the Cerrado could have been avoided had adopted ZDCs been implemented with similar effectiveness and at the same time as the SoyM?

To address these questions, we first compiled attributes of major soy traders (with and without adopted ZDCs) and tracked their sourcing regions across the Amazon and Cerrado biomes from 2006 to 2015. Then, we evaluated the association between the
attributes of these companies and their ZDC adoption status. We assessed the coverage of such ZDCs vis-à-vis threatened forests and forest-dependent species. Finally, we conducted post-hoc (Amazon) and ex-ante (Cerrado) evaluations using the municipal market share of companies with implemented (Amazon) or adopted (Cerrado) ZDCs to estimate actual or potential avoided direct soy-deforestation from ZDC implementation. This research thus provides a more holistic understanding of the dynamic interactions between supply policy adoption, implementation, and outcomes.

2. Methods

2.1. Study area

The study area comprises the Brazilian Amazon and Cerrado biomes (figure 1), including all companies exporting soybeans from those areas.

2.2. Background and hypotheses

2.2.1. ZDC adoption

Adoption of voluntary environmental policies by corporations is often driven by advocacy campaigns, which may result in loss of market shares or market access for the targeted company (Hendry 2006, Chrun et al 2016). Thus, a company’s decision to adopt a sustainability program such as a ZDC is commonly associated with attributes that make it a likely focus of such campaigns (Hendry 2006, Mayer and Gefi 2010, Chrun et al 2016, Nolte et al 2017, Rueda et al 2017). These include relatively high corporate environmental impact (e.g. deforestation), high market influence, and strong pro-environmental preferences within consumer market and headquarter locations such as the EU (Hendry 2006, Nolte et al 2017, Rueda et al 2017). Thus, we hypothesize that ZDC adoption is more likely for companies that source from and have infrastructure in high deforestation areas, are larger, handle more soy, export more soy to the EU, or are headquartered in the EU.

2.2.2. ZDC implementation and market share

In places where the market share of buyers that implement a sustainability policy is higher, producers have fewer opportunities to avoid selling to those buyers, potentially increasing producer costs of non-compliance (Mayer and Gefi 2010, Garrett et al 2019). If committed buyers source only a small proportion of total regional production, only farmers who were already ZDC compliant would have an incentive to continue selling to those buyers, reducing the additionality of the company’s policy in the broader area outside of its supply chain. Based on this logic we hypothesize that deforestation reductions are larger in areas where ZDC companies who implement their commitments have a bigger collective market share.

2.2.3. ZDC coverage

ZDC coverage describes the spatial reach and level of ZDC market share within the commodity production areas. We hypothesize that within a region, higher ZDC market share leads to greater avoided deforestation, assuming ZDC implementation. For example, a high ZDC market share in the Amazon of around 90% (9 million tonnes (Mt)) means that farmers in most soy production regions are under pressure to meet the requirements of ZDC firms. In comparison, the 45% (20 Mt) ZDC market share in the Cerrado will leave more production regions outside ZDC company sourcing. This limits the potential impact of these companies’ policies on conservation, if their policies were implemented (Trase 2018, Zu Ermgassen et al 2020).

2.3. Data and approach

2.3.1. Soy company ZDCs

We derived all names of companies exporting soybeans from Brazil in 2018 from Trase (2020) and researched whether and when these companies had adopted or implemented a ZDC (table S1). By 2018, only the SoyM in the Amazon had been implemented. Producers in violation of the SoyM were excluded from supplying to committed companies. In the Cerrado, to our knowledge, no company has implemented their ZDC across their whole supply chain.

We derived company ZDC adoption and implementation status from corporate reports and online information, Zu Ermgassen et al (2020), and in the case of the SoyM the list of members of the Brazilian national vegetable oil associations (Abiove 2020, Anec 2020). If we could not find a public record of a company’s intention to eliminate deforestation from their supply chain, we assumed that the company did not adopt a ZDC.

2.3.2. Comparing companies’ economic characteristics and reputational risk exposure

We estimated company exposure to high deforestation areas by measuring company exports from (tonnes per year), and the number of soy storage and processing facilities in, high deforestation areas. High deforestation municipalities were defined separately for the Amazon and Cerrado as those in the highest 10% quantile of PRODES deforestation rates between 2016 and 2018 (INPE 2018b).

To characterize company size, we obtained company tax reported share value (in 2018 Brazilian real (BRL)) from the Brazilian Ministry of the Economy (Ministério da Economia 2020), matching corporate tax identifier (Cadastro Nacional de Pessoas Jurídicas (CNPJ)) between the Trase (2020) and tax databases. We derived soy sourcing volumes by company from Trase (tonnes in 2018) (Trase 2020). The main export locations of ZDC and non-ZDC traders were taken from Trase in 2018 (Trase 2020).
Figure 1. Land use and land cover change in the states (two-letter labels) of the Brazilian Amazon (a) and Cerrado (b). Land use and land cover change were derived from Mapbiomas (MapBiomas 2020). Forest, pasture, cropland, soy, and other categories represent land in the year 2019. Forest is divided into areas suitable for soy and other forests. Soy-deforestation includes all forest to soy conversion within 5 years post deforestation (SI §1, figure S2). Matopiba (right), includes the states of Maranhao (MA), Tocantins (TO), Piaui (PI) and Bahia (BA).

We compared all indicators between ZDC and non-ZDC companies using the Wilcoxon rank sign test (Wilcoxon 1945).

2.3.3. ZDC coverage of forests suitable for soy expansion and habitat of threatened, forest-dependent species market share
We calculated ZDC market share as the export share of annual soybean tonnes per municipality traded by ZDC companies in 2018 (Trase 2020). We categorized this market share into five bins, consisting of 0%, >0%–25%, >25%–50%, >50%–75%, and >75%–100% ZDC market share. Municipalities without soybean and thus without market share were labeled ‘no soy’ locations.

We then assessed the degree to which adopted ZDCs cover forests and threatened forest-dependent species’ habitat in areas suitable for soybean production.

We defined soy-suitable areas as those with moderate to high soy-suitability as derived from the Global Agroecological Zoning assessment (agroclimatic soy-suitability derived for high-input, rainfed soybean production), slope <15%, and excluding soils with strong edaphic restriction (IIASA 2012, Soares-Filho et al. 2014). Then, we intersected soy suitability with 2018 forest area derived from Mapbiomas (MapBiomas 2020) (figure 1). Finally, we summarized soy-suitable forest area in each ZDC market share bin.

We derived habitat area of threatened, forest-dependent species as the intersection of species ranges in the International Union of Conservation for Nature’s (IUCN) Red List database (IUCN 2020) for the Amazon and Cerrado (n = 249) and 2018 forest area from Mapbiomas (MapBiomas 2020) (Huang et al. 2021). Next, we quantified the combined species habitat area in all forests and those suitable for soybean expansion. Finally, we calculated the percent of the total summed species habitat area in soy-suitable forests located in municipalities across ZDC market share categories in 2018 (table 1).

2.3.4. Estimating ZDC treatment effect on soy-deforestation
To evaluate the role of the collective, local leverage that companies with ZDCs have to reduce commodity deforestation, we assessed the effect of the SoyM market share on direct soy-deforestation in the Brazilian Amazon. We included all municipalities completely inside the Amazon biome with planted soybeans throughout 2005 and 2015, resulting in 50 municipalities (figure S6).

We defined deforestation for soy as the area of forest converted to soybeans within 5 years after deforestation occurred. This 5 year soy-deforestation attribution captured most conversion from forest to soy in the Amazon between 2001 and 2018 within an 8 year observation period (SI §1, figures S1 and S2) and aligns with prior studies that applied lags between 3 and 5 years (Gibbs et al. 2015, Zu Ermgassen et al. 2020, Song et al. 2021). We derived forest and soy land use from Mapbiomas and excluded forest regrowth after 2000 (MapBiomas 2020).

Because SoyM market share was highly clustered around 0% and 100% (figure S7), we considered
municipalities as treated once the SoyM market share reached $\geq 50\%$ (figure S6). We tested thresholds between $>0\%$ and $\geq 75\%$ and found the same treatment timing and location for all except one municipality (figure S7).

As counterfactuals to our treatment, we used soy-producing municipalities in the Amazon that were not-yet or never treated. By comparing municipalities within the same biome, we created treatment and counterfactual groups subject to similar governance and bioclimatic influences.

To estimate the effect of the SoyM on soy-deforestation, i.e. the average treatment effect on the treated (ATT), we estimated a difference-in-differences (DiD) model with staggered treatment adoption (Callaway and Sant’Anna 2020). We weighted municipal level observations by municipality area to interpret the estimated ATT as the population mean.

The DiD model assumed the treatment to be staggered, irreversible, and binary, and all observations to be untreated in the first timesteps (Callaway and Sant’Anna 2020). Most municipalities satisfied the staggered, irreversible treatment assumption (i.e. remained treated after SoyM market share reached 50% for the first time). Nevertheless, we tested different definitions of the treatment and found our results to be robust (see SI §3 and table S7).

We assume that the timing of treatment was exogenous, that spillovers across sampled municipality outcome and treatment status were limited (i.e. the stable unit treatment value assumption), and that treated and counterfactual municipalities followed parallel trends (see SI §3). We tested if our results were affected by cross-municipality leakage (see SI §3).

2.3.5. Avoided soy-deforestation in the Amazon from the SoyM

We estimated avoided direct soy-deforestation generated by the SoyM in the Amazon biome. To do so, we applied the estimated average treatment effect (ATT) of the SoyM on the treated municipalities (figure S9), by calculating the difference between $s$, the expected outcome without treatment, and $s_2$, the outcome after treatment (figure 2, SI §3).

2.3.6. Potentially avoided soy-deforestation in the Cerrado from implementing existing soy ZDCs

In the Cerrado, we estimated potential avoided soy-deforestation if all companies with adopted ZDCs had implemented these commitments from 2006 to 2015 (table S1). We defined municipalities as treated once ZDC market share reached $\geq 50\%$ (figure S11). For those municipalities, once treated, we reduced the observed soy deforestation based on the estimated ATT from the SoyM. This assumes that effectiveness of implementation in the Cerrado is equal to that observed for the SoyM. Avoided soy-deforestation was the difference between observed and ‘treated’ soy-deforestation (SI §4).

3. Results

3.1. ZDCs were rare amidst smaller soy companies and were substantially lower in the Cerrado

Corporate ZDC adoption rates were greater in the Amazon, where companies took part in the SoyM, than in the Cerrado, as reported previously (Zu Ermgassen et al 2020). In the Cerrado, only seven of 129 companies exporting soybeans had a ZDC, with the first pledge made in 2014 (table S1). In 2018, these seven companies controlled 66% of soy exports from the Cerrado. In the Amazon, 16 of 46 soybean-exporting companies adopted the SoyM, and they handled 95% of 2018 exports.

On average, companies with higher share value, greater sunk investments (e.g. storage, crushing, and refining facilities), and higher soy export volumes were more likely to adopt ZDCs (figures 3(a), (b), (d)–(f) and (h)). Compared to non-ZDC traders, those with ZDCs sourced more soy from municipalities with high deforestation rates (figures 3(c) and (g)) and sourced from municipalities where most soy-deforestation occurred (table 1, figure S4). There is
no evidence that commitment adoption is related to headquarter location. Cerrado ZDC companies have headquarters in Europe, North America, and Brazil, while SoyM companies have headquarters across many regions (table S1).

3.2. Adopted ZDCs in the Amazon and the Cerrado covered less than half of the soy-suitable forested areas

Adopted ZDCs covered less than half of the total remaining forest area suitable for soy expansion, overall and within only those municipalities with planted soy in 2018. About 55% and 53% of the soy-suitable forest in soy-producing municipalities in the Amazon and Cerrado, respectively, was in municipalities where no company had a ZDC (table 1).

3.3. Biodiversity conservation would likely benefit from ZDC implementation, but large habitat areas lacked protection

Of all soy-suitable forest habitat areas, 48% in the Amazon and 90% in the Cerrado were in municipalities with soy production (table 1). If all soy-suitable forests overlapping with the habitats of threatened forest-dependent species ($n = 249$) were cleared, 19% and 55% of these species’ habitat areas in the Amazon and Cerrado, respectively, would be removed. Ten species in the Amazon and three in the Cerrado would go extinct if all soy-suitable forests were cleared because their habitats fall only within these forests.

Municipalities with ZDC market share >50% contained about 20% and 45% of threatened species’ habitat areas within soy-suitable forests in the Amazon and Cerrado, respectively (table 1). In the Amazon, these species benefit from greater protection as a result of the implementation of the SoyM (section 3.4), while in the Cerrado they would only receive some protection from soy expansion if currently adopted ZDCs are actually implemented (section 3.5). Yet, even if adopted ZDCs in the Cerrado were implemented, not all at-risk areas would be covered. Extensive threatened species’ habitat areas (i.e. 29% in the Amazon and 43% in the Cerrado) are in soy-producing municipalities with zero ZDC market share (table 1).

3.4. SoyM signatories more than halved soy-deforestation in the municipalities they source from

Our DiD analysis found that the SoyM reduced direct soy-deforestation in treated municipalities by 57% (95% confidence interval (CI): 31%–73%, table S2, figure 4). Our results were robust against different definitions of the counterfactual group (i.e. not-yet and never treated municipalities), exclusion of pre-SoyM years, and different treatment definitions (tables S2(a)–(d), figures S8(a)–(d)). We found no
Table 1. Soy-suitable forest, deforestation, soy-deforestation, forest cover, and percent of summed species habitat of threatened forest-dependent species across the different ZDC market share categories (at the municipality level) in the Brazilian Amazon and Cerrado.

| ZDC market share | Number of municipalities\(^a\) | Soy-suitable forest in kha (% of ZDC market share category excluding municipalities without soy)\(^a\) | Deforestation in kha (% of ZDC market share category)\(^b\) | Soy-deforestation in kha (% of ZDC market share category)\(^b\) | % of summed species habitat area in soy-suitable forest\(^c\) |
|------------------|-------------------------------|-------------------------------------------------|--------------------------|---------------------------------|--------------------------|
|                  | Amazon | Cerrado | Amazon | Cerrado | Amazon | Cerrado | Amazon | Cerrado | Amazon | Cerrado | Amazon | Cerrado | Amazon | Cerrado |
| No soy           | 312    | 236    | 32 783 | 5470    | 641    | 182    | 0 (0%) | 0 (0%)   | 52%    | 10%     |
| 0%               | 133    | 685    | 15 167 | 19 083  | 372    | 468    | 5 (20%) | 22 (41%) | 29%    | 43%     |
| 1%-25%           | —      | 9      | —      | 606    | 6 (0%) | 27 (3%) | 0 (0%) | 4 (7%)    | —      | 1%       |
| 26%-50%          | 1      | 8      | 44 (0%) | 402 (1%) | 6 (0%) | 13 (1%) | 0 (0%) | 2 (4%)    | 0%     | 1%       |
| 51%-75%          | 1      | 10     | 161 (1%) | 968 (3%) | 6 (0%) | 39 (4%) | 2 (8%) | 8 (15%)   | 0%     | 2%       |
| >75%             | 52     | 155    | 12 411 | 14 757 (41%) | 214 (17%) | 153 (17%) | 1.8 (72%) | 18 (33%) | 20%    | 43%     |
| Total            | 499    | 1103   | 60 566 | 41 285 (100%) | 1245 (100%) | 882 (100%) | 2.5 (100%) | 54 (100%) | 100%   | 100%   |

\(^a\) In 2018.
\(^b\) In 2015. See figure S4 for additional years.
indication of leakage from treated to neighboring municipalities (table S2(e), figure S8(e)).

Compared to a counterfactual where the SoyM had never been implemented, the policy led to 230 993 ha (95% CI: 78 668–475 768 ha) or 53% (95% CI: 28%–70%) of avoided soy-deforestation in the Brazilian Amazon between 2006 and 2015 (figure S9). This exceeds observed 2006–2015 soy-deforestation (204 703 ha) but is only 1.6% of total observed 2006–2015 Amazon deforestation (14 547 858 ha, figure S10).

3.5. ZDC implementation in the Cerrado could have halved soy-deforestation

Had the seven companies that have adopted soy ZDCs (table S1) implemented their commitments in the Cerrado in 2006, they could have contributed an avoided 509 126 ha (95% CI: 278 622–1115 087 ha) or 46% (95% CI: 24%–59%) of direct soy-deforestation and around 5% of overall deforestation between 2006 and 2015 (total observed soy-deforestation: 1115 087 ha, total observed deforestation: 10 032 444 ha, figure S12).

4. Discussion

4.1. Large companies tend to adopt ZDCs, but adoption does not always lead to implementation

ZDC adoption was greater among larger companies with a higher fraction of total soy sourcing within deforestation hotspots and more sunk infrastructure. Such companies face a high risk of being targeted by civil society organization campaigns due to their size, environmental impact, and investments in deforestation-risk regions (Hendry 2006, Rueda et al 2017). Other factors correlated with company size and influence may also be responsible for observed differences. For instance, large companies might benefit from economies of scale, increasing the cost-effectiveness of implementation and mitigating risks by trading several commodities (Grabs and Carodenuto 2021). Since our analytical approach was designed to assess differences between companies with and without ZDCs, further research intended to attribute causes of adoption via ethnographic and/or statistical approaches is needed (Grabs and Carodenuto 2021).

While consumer-oriented campaigns are thought to have played a key role in incentivizing initial commitments by such firms (Gibbs et al 2015, Alix-Garcia and Gibbs 2017), such campaigns cannot target every small firm. Currently proposed due diligence or zero deforestation laws requiring compliance of production with laws and regulations in exporting regions may exclude small and medium-sized firms (European Commission 2021).

Theory suggests that adoption of voluntary policies by larger, more dominant firms can lead to policy spillovers to smaller companies that decide to imitate larger companies (Hendry 2006) to participate in the zero-deforestation market. The SoyM was supported by the two largest soy industry associations in Brazil (Abiove 2020, Anec 2020), leading to high ZDC adoption and implementation among all industry association members in the Amazon including smaller firms. However, ZDC adoption and implementation has not spilled over to smaller firms in the Cerrado biome. Instead ZDC adoption in the Cerrado is even more skewed to the largest firms (table S1). Such large companies are more likely to have the resources needed to implement their policies including more stable sourcing relations with producers that are favorable for policy dissemination (Leijten et al 2022). Yet, while they appear well-positioned to make good on their commitments, none of these companies have implemented their Cerrado ZDCs along their full supply chain.

Although prior studies found a link between the adoption of the SoyM, and trade regulations on genetically modified soy, to be associated with exports to the EU (Garrett et al 2013, Nolte et al 2017), we found that export locations in 2018 were similar between ZDC and non-ZDC companies. The decreasing proportion of exports going to the EU since the SoyM was adopted may have diminished the influence of EU consumer preferences on companies’ incentives to implement new soy ZDCs (table S1). In 2018, Asian markets dominated soy export destinations, while Europe was the second largest export market (figure S5). Yet, none of the companies that adopted ZDCs in the Cerrado have their headquarters in Asia, which suggests lower consumer demand.
for ‘environmentally-friendly’ soy and/or less non-governmental organization (NGO) presence in those countries to pressure companies into greater ZDC action. Another potential explanation for the lack of implementation in the Cerrado compared to the Amazon is that there were fewer farms present in the Amazon during the initial SoyM adoption and implementation period in comparison to the highly competitive market for soy trading in the Cerrado. NGOs directed significant pressure at individual firms with follow-up reporting on deforestation within these firms’ supply chains (Greenpeace 2006). Naming and shaming campaigns have been less visible in the Cerrado. This lack of pressure from civil society did not encourage prompt action by firms. Finally, the political context has significantly changed since the SoyM under the conservative Bolsonaro presidency, which has bolstered efforts to reduce, rather than expand, deforestation control (de Area Leão Pereira et al 2020, Garrett et al 2021).

4.2. Limited ZDC coverage for soy-suitable forests and forest-dependent species habitat

We found that more than half of soy-suitable forests and forest-dependent species habitats in the Brazilian Amazon and Cerrado are in municipalities without meaningful ZDC market shares, resulting in a major conservation gap. Particularly in the Cerrado, where public policies restrict clearing on only 20%–35% of a private property (NVP 2012), soy-suitable forests outside ZDC sourcing regions would remain vulnerable to soy-deforestation even if ZDC companies were to implement their pledges. In the Amazon, stronger public policies (e.g. restricting clearing on 50%–80% of private properties (NVP 2012)), and limited accessibility may reduce the risk of soy-deforestation even if many areas lack ZDC presence (figure 1). Our results emphasize the concern that because supply chain governance is a constraint only to those producers within specific ZDC supply chains and does not cover all commodities, its ability to meet conservation goals across landscapes and large regions is limited.

4.3. The SoyM reduced deforestation, but it is contribution to avoided deforestation in Brazil has been small

While our finding that the SoyM led to a 57% reduction of soy-deforestation in treated municipalities confirms that ZDCs have effectively reduced forest loss from soybean expansion in the Amazon, the impact of the SoyM on overall deforestation in Brazil, across commodities and regions, appears limited. The 57% reduction translated to an avoided 26 666 ha yr$^{-1}$, or just 1.6% of overall Amazon deforestation over the study period. Moreover, while we found no evidence of cross-municipality leakage in our sample municipalities in the Amazon (table S2, figure S8(e)), leakage may have occurred to municipalities that did not produce soy in 2005, other Brazilian biomes, or other countries (Viloria et al 2022, Gibbs et al 2015, Noojipady et al 2017, Dou et al 2018, Kuschnig et al 2021). Thus, our findings serve as an upper-bound estimate of the SoyM’s contribution to reducing (soy-)deforestation in Brazil.

Yet, our estimate of avoided deforestation is much lower than the only previous counterfactual-based assessment by Heilmayr et al (2020), who estimated that the SoyM reduced overall Amazon biome deforestation by 1800 000 ha (95% CI: ±90 000) or 35% (95% CI: ±16) between 2006 and 2016.

Several methodological differences help explain differing findings. We estimated the impacts of the SoyM only in municipalities with high ZDC market share. In contrast, Heilmayr et al (2020) assumed that the SoyM applied to all soy-suitable areas in the Amazon, including those without SoyM company presence. Our approach therefore reduced the potentially affected area to those areas where SoyM signatories could directly impact producers’ deforestation practices. Second, while our outcome variable was soy-deforestation, Heilmayr et al (2020) used overall deforestation, which likely includes non-soy deforestation (e.g. forest clearance for cattle ranching). Finally, Heilmayr et al (2020) applied a triple DiD estimator, comparing pre and post-SoyM implementation, soy-suitable and not-suitable locations, and Amazon and Cerrado biomes. Our DiD estimator instead compared pre and post-treatment and treated versus not-yet-treated municipalities in the Amazon biome. This allowed us to avoid potentially confounding effects between the Amazon and Cerrado biomes driven by different environmental laws, monitoring and enforcement as part of implementation, and deforestation leakage.

Thus, compared to Heilmayr et al (2020), our approach likely has greater internal validity, or a more trustworthy cause and effect relationship between ZDC implementation and soy-deforestation reductions in Amazon soy-producing municipalities. Yet, our estimates may suffer from lower external validity because they cannot capture deforestation processes outside of soy-producing municipalities. We caution generalizing our findings to different social, environmental, and governance settings.

4.4. Implementation of current ZDCs in the Cerrado may conserve less forest than previously estimated

Our results suggest that had companies with an adopted ZDC in the Cerrado implemented their commitments with the same effectiveness as the SoyM, they could have halved observed soy-deforestation in the biome between 2006 and 2015. This estimate assumes that the implementation of ZDCs in the Cerrado would have had the same effect on soy-deforestation as the SoyM, a strong assumption given that the SoyM is supported among more companies, restricted to
a comparably small area (Rausch and Gibbs 2021), and located in a region with stricter environmental laws (NVP 2012), providing synergies in monitoring and enforcement of the commitment (Lambin et al 2014, Garrett et al 2019). At the same time, the Cerrado faced high pressure for soy expansion, possibly in part due to displaced demand from the Amazon because of SoyM implementation (Noojipady et al 2017, Rausch et al 2019). Some research suggests that the SoyM induced additional deforestation in the Cerrado and other regions outside Brazil (Villoria et al 2022, Noojipady et al 2017). Yet, availability of already cleared land highly suitable for soy production in the Cerrado could have absorbed some of the displaced demand, allowing soy expansion without additional deforestation (Nepstad et al 2019, Rausch et al 2019).

Thus, our estimate is likely the upper bound of the potential impact of implementing adopted ZDCs in the Cerrado. Yet, our projected reduction in Cerrado soy-deforestation (50 913 ha yr$^{-1}$) based on the implementation of currently adopted ZDCs and the market share of companies with adopted ZDCs (figure S11, table S1) is only half of the avoided deforestation estimated by Soterroni et al (2019) (120 000 ha yr$^{-1}$) who assumed that all companies would adopt and implement a ZDC. Our approach, incorporating the municipal ZDC market share into estimating ZDCs’ potential impact, thus provides a more plausible best-case estimate of the likely conservation benefits of currently adopted ZDCs in the Cerrado. Indeed, deforestation leakage from the Cerrado to other biomes and countries may still reduce the impact of these ZDCs on global avoided deforestation (Villoria et al 2022).

5. Conclusion

Supply chain sustainability policies are prominent in global food system governance discussions. Using new spatially and temporally explicit data on soy company sourcing locations and land use in the Brazilian Amazon and Cerrado biomes, we explored factors that are associated with ZDC adoption, and how spatial and temporally heterogeneous ZDC adoption and implementation may contribute to conservation goals. We empirically tested how incomplete ZDC market coverage, measured as the collective regional market share of companies with adopted ZDCs, affected soy-deforestation in the Amazon, and how it could constrain conservation benefits from implementing existing ZDCs in the Cerrado. Yet, variable adoption and implementation across companies and space leave many places exposed to soy buyers without ZDCs. The lack of ZDC implementation and the low adoption by small and medium firms in the Cerrado restricts the potential impact of ZDCs in this highly threatened biome.

Our analysis confirms that implementation of corporate ZDCs can reduce commodity deforestation in places where these companies have substantial market share. We expect that this general mechanism will hold true across commodities and geographies, yet local levels of ZDC effectiveness depend upon implementation approaches, supply chain and market structure, and complementary public environmental policies. For example, unlike soy, a capital-intensive activity where producers mostly sell directly to trading companies, cattle, oil palm, and cocoa supply chains are commonly multi-tier (Lyons-White and Knight 2018, Grabs et al 2021, Cammelli et al 2022, Levy et al 2022). This increases the complexity of supply chain monitoring, which may, for example, provide additional opportunities for laundering if not all indirect suppliers are monitored. Moreover, the risk of exacerbating precarious supplier livelihoods and pushing producers to local leakage markets may be greater in other supply chains (Lyons-White et al 2020, Grabs et al 2021). This could make ZDC impacts on deforestation for a given market share substantially lower than has occurred in the Brazilian Amazon for soy. Measuring these relationships across commodities requires further scientific attention.

Our results also point to current limitations of supply chain governance. If supply chain policies intend to contribute to the task of tackling deforestation in Brazil, it is crucial to expand zero-deforestation supply chain policies beyond soy. Recent commitments to eliminate deforestation from the cattle supply chain in the Brazilian Amazon have been promising, but the lack of monitoring of indirect suppliers, the narrow focus on the Amazon biome, and limited adoption by smaller slaughterhouses undermined their contribution to reducing deforestation (Alix-Garcia and Gibbs 2017, Klingler et al 2018, Levy et al 2022). Due-diligence zero-deforestation and other forest-focused trade regulations, as proposed by the European Commission (Keohel et al 2019, Bager et al 2020, European Commission 2021) could target more companies independent of their size and public exposure, include all forest risk commodities, and cover all regions. However, supply chain governance should not be understood as a substitute for state-led forest policies, which are critical to enable zero-deforestation monitoring and enforcement, have better potential to cover multiple types of commodities, land users, and regions, and may thereby be better positioned to mitigate leakage (Garrett et al 2019, Sellare et al 2022).

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.
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Author contributions

FG, RG, and KMC designed the research. FG analyzed the data with support from FC. FG wrote the original draft. FG, RG, KMC, and FC developed and further contributed to writing, reviewing, and editing.

Conflict of interest

The authors declare no conflict of interest.

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