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Brazil's Amazon Soy Moratorium reduced deforestation

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Between 2004 and 2012, multiple policies contributed to one of the great conservation successes of the twenty-first century—an 84% decrease in the rate of Brazilian Amazon deforestation. Among the most prominent of these policies is the Amazon Soy Moratorium (ASM), an agreement by grain traders not to purchase soy grown on recently deforested land. The ASM inspired widespread adoption of similar zero-deforestation commitments, but its impact is poorly understood due to its overlap with other conservation policies. Here, we apply an econometric triple-differences model to remotely sensed deforestation data to isolate the ASM's impact within Brazil's Arc of Deforestation. We show that the ASM reduced deforestation in soy-suitable locations in the Amazon by 0.66 ± 0.32 percentage points relative to a counterfactual control, preventing 18,000 ± 9,000 km² of deforestation over its first decade (2006–2016). Although these results highlight potential benefits of private conservation policies, the ASM's success was dependent on complementarities with public property registries and deforestation monitoring.

The scale and pace of Brazilian Amazon deforestation in the early 2000s provoked widespread concern about biodiversity loss, endangerment of indigenous livelihoods, and local to global climate impacts[1–3]. In response, policymakers and other stakeholders adopted a broad array of policies to reduce deforestation[4,5]. Government interventions included, among other policies, the designation of indigenous lands and new conservation areas, elevated penalties against and enforcement of deforestation restrictions, and sanctions directed at local jurisdictions with the highest rates of deforestation[6–12]. At the same time, private actors pioneered several interventions to remove deforestation from commodity supply chains, including the Amazon Soy Moratorium (ASM) and agreements in the cattle sector[13–15]. While these public and private policies contributed to an 84% decrease in the rate of deforestation in the Brazilian Amazon between 2004 and 2012 (falling from 27,800 km² to 4,500 km²), deforestation rates doubled between 2012 and 2019 (reaching 9,800 km²)[16]. To sustain forest conservation in the Amazon, and to replicate Brazil's success globally, the scientific community must provide a deeper understanding of the relative contributions and interactions among the policies that contributed to Brazil's deforestation decline.

The ASM was set in motion in May 2006, when a provocative Greenpeace report linked three American commodities traders (Cargill, Bunge and ADM) to millions of hectares of Amazon deforestation and called for the companies to withdraw from the region[17]. By July of the same year, the Brazilian Association of Vegetable Oil Industries and National Association of Grain Exporters responded by announcing the ASM—a 2-year ban on the purchase of soy from newly deforested areas in the Amazon biome[18–20]. Together, these organizations were responsible for 90% of the trade in soy produced in the Amazon[21]. The ASM was renewed annually or biannually until 2016, when it was renewed indefinitely. The original agreement prohibited soy production on lands cleared after 24 July 2006, although the date was later revised to 22 July 2008 to align with a cut-off established in the 2012 revision of Brazil's Forest Code[10].

To monitor and enforce its restrictions, the ASM integrates a variety of public and private institutions[22]. Monitoring and enforcement is overseen by the soy working group (*Grupo de Trabalho da Soja* in Portuguese; hereafter, GTS)—a partnership between soy traders, non-governmental organizations and government agencies[23]. Each year, the GTS commissions maps of soy extent in the Amazon. In municipalities with a sizeable amount of soy (>5,000 ha for most years), areas of new expansion are assessed for overlap with post-2008 deforestation, as identified by the government's deforestation monitoring system (*Projeto de Monitoramento do Desmatamento na Amazônia Legal por Satélite* in Portuguese; hereafter, PRODES). To link violations to specific actors, the ASM previously encouraged and now requires that soy producers register their properties in the Rural Environmental Registry (*Cadastro Ambiental Rural* in Portuguese; hereafter, CAR). Using a combination of information in the CAR, satellite data and field visits, the GTS prepares an annual list of farms with ASM violations. Soy traders are required to reference this list to determine whether potential suppliers have violated the ASM.

By prohibiting the purchase of soy grown on recently cleared lands, the ASM creates multiple disincentives that could decrease deforestation in the Amazon. Soy farmers who believe that the ASM will restrict the sale of non-compliant soy are unlikely to invest in the direct conversion of forests to soy production[24]. In addition, the ASM prohibits soy expansion into pastures or other croplands that were cleared after the historic cut-off. As a result, the ASM may limit the expected revenues from future land uses for currently forested lands, decreasing the speculative value of deforestation for cattle ranchers and other investors[25]. Farmer opposition to the ASM and Brazil's Forest Code has inspired efforts to end these land use restrictions, which have intensified under the Bolsonaro administration[26,27].

The impacts of the ASM are of particular interest to inform similar private supply-chain interventions in other sectors and geographies[15,22]. Since these policies are voluntary, there is concern

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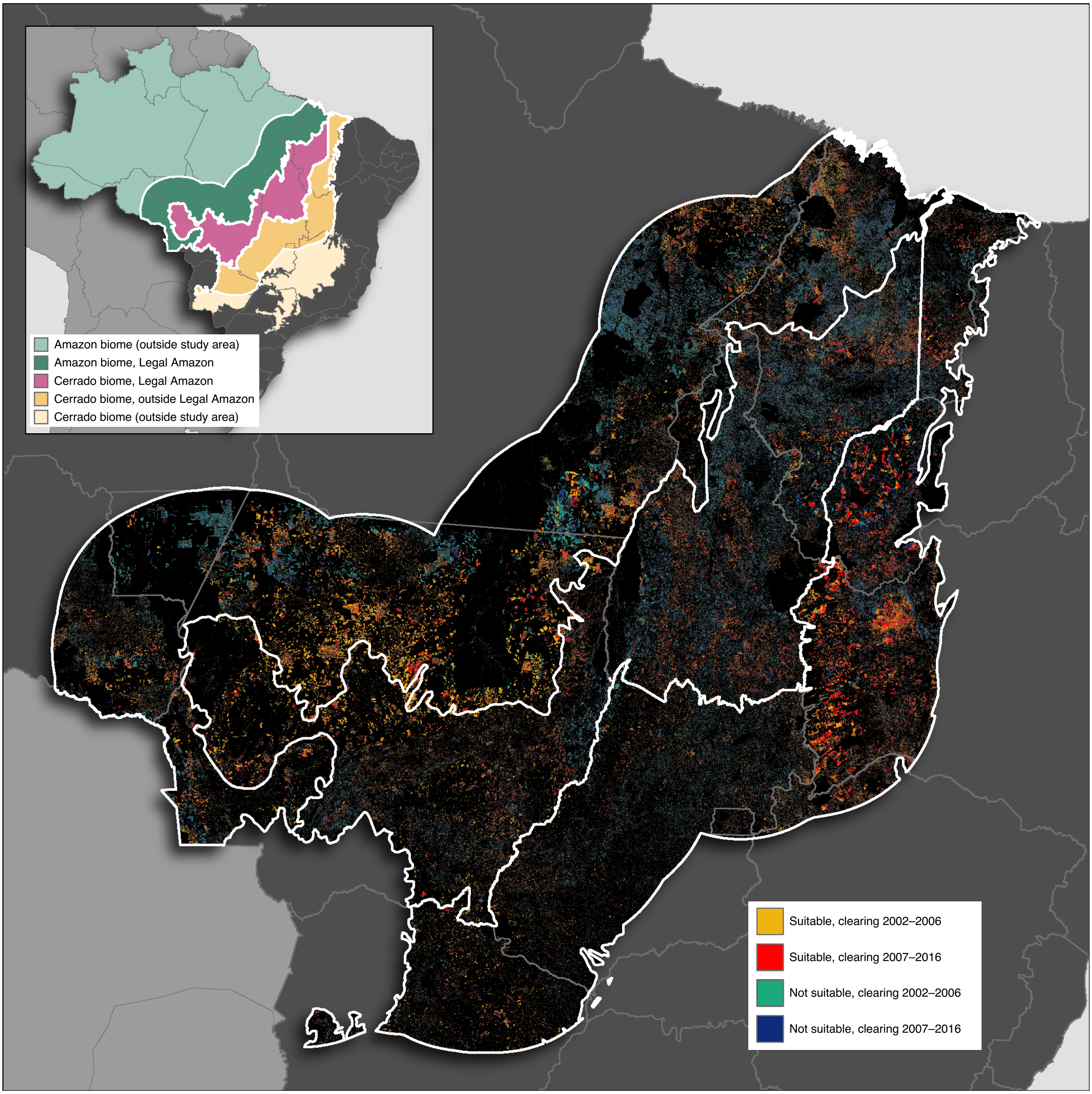

Fig. 1 | Deforestation patterns across Brazil's Arc of Deforestation. Our study focuses on the portions of the Amazon and Cerrado biomes located within 300 km of either the Amazon biome or Legal Amazon boundary (inset). Our analysis measures the impact of the ASM by comparing post-ASM changes in deforestation rates occurring on soy-suitable portions of the Amazon biome, relative to non-suitable locations, or locations in the Cerrado biome portion of the Legal Amazon (main panel).

that supply-chain interventions will not generate real conservation benefits[28]. However, recent research has revealed several trends that suggest that the ASM has played a role in reducing Amazon deforestation. First, rates of deforestation and soy conversion have declined dramatically since the early 2000s[13,29–32]. In addition, the share of new soy planted on recently cleared lands and the share of recently deforested areas converted to soy have both sharply declined[13,29,30]. At the same time, soy has continued to expand in the Amazon, predominately over pasture[29,33]. Accordingly, compliance with the ASM has been remarkably high[24]. The GTS has identified only 64,316 ha of soy that were planted in violation of the moratorium, accounting for 1.4% of all soy grown and 1.2% of all deforestation in the Amazon biome[34]. Nevertheless, these studies do not integrate formal counterfactual analysis to isolate the impacts of the ASM from contemporaneous policy and economic changes. As a result, the causal effect of the ASM on deforestation is still unknown.

In this study, we seek to attribute deforestation reductions to the ASM, to quantify that impact and to document the mechanisms by which the ASM has achieved success. We focus our study on Brazil's Arc of Deforestation, which we define as the portions of the

Amazon and Cerrado biomes that fall within 300 km of the Amazon biome or Legal Amazon borders (Fig. 1). To measure the ASM's impact, we leverage a natural experiment made possible by the policy's distinct commodity and geographic focus (that is, soy production in the Amazon biome). We use a triple-differences model that isolates post-ASM changes in deforestation rates occurring only on soy-suitable portions of the Amazon biome relative to forests located in the Cerrado biome or in non-soy-suitable locations in the Amazon biome (Methods). This model and the extensions described in the Methods and Supplementary Information allow us to isolate the impact of the ASM from the impacts of concurrent public policy reforms, such as the federal government's Action Plan for Deforestation Prevention and Control in the Legal Amazon (PPCDAm), the expansion of conservation and indigenous preserves and the introduction of public property registries[5,9,35,36]. Without careful consideration of these policies, their impact on deforestation rates might be inappropriately attributed to the ASM. In addition, we explore deforestation patterns outside of the boundaries of the ASM to assess whether leakage has undermined the benefits of the ASM or biased our results. Finally, we quantify heterogeneity in the impacts of the ASM to help identify the policy design elements that have contributed to its effective implementation. We anticipate that careful consideration of the ASM's impacts can guide effective implementation of sustainable supply-chain interventions in other sectors and contribute to sustained protection of the Amazon's forests and communities.

Results

Avoided deforestation. The ASM had a substantial effect on deforestation rates in the Amazon. Before its adoption in 2006, deforestation trends were similar across the Amazon and Cerrado portions of the study region, declining sharply after reaching a peak in 2003 (Fig. 2). After 2006, deforestation rates stabilized and/or increased in the Cerrado but continued to decline within the Amazon biome, except for in 2016 when deforestation spiked across both biomes due to widespread burning that was exacerbated by El Nino–Southern Oscillation-related drought conditions[37]. This cross-biome divergence in deforestation rates was most pronounced on soy-suitable lands (Fig. 2a,b). Before the adoption of the ASM, deforestation rates were slightly higher on soy-suitable lands in the Amazon biome (3.2% per year) than within the Cerrado portion of the Legal Amazon (2.7% per year) as well as the portion of the Cerrado biome outside of the Legal Amazon (2.8% per year). Between 2006 and 2016, soy-suitable deforestation rates in the Amazon biome fell to 1.1% per year—0.24 percentage points (pp) per year below the rate of soy-suitable deforestation in the Cerrado portion of the Legal Amazon, and 0.89 pp per year below the rate in the Cerrado biome outside of the Legal Amazon. These broad trends are consistent with a variety of studies that have argued that the dramatic decline in deforestation experienced after 2006 is indicative of the ASM's effectiveness[13,29,30,38–40].

Our econometric models isolate and quantify the ASM's impacts by comparing relative trends in deforestation rates across biomes and soy suitability classes (Table 1). Relative to the Cerrado portion of the Legal Amazon, the annual deforestation rate on soy-suitable locations declined by 0.70 ± 0.37 pp in the Amazon biome after the adoption of the ASM (all error bounds describe the 95% confidence interval). Similarly, post-ASM deforestation in soy-suitable regions of the Amazon biome declined by 0.98 ± 0.25 pp relative to non-soy-suitable portions of the biome. Using a triple-differences model that integrates both of these comparisons, we estimate that the ASM reduced annual deforestation by 0.66 ± 0.32 pp. This smaller estimated effect reflects the fact that soy-suitable areas of the Cerrado biome also experienced a relative decline (0.42 ± 0.23 pp) in deforestation in the latter half of our study period. To quantify what would have happened had the ASM never been adopted, we construct a counterfactual scenario in which we add our estimated treatment effect (0.66 ± 0.32 pp) to historical 2006–2016 deforestation rates. When compared with this counterfactual scenario, the ASM reduced deforestation rates by 35 ± 16%, contributing 18,000 ± 9,000 km^2 of avoided deforestation in the Amazon biome. As a point of comparison, previous research found that public policies in the Amazon reduced deforestation by 54%[5]. Our results are robust to additional model specifications that use alternative functional forms, definitions of soy suitability, subsamples and control variables (see Supplementary Information). Parallel trends in deforestation rates before the ASM's implementation give us additional confidence in the validity of our estimates (Fig. 2c).

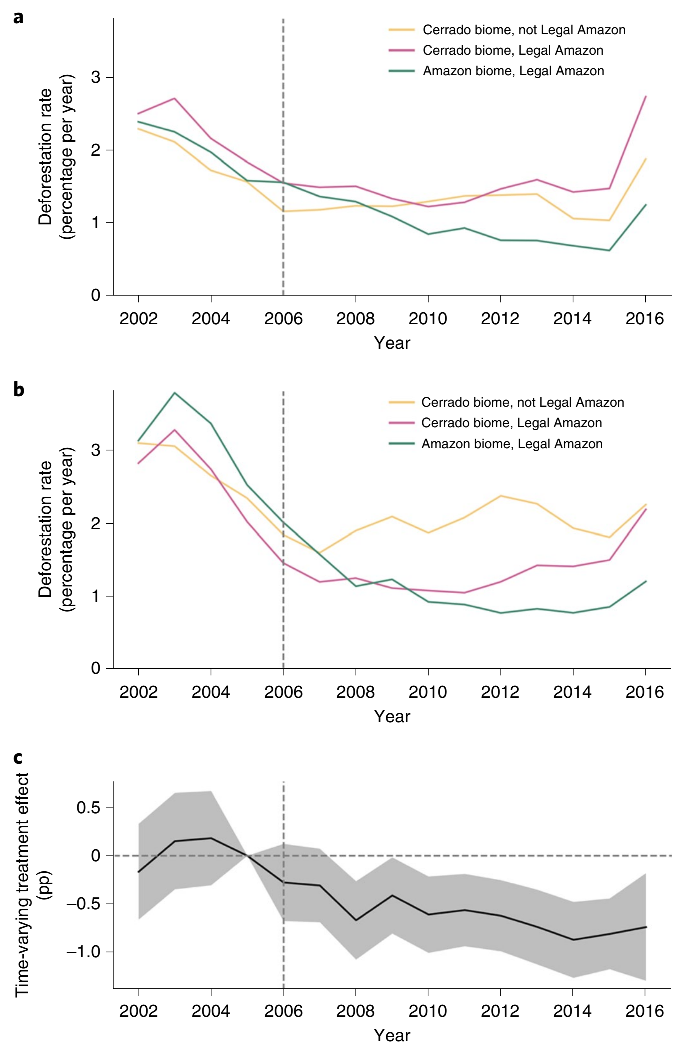

Fig. 2 | Time-varying impacts of the ASM. a,**b**, We differentiate regional deforestation trends in locations that are not suitable for soy (**a**) and in locations that are soy suitable (**b**). Our primary triple-differences model specification compares the post-ASM change in deforestation rates across ecological biomes (green versus pink lines) and across locations with differential suitability for soy production (**a** versus **b**). **c**, Temporal variation in the estimated treatment effect of the ASM based on this triple-difference estimator within the Legal Amazon, with the shaded area representing the 95% confidence interval. The dashed vertical lines in **a**–**c** depict the year (2006) in which the ASM was adopted.

Further evidence of the ASM's impact can be seen in changing rates and locations of soy establishment across the study region (Fig. 3). Consistent with previous studies, we found that the rate of soy expansion into previously cleared locations increased across

Table 1 | Estimates of avoided deforestation as a result of the ASM

	1	2	3	4	5
	Amazon DD	**Cerrado DD**	**Soy-suitable DD**	**Non-soy-suitable DD**	**Triple difference**
Suitable for soy × post-ASM	−0.00975*** (0.00126)	−0.00420*** (0.00116)			−0.00330*** (0.00122)
Amazon biome × post-ASM			−0.00696*** (0.00189)	−0.00129 (0.00107)	−0.000208 (0.00126)
Amazon biome × suitable for soy × post-ASM					−0.00656*** (0.00163)
Sample	Within-Amazon biome	Outside-Amazon biome	Within soy-suitable areas	Outside soy-suitable areas	All points
Number of points	161,862	113,033	141,234	138,126	279,360
Number of municipalities	330	336	493	545	563

The columns present difference-in-differences (DD) and triple-difference regressions contrasting changes in deforestation rates across biomes and soy suitability ratings. The models were estimated using forested points in the Legal Amazon. They include additional covariates and interaction terms, as described in the Methods. All regressions are linear probability models using a binary indicator of deforestation as the dependent variable. Coefficient estimates can be interpreted as a change in the probability of deforestation, measured in percentage points. Standard errors, clustered by municipality, are given in parentheses. ***$P < 0.01$.

the entire study region in the post-ASM period[29,30,39]. Although the Amazon biome saw the greatest increases in soy establishment in previously cleared areas, it experienced the greatest relative declines in soy establishment in previously forested locations. Preferential planting of soy on previously cleared land provides additional support for the ASM's effectiveness and highlights the potential for supply-chain governance to reduce deforestation while allowing for continued cropland expansion. While this effect would be expected to reduce soy-driven deforestation leakage to other biomes, it could accelerate indirect land use change due to displaced cattle ranching[41]. We explore this concern further in our discussion of leakage dynamics below.

Complementarities with public policies. The ASM is part of a mosaic of public and private policies that have reduced deforestation in Brazil (Methods and Supplementary Fig. 3)[7,9,11,12,42,43]. Declines in deforestation predate the adoption of the ASM and extend beyond the Amazon biome. In addition, our estimate of the impact of the ASM (−0.66 pp) represents only 25% of the 2.6 pp decrease in deforestation rates that occurred between 2002 and 2016 on soy-suitable locations in the Amazon biome portion of the Arc of Deforestation. We assess the overlapping impacts of the ASM and public reforms, including those contained within the PPCDAm, by exploring differences in deforestation trends across the Amazon biome, the Legal Amazon portion of the Cerrado biome and the portion of the Cerrado biome falling outside of the Legal Amazon (Methods and Supplementary Table 2, column 6). We show that, after the adoption of the PPCDAm in 2004, the Legal Amazon experienced a 0.46 ± 0.44 pp decrease in deforestation across biomes and soy suitability classes. However, soy-suitable locations within the Amazon biome experienced a significant ($P < 0.05$) additional decrease in deforestation after the adoption of the ASM in 2006. Further tests outlined in the Methods and Supplementary Information provide evidence that the estimated impacts of the ASM are additional to impacts from a variety of public policies that previous studies have recognized for their conservation impacts. These include heightened public deforestation monitoring, Central Bank restrictions on rural credit for farmers that violated forest requirements, and the government's blacklist of priority municipalities (Supplementary Table 2, columns 1–4)[6–8,11,12,44].

Nevertheless, the ASM only reduced deforestation when its threat of market sanctions was reinforced through GTS monitoring or property-level registration in the CAR (Table 2, column 4). Although the ASM nominally applies to the entirety of the Amazon biome in Brazil, its full implementation is restricted to those locations where the GTS monitors for violations (see Supplementary Information). Furthermore, the ASM now requires farmers to register their properties with the CAR, to help assign culpability for violations and to encourage farmers to meet public forest laws. We mapped the spatiotemporal footprints of the GTS monitoring system and CAR property registrations within the state of Mato Grosso to explore interactions between these policy design elements. Deforestation reductions did not occur in locations that were neither monitored by GTS nor registered with the CAR (−0.16 pp; $P = 0.46$). Similarly, properties that were registered with the CAR outside of the ASM's spatiotemporal footprint did not experience a significant decline in deforestation (0.050 pp; $P = 0.70$). Post-ASM deforestation declines in the Amazon biome were concentrated in places that were either monitored by GTS (−1.14 pp; $P < 0.01$) or registered in the CAR (−1.15 pp; $P < 0.01$). Locations where the ASM was fully monitored and enforced through both property registration and GTS monitoring experienced the greatest decrease in deforestation (1.53 pp; $P < 0.01$). The complementary interaction between CAR registration and the ASM could reflect either increased registration in the CAR by properties selling into ASM supply chains, or improved enforcement of the ASM as a result of access to CAR registration data. The lack of statistically significant impacts from CAR registration in the absence of market sanctions, or from the ASM's threats of market sanctions in the absence of monitoring and enforcement, provide additional evidence to support a causal interpretation of the relationship between the ASM and declining deforestation. In addition, these results provide context for the interpretation of previous studies assessing the conservation impacts of the CAR; the importance of interactions between property registration and private sanctions could be one explanation for observed heterogeneities in the CAR's conservation benefits[35,45,46].

The ASM has leveraged existing public institutions, such as property registries (CAR) and deforestation monitoring (PRODES), to reduce implementation costs and increase its credibility among a diversity of stakeholders[47]. Our results indicate that these public investments played a critical role in enabling the ASM's effectiveness. For example, the GTS's use of PRODES deforestation data allowed for the rapid deployment of a monitoring system that was trusted by diverse stakeholders. Similarly, the combined effect of property-level accountability from the CAR and the ASM's sanctions achieved deforestation reductions that neither policy was able to achieve in the absence of the other[35,46]. The impacts from the overlapping adoption of the ASM, GTS monitoring and CAR

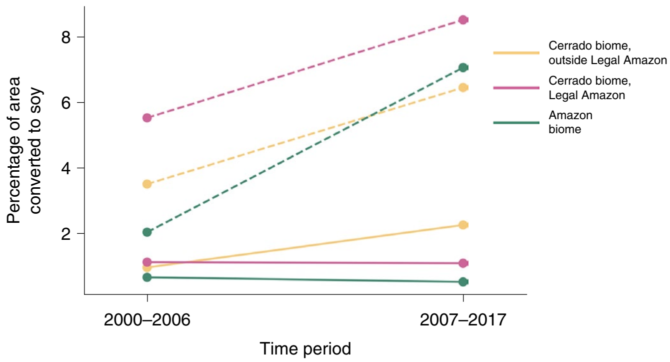

Fig. 3 | Changes in patterns of soy establishment. We differentiate soy establishment trends by region (colour) and starting land use (dashed lines: non-forested locations; solid lines: forested locations). The Amazon biome experienced the largest relative increase in soy establishment in non-forested locations and the largest relative decrease in soy establishment in forested locations.

registration aggregate nonlinearly, highlighting the potential for complementarities in public and private policies to amplify their individual impacts[48–51].

Leakage. The ASM's focus on soy-driven deforestation in the Amazon may have encouraged leakage of deforestation by, for example, pushing soy production into other biomes or displacing cattle ranching into new forest frontiers[20,41,52,53]. Such leakage poses two potential challenges to the interpretation of our primary results[54]. First, by affecting deforestation rates in our control units, leakage could bias our estimate of avoided deforestation within the Amazon biome. Second, leakage could weaken the ASM's aggregate carbon and biodiversity impacts by trading avoided deforestation within its footprint for accelerated deforestation in other locations. Below, we evaluate the evidence for and implications of three leakage pathways cited in previous assessments of land use change dynamics in Brazil: leakage across the biome boundary; indirect land use change; and the exploitation of gaps in the ASM's rules and monitoring.

By drawing attention to the Amazon biome, the ASM could have pushed soy-driven deforestation into the neighbouring Cerrado. Such spillovers are typically thought to concentrate near a policy's boundary[20,52,53], and ongoing agricultural expansion has been observed in the Cerrado during the post-ASM period[55–57,21]. However, soy-suitable locations in the Cerrado that were close to the biome boundary did not experience a relative increase in deforestation compared with more distant soy-suitable locations (Table 3, columns 1–3). While this provides some evidence against cross-biome leakage, it does not rule out the possibility that leakage has affected both proximate and distant portions of the Cerrado. This is an important consideration given the growing share of soy-driven deforestation occurring in the more distant portions of the Cerrado that fall outside of the Legal Amazon (Figs. 2 and 3)[20,21,40,52,56]. To explore whether the ASM encouraged the emergence of new soy frontiers in the Cerrado, we tested whether different regions experienced a post-ASM relative increase in deforestation on soy-suitable locations compared with non-suitable locations (Supplementary Table 7). After the adoption of the ASM, soy-suitable locations in the Cerrado experienced a similar or greater decline in deforestation compared with non-suitable locations. These results provide no evidence to support the concern that the ASM caused significant cross-biome leakage of soy-driven deforestation.

Soy expansion into non-forested locations accelerated after the adoption of the ASM (Fig. 3), which could have encouraged and enabled additional forest-to-pasture conversion[41]. At the same time, the ASM may have disincentivized pasture establishment on soy-suitable forests by prohibiting the future establishment of soy on recently cleared pastures, thereby weakening one incentive for speculative clearing. To explore these contrasting dynamics, we repeated our primary analysis using only locations that were not converted to soy by 2017 (Table 3, columns 4 and 5). We find that the Amazon biome and the proximate portions of the Cerrado biome did not experience significant post-ASM increases in deforestation for non-soy uses relative to more distant portions of the Cerrado. While previous research raised the concern that indirect land use change might undermine the effectiveness of the ASM[41], our results are consistent with multiple subsequent studies that showed that indirect land use change in the Amazon was rare or declined dramatically after the adoption of the ASM[39,58,59]. Future research exploring the impact of the ASM on land markets and the behaviour of ranchers could provide additional insights into the indirect land use change effects of single-commodity supply-chain interventions.

A final concern is that farmers could exploit gaps in the ASM's restrictions, monitoring and enforcement to undermine the policy's

Table 2 | Complementarities between the ASM, CAR and monitoring by the GTS

	1	2	3	4
ASM only	−0.00656*** (0.00211)	−0.00237 (0.00217)	−0.00548*** (0.00204)	−0.00160 (0.00215)
CAR only		0.00007 (0.00128)		−0.00050 (0.00128)
ASM and CAR		−0.01174*** (0.00252)		−0.01146*** (0.00239)
ASM and GTS			−0.01300*** (0.00245)	−0.01141*** (0.00247)
ASM, CAR and GTS				−0.01526*** (0.00285)
Number of points	102,246	102,246	102,246	102,246
Number of municipalities	186	186	186	186

The models were estimated using forested, soy-suitable points in the states of Mato Grosso and Pará. They include additional covariates and interaction terms, as described in the Methods. All regressions are linear probability models using a binary indicator of deforestation as the dependent variable. Coefficient estimates can be interpreted as a change in the probability of deforestation, measured in percentage points. Estimates presented in this table represent linear combinations of coefficients on individual and interaction terms to capture aggregate effects of multiple policies. Standard errors, clustered by municipality, are given in parentheses. ***$P < 0.01$.

Table 3 | Tests for cross-biome leakage, indirect land use change, evasion and on-farm leakage

	All points	Soy suitable		Not converted to soy		Not GTS monitored	Properties with soy-suitable land		Properties growing soy in 2000	
							All points	Not converted to soy	All points	Not converted to soy
	1	2	3	4	5	6	7	8	9	10
Post-ASM × Amazon biome	−0.000708 (0.00129)			−0.00180* (0.000988)	−0.00156 (0.00109)	−0.00224 (0.00192)	−0.00478** (0.00190)	−0.000872 (0.00129)	−0.0194** (0.00866)	0.0000749 (0.00490)
Post-ASM × Amazon biome × suitable for soy	−0.00538*** (0.00190)					0.00261 (0.00248)				
Post-ASM × close	−0.00150 (0.00117)	0.00279 (0.00204)			0.000393 (0.00102)					
Post-ASM × close × suitable for soy	0.00255 (0.00237)									
Post-ASM × proximity			0.00200 (0.00713)							
Number of points	279,360	57,963	57,963	272,836	272,836	83,680	101,014	95,812	4,990	4,433
Number of municipalities	563	286	286	563	563	467	475	474	111	108

The models were estimated using forested points located within the Legal Amazon. They include additional covariates and interaction terms, as described in the Supplementary Information. All regressions are linear probability models using a binary indicator of deforestation as the dependent variable. Coefficient estimates can be interpreted as a change in the probability of deforestation, measured in percentage points. Standard errors, clustered by municipality, are given in parentheses. $^*P < 0.1$; $^{**}P < 0.05$; $^{***}P < 0.01$.

effectiveness. For example, farmers in the Amazon biome might respond to the ASM by accelerating forest-to-soy conversion outside of the GTS' monitoring footprint[60]. However, compared with deforestation rates in the Cerrado, we find that unmonitored portions of the Amazon biome did not experience a relative increase in post-ASM deforestation (Table 3, column 6), suggesting that farmers did not change their behaviour to exploit monitoring gaps. Second, since the ASM does not sanction farmers for deforesting land on their farms that is not planted with soy, the ASM may encourage soy farmers to increase deforestation for other uses[13,39,61]. Instead, consistent with other studies[39], we find that soy properties in the Amazon did not experience a significant post-ASM increase in non-soy deforestation relative to properties in the Cerrado (Table 3, columns 8 and 10). Declines in aggregate deforestation rates on these properties provide further evidence supporting our broad conclusion that the ASM reduced deforestation (Table 3, columns 7 and 9).

These results and the expanded discussion in the Supplementary Information emphasize that cross-biome and on-farm leakage and indirect land use change did not lead to a significant, observable increase in deforestation within the Amazon biome or the nearby Legal Amazon portions of the Cerrado. It is possible that complementary conservation policies have inhibited leakage within the Legal Amazon. Similarly, agricultural intensification induced by the ASM could moderate market-mediated leakage[62,63]. Importantly, all observations we used for controls in our primary analyses fall within the Legal Amazon. As a result, leakage should not bias our primary finding that the ASM reduced deforestation on soy-suitable portions of the Amazon biome by 0.66 ± 0.32 pp. Nevertheless, our empirical approach does not allow us to rule out more distant and indirect forms of leakage and, consequently, we are unable to make claims of the ASM's effectiveness in reducing aggregate global deforestation[64,65]. Future research using simulation models or broader scales of analysis could better quantify the global effects of the ASM.

Conclusions

The ASM reduced deforestation in the Brazilian Amazon, demonstrating that private, zero-deforestation agreements in agricultural supply chains can yield meaningful conservation benefits. The determinants of the ASM's effectiveness provide multiple insights that are directly relevant to ongoing efforts to extend zero-deforestation commitments to other geographies and commodities. First, the ASM was adopted by traders who purchased 90% of the soy produced in the Amazon[21]. This level of market penetration ensured a consistent and strong market signal for compliance and provided protections against leakage. Efforts to expand the ASM into the Cerrado, where less than half of soy exports are covered by company-specific zero-deforestation commitments, will face greater barriers in achieving widespread reductions in deforestation[20,56,66].

Second, the ASM is only one part of the diverse mix of policies that collectively yielded a dramatic decline in Amazon deforestation. Between 2003 and 2016, soy-suitable deforestation in the Amazon biome declined by 2.6 pp. We find that the ASM contributed one-quarter of this decline. However, even in achieving this success, the ASM was dependent on critical complementarities with public conservation policies. Our analysis indicates that public deforestation monitoring and property registration were essential preconditions for the ASM's success. Supply-chain interventions that attempt to circumvent governments that are unwilling or unable to provide a strong enabling environment may struggle to replicate the ASM's impact.

Finally, despite the ASM's success, debates over whether to continue the ASM in its early years and recent political changes in Brazil have highlighted the potentially tenuous nature of all forest conservation policies. In 2019, members of the Bolsonaro government joined with the association representing Brazilian soybean farmers, Aprosoja, in criticizing the ASM as an inequitable and undemocratic breach of Brazil's Forest Code by multinational corporations[67]. At the same time, the government has sought to weaken conservation requirements in the Forest Code. In the end, seemingly redundant public and private mandates may serve as an important buffer against policy inconsistencies emerging from changes in either business or political cycles.

Methods

Study region. Our analysis focused on the Brazilian Amazon and Cerrado biomes, where deforestation and soy expansion were prominent during our study period (2002–2016)[40]. The Amazon biome, where the ASM applies, covers 4.2 million km^2 and shares a 6,165-km border with the neighbouring Cerrado biome. We further restricted our analysis to those portions of the Amazon and Cerrado biomes falling within 300 km of the eastern borders of either the Amazon biome or the Legal Amazon (Fig. 1). This region roughly corresponds with Brazil's Arc of Deforestation and covers 96% of the Amazon biome's 2017 planted soy area, 96% of the soy established on Amazon forests and 94% of the forests monitored by the GTS between 2007 and 2014. By limiting our focus to this Arc of Deforestation, we exclude the more distant interior of the Amazon biome—a region that has experienced very different drivers and rates of deforestation (see Supplementary Fig. 1)[68]. In contrast, our focus on the Arc of Deforestation improves the comparability of deforestation trends, as evidenced by parallel trends in pre-ASM deforestation rates (Fig. 2).

In addition, we focus our primary analyses on the portion of our sample falling inside the Legal Amazon. Due to proximity and common state governments, we believe the Cerrado biome portion of the Legal Amazon provides the strongest control for deforestation changes in the Amazon biome. We include observations falling outside the Legal Amazon in a model extension to test the robustness of our results (see Supplementary Information).

Data. Across our study region, we sampled observations at each vertex of a grid of evenly spaced (2 km) horizontal and vertical lines. This produced 616,274 sample points, 246,943 of which fall inside the Amazon biome and 369,331 of which fall inside the Cerrado biome. For each of these points, we identified whether and when deforestation events occurred using the MapBiomas Collection 2.3 data product[69]. We extracted a variety of other attributes, as detailed in the Supplementary Information.

Research design. The ASM's geographic and commodity focus allows for a triple-differences research design to isolate the causal impact of the ASM. The ASM applies only to the Amazon biome, an ecological designation that does not follow political borders. The biome boundary bisects multiple municipalities and states and differs from the Legal Amazon, an administrative designation that serves to define the boundary of several public policies meant to reduce deforestation (Fig. 1). As a result, contrasting deforestation trajectories before and after the adoption of the ASM across either side of the biome boundary can help isolate the ASM's impacts while also controlling for the effects of public policies. Second, the ASM applies only to soy production and does not restrict the use of cleared land for other purposes. Since 90% of soy is planted in locations that meet specific soil and climatic suitability conditions, the ASM's direct conservation benefits should be concentrated on these biophysically suitable lands[10]. We contrast deforestation trends on soy-suitable and non-suitable lands to control for additional policy and economic changes that might have led to declining deforestation across the entirety of the Amazon biome[4,5,10,70].

Our primary model specification combines these two comparisons through a triple-differences research design in which we compare deforestation across ecological biomes (first difference) after the adoption of the ASM (second difference) and across locations with differential suitability for soy production (third difference). We specify this model as a linear probability of the likelihood that a point i, in municipality m, in state s, is deforested in year t (D_{imst}). The full model is presented in equation (1).

$$\begin{aligned} D_{imst} &= \beta_0 + \beta_1 \mathrm{Biome}_i + \beta_2 \mathrm{SoySuit}_i + \beta_3 \mathrm{Biome}_i \times \mathrm{SoySuit}_i \\ &+ \beta_4 \mathrm{Biome}_i \times \mathrm{Post{-}ASM}_t + \beta_5 \mathrm{SoySuit}_i \times \mathrm{Post{-}ASM}_t + \\ &\beta_6 \mathrm{Biome}_i \times \mathrm{SoySuit}_i \times \mathrm{Post{-}ASM}_t \\ &+ \alpha X_{it} + \gamma_{st} + \zeta_m + \epsilon_{imt} \end{aligned} \quad (1)$$

Biome_i is a binary variable that indicates whether point i falls within the boundaries of the Amazon biome. $\mathrm{SoySuit}_i$ indicates whether the point has been classified as suitable for soy production. $\mathrm{Post{-}ASM}_t$ indicates whether the year of observation occurs after the ASM's adoption in 2006. X_{it} is a matrix of economic and biophysical control variables described in Supplementary Table 1. γ_{st} are a series of state × year fixed effects and ζ_m are municipality-specific fixed effects. We clustered standard errors by municipality to allow for temporal and spatial correlations in our error term, ϵ_{imt}.

The parameter of interest is β_6, which isolates the post-ASM deviation in deforestation rates that occurs on soy-suitable portions of the Amazon biome. Under a set of assumptions (described below), this coefficient can be interpreted as the average treatment effect of the ASM on soy-suitable forests in the Amazon biome (that is, the average treatment effect on the treated, ATT). To provide a more intuitive metric of impact, we used the ATT to estimate the area of avoided deforestation attributed to the ASM. To do so, we first calculated the observed baseline rate of deforestation within soy-suitable portions of the Amazon biome in each of the post-treatment years (2006–2016). We then added the estimated ATT (0.64 pp) to these deforestation rates to estimate the counterfactual trend in deforestation. Beginning with the area of forests observed in 2005 within soy-suitable portions of the Amazon biome, we projected total deforestation through 2016 using both the counterfactual and baseline deforestation rates. We estimated the amount of avoided deforestation attributed to the ASM as the difference in the area of forests remaining in 2016 under the baseline and no-ASM counterfactual conditions.

We believe that our triple-differences research design addresses multiple potential sources of confounding that could complicate causal inference in our setting. First, differencing across biomes using soy-suitable locations allows us to control for market changes that could have affected deforestation rates across all soy-suitable locations. For example, the decline in agricultural commodity prices in the late 2000s has been identified as one driver of the decline in deforestation for soy[5]. The strength of our triple-differences estimator emerges because this market effect is unlikely to differ systematically across the Amazon biome boundary. Second, differencing across soy suitability classes within the Amazon biome allows us to control for economic and policy changes that would have affected all Amazon deforestation. For example, public attention and anti-deforestation enforcement was probably concentrated in the Amazon biome. Contrasts between soy-suitable and non-suitable forests within the biome can thus better isolate the effect of the ASM.

Mathematically, the basic triple-differences estimator without additional covariates can be expressed as a series of differences in post-treatment changes in mean deforestation rates. Let $\bar{y}_{\mathrm{suit},b,t}$ represent the mean deforestation rate for the portion of our sample falling within suitability class suit (S = soy suitable; N = not soy suitable), biome b (C = Cerrado; A = Amazon) and period t (pre- or post-ASM). The triple-differences estimator can be expressed using equation (2).

$$\begin{aligned} \phi = &\underbrace{\left[\left(\bar{y}_{\mathrm{S,A,Post}} - \bar{y}_{\mathrm{S,A,Pre}}\right) - \left(\bar{y}_{\mathrm{S,C,Post}} - \bar{y}_{\mathrm{S,C,Pre}}\right)\right]}_{\mathrm{Soy-suitable\ DD}} \\ &- \underbrace{\left[\left(\bar{y}_{\mathrm{N,A,Post}} - \bar{y}_{\mathrm{N,A,Pre}}\right) - \left(\bar{y}_{\mathrm{N,C,Post}} - \bar{y}_{\mathrm{N,C,Pre}}\right)\right]}_{\mathrm{Non-soy-suitable\ DD}} \end{aligned} \quad (2)$$

Equation (2) can be partitioned into two terms that represent the estimator emerging from alternative difference-in-differences (DD) models. The soy-suitable difference-in-differences model captures post-ASM cross-biome divergence in deforestation rates on soy-suitable lands. If the ASM was effective, one would expect this term to take a negative value. In contrast, the non-soy-suitable difference-in-differences model quantifies post-ASM cross-biome divergence in deforestation rates on non-soy-suitable lands. Our assumption is that the ASM should not directly affect any of the terms in this second difference in differences since all terms measure deforestation on points that are unsuitable for soy production. As a result, our expectation is that this second difference in differences would be equal to 0 and could serve as a placebo test.

The terms in equation (2) can be re-arranged to yield two additional difference-in-differences estimators, as depicted in equation (3):

$$\begin{aligned} \phi = &\underbrace{\left[\left(\bar{y}_{\mathrm{S,A,Post}} - \bar{y}_{\mathrm{S,A,Pre}}\right) - \left(\bar{y}_{\mathrm{N,A,Post}} - \bar{y}_{\mathrm{N,A,Pre}}\right)\right]}_{\mathrm{Amazon\ DD}} \\ &- \underbrace{\left[\left(\bar{y}_{\mathrm{S,C,Post}} - \bar{y}_{\mathrm{S,C,Pre}}\right) - \left(\bar{y}_{\mathrm{N,C,Post}} - \bar{y}_{\mathrm{N,C,Pre}}\right)\right]}_{\mathrm{Cerrado\ DD}} \end{aligned} \quad (3)$$

Once again, the triple-differences estimator can be partitioned into coefficients that emerge from a difference-in-differences model assessing the impact of the ASM (Amazon DD) and a secondary difference-in-differences model (Cerrado DD) that is unlikely to be directly affected by the ASM.

We estimated each of the four difference-in-differences models motivated by equations (2) and (3) by modifying our primary specification (equation (1)) by restricting our sample and dropping extraneous interaction terms. Both difference-in-differences models testing the impact of the ASM indicate a significant impact (Table 1, columns 1 and 3). The first placebo model finds an insignificant post-ASM decline in deforestation on non-soy-suitable locations within the Amazon biome (Table 1, column 2). However, the second placebo model indicates that soy-suitable locations in the Cerrado experienced a significant post-ASM decline in deforestation relative to other portions of the Cerrado (Table 1, column 4). This decline could be indicative of economic or political changes that differentially affected deforestation rates on soy-suitable lands throughout the Legal Amazon. For example, increased enforcement of deforestation restrictions that were implemented by the government could have had impacts across the entirety of the Legal Amazon. If these policies had a bigger effect on more capitalized soy producers than on cattle ranchers, this could lead to the significant negative coefficients observed in both difference-in-differences models illustrated in equation (2). In light of this result, we rely on the triple-differences estimator as our primary specification since it removes the impact observed in the Cerrado from any estimate of the ASM's impact in the Amazon biome. We provide a description of the key assumptions of this model below, and present a variety of robustness tests in the Supplementary Information (for example, Supplementary Tables 2–5 and Supplementary Fig. 2).

Parallel paths and time-varying treatment effects. A fundamental assumption of the difference-in-differences estimator is that, in the absence of treatment, both the control and treatment observations would have experienced parallel paths in the outcome variable. While it is impossible to test this assumption, we followed common practice by testing for parallel paths in the pre-treatment period[71,72]. To do so, we modified our primary model specification (equation (1)) by replacing our Post-ASM$_t$ variable with a matrix of indicator variables for each year (Year$_t$), as depicted in equation (4).

$$D_{imst} = \beta_0 + \beta_1 \mathrm{Biome}_i + \beta_2 \mathrm{SoySuit}_i + \beta_3 \mathrm{Biome}_i \times \mathrm{SoySuit}_i + \eta_t \mathrm{Biome}_i \times \mathrm{Year}_t + \lambda_t \mathrm{SoySuit}_i \times \mathrm{Year}_t + \phi_t \mathrm{Biome}_i \times \mathrm{SoySuit}_i \times \mathrm{Year}_t + \alpha X_{it} + \gamma_{st} + \epsilon_{imt} \quad (4)$$

The vector of coefficients ϕ_t measures the annual deviation in deforestation experienced on soy-suitable portions of the Amazon biome. Significant pre-treatment differences between deforestation in these treated locations compared with control locations would indicate that the two groups do not follow parallel pre-treatment paths. In contrast, changes in post-treatment coefficients can help to identify time-varying treatment effects. The coefficient estimates from this model are presented in Fig. 2c. We found no evidence to suggest significant pre-treatment differences in deforestation trends across the treatment and control. Furthermore, the absence of a pre-treatment relative increase in deforestation is consistent with our understanding that ASM adoption was unexpected and, as a result, there was little anticipatory change in deforestation behaviour.

Although parallel pre-treatment trends are suggestive of parallel trends across the study period, they are not proof that the assumption holds. In our setting, policies or economic conditions that change post-ASM deforestation rates on soy-suitable locations in the Amazon biome but do not affect non-soy-suitable locations in the Amazon biome nor soy-suitable locations in the Cerrado could lead to violations of this assumption. For example, a decline in soy prices localized within the Amazon biome and occurring after 2006 could result in a decline in deforestation within our treated units that would be falsely attributed to the ASM. However, we find no evidence to suggest that such effects would be localized in a way that would lead to violations of the parallel trends assumption. Furthermore, although many policies to reduce deforestation were adopted in the mid-2000s[4,5,29], these policies all would be anticipated to affect deforestation rates across both our treatment and control units. For example, the adoption of the PPCDAm would have affected deforestation in both the Cerrado and Amazon portions of the Legal Amazon, while the adoption of the zero-deforestation cattle agreements would have affected deforestation across both soy-suitable and non-suitable locations within the Amazon biome. As a result, we believe that the parallel trends assumption is reasonable in our empirical setting.

Leakage and the stable unit treatment value assumption (SUTVA). The SUTVA is another important consideration for our study[73]. For SUTVA to hold, the assignment of treatment to one set of units must not affect the outcomes observed in other units. However, multiple observers have raised concerns that the ASM might have induced leakage within affected farms[13,39,61], to farms in the Cerrado biome[52,53] or to cattle ranches[41]. Since our control observations include all of these groups, such leakage dynamics could violate SUTVA and bias our estimates of the ASM's impact upward.

To explore whether spillovers are likely to inflate our estimates of the ASM's impacts, we developed a series of models that compare deforestation of untreated locations that are spatially or economically proximate to treated units with more remote locations. If, after adoption of the ASM, proximate locations experienced a significant increase in deforestation compared with more distant locations, this could be evidence of spillovers induced by the ASM[74]. We use these models to explore four different leakage pathways: (1) leakage to the Cerrado; (2) indirect land use change; (3) evasion; and (4) on-farm leakage.

Leakage to the Cerrado

The ASM may have reduced deforestation for soy in the Amazon while increasing deforestation for soy in the Cerrado biome[20,52,53,75]. Since displaced farmers are likely to invest near their initially targeted location for expansion[53], we hypothesize that soy expansion that was displaced by the ASM would be concentrated in the portion of the Cerrado that is closest to the Amazon biome boundary. We explored the possibility of cross-biome leakage by contrasting deforestation trends in the soy-suitable portions of the Cerrado that are near the biome boundary with more distant portions of the Cerrado. We followed Moffette and Gibbs[53] and used two different metrics to measure proximity: (1) proximity to the border, as measured by an inverse distance formula (equation (5)); and (2) a binary variable indicating whether a location is within 100 km of the biome border. Models using both of these metrics show that soy-suitable locations in the Cerrado that were close to the Amazon biome boundary did not experience a significant, relative increase in deforestation when compared with more distant locations in the Legal Amazon portion of the Cerrado (Table 3, columns 2 and 3). Controlling for proximity among our control observations in our primary specification did not substantively change the primary results of our analysis (Table 3, column 1).

$$\mathrm{Proximity}_i = \left| \frac{\mathrm{Dist}_i}{\mathrm{MaxDist}} - 1 \right| \quad (5)$$

It is worth noting that, in contrast with our null result, Moffette and Gibbs[53] found evidence for deforestation leakage near the biome boundary. However, their study was limited to Mato Grosso state, whereas our study includes the entirety of the Amazon–Cerrado boundary. When we restricted our model to include only those points falling inside Mato Grosso, we also found a significant leakage effect (Supplementary Table 6, column 2). However, the rest of our sample exhibits a statistically insignificant decrease in deforestation near the biome boundary (Supplementary Table 6, column 3). After combining these samples, we found no evidence for spillovers to the proximate Cerrado (Supplementary Table 6, column 1).

It is also possible that the ASM accelerated soy-driven deforestation in portions of the Cerrado that are further from the biome boundary. For example, several studies have highlighted the growing share of soy-driven deforestation occurring in the Matopiba region[20,52,56]. All locations within our study region would be exposed to such distant leakage and, as a result, it is difficult to identify specific locations that could serve as a clear control group to identify such leakage. Nevertheless, we can assess post-ASM changes in deforestation on soy-suitable locations compared with non-suitable locations in regions that may have experienced an anomalous increase in soy-driven deforestation. We ran this difference-in-differences model across a variety of Cerrado sub-regions (Supplementary Table 7). We did not find any portions of the Cerrado that experienced a significant increase in soy-suitable deforestation after the adoption of the ASM.

Indirect land use change. The ASM may have encouraged expansion of soy into pastures, displacing production while simultaneously capitalizing ranchers and, as a result, indirectly increasing conversion of forests[41]. Given the costs associated with moving operations over long distances or managing multiple distant properties[53], indirect land use change caused by the ASM would probably be concentrated within the Amazon biome or close to the Amazon biome boundary. To explore this possibility, we ran additional analyses on the population of forested pixels that were not converted to soy by 2017, enabling us to track non-soy deforestation trends. We found no evidence of post-ASM relative increases in non-soy deforestation in the Amazon biome (Table 3, column 4) or the nearby portions of the Cerrado biome (Table 3, column 5). Interestingly, we found a marginally significant ($P=0.08$) relative decline in non-soy deforestation within the Amazon biome after the adoption of the ASM. This could indicate that the ASM had secondary effects in discouraging speculative clearing in the Amazon[25].

Evasion. If farmers were aware of the spatial extent of GTS monitoring, unmonitored regions may have provided a tempting location for the expansion of soy. To test for this possibility, we contrasted deforestation trends on unmonitored, soy-suitable portions of the Amazon biome with deforestation trends in soy-suitable locations in the Cerrado biome (Table 3, column 6). Unmonitored locations in the Amazon biome experienced a statistically insignificant relative decline in deforestation compared with locations in the Cerrado.

On-farm leakage. The ASM only sanctions the production of soy on recently deforested lands, allowing farmers to clear forests on their properties as long as they do not use this land for soy production. As a result, the ASM may encourage farmers to accelerate deforestation on their properties for other land uses, including corn or cattle production[13,39,61,76]. To test for this possibility, we explored deforestation dynamics for non-soy uses occurring on soy properties. We defined soy properties using two approaches: (1) CAR-registered properties that had any soy-suitable land; and (2) CAR-registered properties that had planted soy by the year 2000. Restricting our sample to the population of points that fell within soy properties, we ran a difference-in-differences model exploring the post-ASM change in deforestation occurring in the Amazon's soy properties, relative to soy properties in the Cerrado (Table 3, columns 7 and 9). Significant, negative treatment effects provide further evidence that the ASM reduced aggregate deforestation rates. We then further restricted our sample to the population of points that had not been converted to soy by the year 2017 and re-ran the models (Table 3, columns 8 and 10). Insignificant but precisely estimated null results indicate that the ASM has not induced widespread on-farm leakage of deforestation.

These empirical models cannot rule out more distant and diffuse forms of leakage, such as accelerated deforestation in other countries. Such distant leakage operates through regional or global markets, does not lend itself well for empirical estimation and might be better suited for analysis through general equilibrium modelling[77,78]. Nevertheless, we believe that our tests provide important evidence to allay concerns that our estimates of the ASM's impact may be biased due to SUTVA violations. Our primary specification draws its controls from non-soy-suitable locations in the Amazon biome, as well as the proximate portions of the Cerrado biome that fall within the Legal Amazon. The fact that these locations have not experienced significant post-2006 increases in deforestation relative to more distant observations gives us greater confidence in our primary results. Indeed, negative signs on several of our potential leakage parameters indicate that our estimates may be more exposed to underestimation than overestimation.

Policy complementarities. Although the ASM nominally applies to the entirety of the Amazon biome, its monitoring through the GTS has been limited to areas that meet specific criteria (see Supplementary methods, Supplementary Fig. 3). In addition, the ASM has relied on public registries to enforce deforestation restrictions. To assess the overlapping impact of these policies, we identified which points i were ever registered with the CAR (CAR_i) or monitored by the GTS (GTS_i). We then identified the years y in which those points were registered (CAR_Now_{it}) or monitored (GTS_Now_{it}). Finally, we added an indicator for observations located within the Amazon biome and representing years after the adoption of the ASM (ASM_Now_{it}). Combining these terms, we developed a model that explored the individual and combined effects of the GTS, CAR and ASM. Since all GTS monitoring occurred within the Amazon biome after the adoption of the ASM, a full factorial design was not possible. The full model is presented in equation (6).

$$\begin{aligned}D_{imst} &= \beta_0 + \beta_1\text{Biome}_i + \beta_2\text{GTS}_i + \beta_3\text{CAR}_i + \\ &\beta_4\text{Biome}_i \times \text{GTS}_i + \beta_5\text{Biome}_i \times \text{CAR}_i + \beta_6\text{GTS}_i \times \\ &\text{CAR}_i + \beta_7\text{Biome}_i \times \text{GTS}_i \times \text{CAR}_i + \phi_1\text{ASM\_Now}_{it} + \\ &\phi_2\text{CAR\_Now}_{it} + \phi_3\text{GTS\_Now}_{it} + \phi_4\text{CAR\_Now}_{it} \times \\ &\text{GTS\_Now}_{it} + \phi_5\text{ASM\_Now}_{it} \times \text{CAR\_Now}_{it} + \alpha X_{it} \\ &+ \gamma_{st} + \epsilon_{imt}\end{aligned} \quad (6)$$

Each of the ϕ coefficients measures an individual or interaction effect between the three treatments. We present the linear combinations of these coefficients to quantify the deviation in deforestation rates on points that are: (1) only exposed to the ASM; (2) only exposed to CAR registration; (3) exposed to both the ASM and GTS monitoring; (4) exposed to both the ASM and CAR registration; and (5) exposed to the ASM, GTS monitoring and CAR registration. The results from this regression are presented in Table 2.

Data availability

All of the data needed to replicate this study are available through the Harvard Dataverse at https://doi.org/10.7910/DVN/LE42B1.

Code availability

All of the code needed to reproduce the results, figures and tables is available at https://github.com/rheilmayr/asm.

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Author contributions

R.H., L.L.R. and H.K.G. designed the research. R.H., L.L.R. and J.M. collected the data. R.H. and L.L.R. conducted the analysis. R.H., L.L.R. and H.K.G. wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information

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