Addressing indirect sourcing in zero deforestation commodity supply chains

Erasmus K.H.J. zu Ermgassen¹,²*, Mairon G. Bastos Lima³, Helen Bellfield⁴, Adeline Dontenville⁵, Toby Gardner³, Javier Godar³, Robert Heilmayr⁶, Rosa Indenbaum³, Tiago N.P. dos Reis¹,⁴, Vivian Ribeiro³, Itohan-osia Abu⁷, Zoltan Szantoi⁸,⁹, Patrick Meyfroidt¹,²

Affiliations
¹ Georges Lemaître Earth and Climate Research Centre, Earth and Life Institute, UCLouvain, Bâtiment Mercator, Place Louis Pasteur 3, B-1348 Louvain-la-Neuve, Belgium.
² Fonds de la Recherche Scientifique F. R. S.-FNRS, Rue d'Egmont 5, B-1000 Brussels, Belgium.
³ Stockholm Environment Institute, Linnégatan 87D, 115 23 Stockholm, Sweden.
⁴ Global Canopy, 3 Frewin Court, Oxford OX1 3HZ, United Kingdom.
⁵ European Forest Institute, Sant Pau Historic site, Sant Leopold Pavillon, St. Antoni M. Claret, 167, 08025 Barcelona, Spain.
⁶ Environmental Studies Program and Bren School of Environmental Science, University of California, Santa Barbara, Santa Barbara, CA 93106, USA.
⁷ Julius-Maximilians-University of Würzburg, Institute for Geography and Geology, Department of Remote Sensing, Oswald-Külpe-Weg 86, 97074 Würzburg, Germany.
⁸ European Space Agency, Directorate of EO Programmes, Science Applications & Climate Department, Frascati, 00044, Italy.
⁹ Stellenbosch University, Stellenbosch, 7602, South Africa.

*erasmus.zuermgassen@uclouvain.be

Abstract
The trade in agricultural commodities is a backbone of the global economy but is a major cause of negative social and environmental impacts, not least deforestation. Commodity traders are key actors in efforts to eliminate deforestation - they are active in the regions where commodities are produced and represent a ‘pinch-point’ in global trade that provides a powerful lever for change. However, the procurement strategies of traders remain opaque. Here, we catalogue traders’ sourcing across four sectors with high rates of commodity-driven deforestation: South American soy, Côte d’Ivoire cocoa, Indonesian palm oil, and Brazilian live cattle exports. We show that traders often source more than 40% of commodities ‘indirectly’ via local intermediaries, and that indirect sourcing is a major blind spot for sustainable sourcing initiatives. To eliminate deforestation, indirect sourcing must be included in sectoral initiatives, and landscape or jurisdictional approaches, which internalize indirect sourcing, must be scaled up.

Acknowledgments
We thank Rachael Garrett, Ben Ayre, Bernardo Loureiro, Ailsa Sinclair, and the participants of the PRME UK and Ireland Business and Society Research Development Workshop for helpful feedback. Computational resources have been provided by the Consortium des Équipements de Calcul Intensif (CÉCI), funded by the Fonds de la Recherche Scientifique de Belgique (F.R.S.-FNRS) under Grant No. 2.5020.11 and by the Walloon Region, and Formas (grant 2016-00351).
Introduction
The trade in agricultural commodities - products including cotton, coffee, cocoa, grains, oilseeds, and livestock - is a mainstay of the global economy, providing food, fuel, and fibre to consumers around the world. The long, complex supply chains which process and transport these products bridge the gap between producers and consumers, but are criticised for masking negative socio-environmental impacts and obfuscating the allocation of responsibility for these impacts. A particular concern for commodities produced in the tropics is habitat destruction - the loss and degradation of forests and other natural ecosystems to expanding agriculture. Almost one-third of forest loss is driven by commodity production (1). Many companies have made zero deforestation commitments, though progress in implementing deforestation-free supply chains remains slow (1, 2).

Commodity traders (or simply ‘traders’) have a key role in achieving deforestation-free sourcing. Traders, including multinationals such as Cargill, Olam, and Bunge, as well as many smaller companies, handle the procurement, processing, and export of commodities from producer to consumer countries. Downstream companies (i.e., companies operating closer to consumers and further from farmers) ultimately rely on traders to implement their sustainable sourcing commitments on-the-ground. Commodity trading is consolidated, creating a ‘pinch-point’ in global supply chains with a small number of traders handling a majority of the world’s trade in each product. This market concentration creates an opportunity where a small number of companies have the leverage to improve the sustainability of a large proportion of the world’s sourcing (3). Though traders are sometimes considered a ‘missing’ or ‘hidden’ link in supply chain governance (4), there is increasing emphasis on their role. At the 2021 UN Climate conference (COP-26), ten of the world’s largest commodity traders published a ‘shared commitment to halting forest loss’, and the European Union has published proposed legislation which requires traders to ‘submit a due diligence statement… thereby becoming liable for compliance of the relevant commodity’ - i.e., imposing a legal responsibility for trading companies to ensure their sourcing is not linked to deforestation (5). As of January 2022, Germany and France have already passed legislation imposing new due diligence requirements, with similar bills focused on deforestation also being considered in the UK and USA.

Despite the importance of traders’ actions for sustainable procurement efforts, few studies address how traders operate in countries of production (4, 6). The academic literature on sustainable supply chains is instead focused on apparel, automotive, chemical, electronics, and retail companies (7, 8), and where studies do analyse traders’ sourcing, they use varying terminology (Table S1) and focus on single sectors (2, 9–12), limiting learning across contexts.

In this study, we present a framework distinguishing traders’ ‘direct’ sourcing from producers (i.e., farmers) and ‘indirect’ sourcing via local intermediaries. Then, for four deforestation-risk contexts (South American soy, Côte d’Ivoire cocoa, Indonesian palm oil, and Brazilian live cattle exports), we assemble new data - including detailed shipment data, corporate reports and disclosures, facility processing capacities, animal movement records, and farm production data - to quantify the sourcing strategies of trading companies covering the top 60% of trade in each context. We reveal that indirect sourcing is a widespread and often dominant strategy and review why it is so common. We then document how corporate sustainable procurement strategies largely ignore indirect sourcing, undermining progress on zero deforestation goals. Finally, we discuss ways of achieving more progress on zero deforestation commodity production, given the reality that large parts of the supply chain are and will continue to be indirectly sourced via local intermediaries. There are no silver bullets, but to deliver on promises to eliminate deforestation from commodity supply chains,
efforts for sector-wide transparency and jurisdictional sourcing must be scaled up and combined with other sustainable procurement approaches.

**Direct and indirect sourcing**
Sustainability risks can occur at any level of the supply chain, but in agricultural commodity supply chains they are usually concentrated at the location of production. Deforestation, other forms of ecosystem degradation, and negative social impacts such as child or forced labour occur more commonly on farms rather than higher up among intermediaries in the supply chain. We therefore classify traders' sourcing strategies by making a key distinction between products that trading companies source ‘directly’ from producers, vs ‘indirectly’ from other intermediaries (e.g. brokers, aggregators) in the supply chain. Without taking active steps to overcome information asymmetries, companies inevitably have less information about the origin of products sourced indirectly, rather than directly. The terms ‘direct sourcing’ and ‘indirect sourcing’ are commonly referred to in industry documents and academic research, but not used consistently across contexts (Table S1). We propose the following framework (Figure 1):

1) **A direct supplier** (sometimes referred to as a ‘tier-1’ supplier) is the actor in the supply chain from whom a company purchases and takes physical control or ‘custody’ over a product.
2) **Indirect suppliers** are all the actors in the supply chain which are more than one tier removed from the company (i.e., a direct supplier's own suppliers).
3) **Direct sourcing** is when the company procures a product from the original producer - i.e., the supply chain does not involve indirect suppliers. In vertically integrated supply chains, the focal company produces the commodity themselves.
4) **Indirect sourcing** is procurement from a supply chain which includes indirect suppliers. Indirect sourcing can sometimes be localised to a specific geography. When the intermediary has a geographic location (e.g., a farmer cooperative or a storage company operating a silo), then the raw product can be assumed to come from the surrounding landscape. This knowledge of the approximate location of commodities can be valuable for the purposes of assessing and triaging sustainability risks in supply chains.

[Insert Fig. 1 about here]

**Deforestation risk commodities**
From 2001-2015, cattle, palm oil, soy, and cocoa production were the four leading drivers of commodity-driven deforestation (13). We analysed the sourcing strategies of trading companies across the leading producing regions of each commodity, described below.

**South American soy:** Together, Brazil, Argentina, and Paraguay produce more than half of the world’s soy (14). The harvested area in these three countries more than tripled in the last thirty years to cover over 50 Mha (14). As a result of this expansion, soy has been both a direct and indirect driver of deforestation across the Brazilian Amazon and Cerrado, and the Paraguayan and Argentinian Chaco (15). In 2018, seven trading companies (Cargill, Bunge, Archer Daniels Midland, Louis Dreyfus, COFCO, Viterra, and Amaggi) handled 62.5% of exports from the region (Figure 2). Most soy is produced by large-scale producers (farming areas of more than 1,000 ha (16)), who may operate their own silos (grain storage facilities) or have soy production part-financed by trading companies. Soy traders may either have direct contracts with soy producers, buy from groups of farmers (cooperatives) who operate a shared silo, or accept delivery from aggregators who in turn buy from a variety of farmers, with sourcing switching depending on the season (Figure 1).
Côte d’Ivoire cocoa: In Côte d’Ivoire, hundreds of thousands of smallholder farmers produce 45% of the world’s cocoa harvest (14). Cocoa makes up more than 20% of Côte d’Ivoire’s export revenues though the sector is troubled by persistent poverty, child labor, and deforestation. Forest cover in Côte d’Ivoire fell from 15% in 1986 to 9% in 2015, in large part because of the expansion of cocoa (17). In 2019, eight companies (Cargill, Barry Callebaut, Olam, Touton, Sucden, S3C, Ecom, and Africa Sourcing) handled 60.6% of exports (Figure 2). In practice all of their cocoa sourcing is indirect, as cocoa is not purchased from smallholder farmers directly but from cooperatives or other middlemen: local ‘pisteurs’ who visit villages collecting cocoa before selling on to larger-scale local intermediaries, ‘traitants’ (Figure 2). Despite efforts by the coffee and cocoa board (Conseil Café Cacao, CCC) to register pisteurs and traitants, many work unlicensed. From the perspective of monitoring supply chain risks, cocoa sourced from cooperatives is localised, in that it comes from the region where the cooperative has members. In contrast, cocoa bought from traitants (often exchanged at the port) may have a completely unknown origin.

Indonesian palm oil: Indonesia produces 60% of the world’s oil palm fruit, fueled through recent rapid expansion: between 1995 and 2015, 450,000 ha of new plantations were established each year, driving more than 100,000 ha yr\(^{-1}\) of deforestation (18). In 2018, four companies (Sinar Mas, Musim Mas, Wilmar, and Royal Golden Eagle) handled 64% of exports. Palm oil flows from plantations (which may be smallholder or industry-owned production) to local mills, refineries, and traders. Thirty-four percent of oil palm fruit in Indonesia is produced by smallholder farmers (19). Smallholders may contract their land to plantation companies, or they may produce palm fruits as part of a company scheme (also known as ‘plasma schemes’) selling to a specific company’s mills. Smallholders may operate independently or organise themselves into cooperatives. Independent smallholders can themselves sell to local mills, though most sell via local aggregators who then sell to mills (20). Traders may operate mills and refineries themselves, though the majority of the mills are independent - also known as “third-party” mills.

Brazilian live cattle exports: The Brazilian cattle sector is the leading driver of tropical deforestation. Brazil is the world’s largest exporter of cattle products (including beef, offal, and live cattle), though here we focus specifically on the live cattle trade because it is comparatively understudied while being a hotspot of deforestation. Brazil exports 200,000-790,000 live cattle per year, with 85% of exports (2010-2019) originating from the Amazon state of Pará. Because of their concentration in the Amazon, live cattle exports are linked to 11.6% of deforestation risk though they make up only 3.9% of cattle exports from Brazil by value (12). In 2019, four companies, Minerva Global Foods (henceforth ‘Minerva’), Agroexport Trading, Bull Log Trading, and Mercúrio Alimentos handled 70.2% of exports (Supplementary text). While some ‘full-cycle’ ranches rear cattle from birth to export (or slaughter), cattle are often moved multiple times in their lifetime (Figure 2). They may be born on one farm, reared on another, and fattened on a third before being exported. In these cases, the property selling to the trader (the direct supplier) is only the last tier in the supply chain from birth to export.

Results

Commodities are commonly sourced from local intermediaries by traders. Where we were able to differentiate direct and indirect sourcing for more than half of a trader’s supply chain, we found that indirect sourcing made up 12-42% of soy sourcing, 15-90% of palm oil sourcing, 94-99%
of live cattle exports, and 100% of cocoa sourcing (Figure 3). Agricultural commodity supply chains have multiple tiers already within producer countries, with each direct supplier in turn buying from dozens to hundreds of indirect suppliers. In Côte d’Ivoire’s cocoa sector, for example, Barry Callebaut’s cooperatives included a median 504 member farms (IQR: 359-826, range: 151-3,463). Each of Minerva’s direct suppliers in-turn bought cattle from a median of 20 other properties (IQR: 7-59, range: 1-1334).

In terms of traders’ understanding of the ultimate origin of their sourcing, we highlight the difference between products sourced through farmer cooperatives (localised indirect sourcing) versus other brokers and aggregators. For palm oil and cocoa, respectively, 4-7% and 29-76% of each trader’s sourcing was localised, in that it was sourced from farmer cooperatives, which can be mapped in space to give an approximate origin for products (Figure 3).

**What drives indirect sourcing?** Historically, there has been little pressure for traders to source directly from or identify the original producers of commodities. By definition, a commodity is a basic good that is ‘interchangeable with other products of the same type’ (21). Commodity exchanges and trade associations, such as the Chicago Board of Trade, São Paulo B3, and the Cocoa Association of London, have been developed to maximise this interchangeability. Commodities (and their contracts) are classified into standardized grades based on product characteristics (22). Soybean contracts, for example, will list acceptable ranges for each shipment’s oil content, moisture content, contamination with other materials (‘foreign matter’), and the percentage of damaged beans or green beans. These grading systems - which do not include information about sustainability - give traders flexibility to fulfill commodity contracts using products of any origin but of the same grade, as dictated by price and logistics.

This fungibility is particularly apparent in spot markets, where traders make short-term, opportunistic trades. The sourcing of cattle by traders, for example, operates almost exclusively as a spot market, as farmers rarely sign long term supplier contracts. In the palm oil sector traders often commit to purchases over periods of three to nine months from a given direct supplier (10), though palm oil refineries and traders also make opportunistic purchases (‘spot trades’). These purchases may be used to top-up volumes when supply drops below a facility’s target or to take advantage of palm oil that becomes available at a low price. In these cases, the origin of the palm oil is a secondary consideration and information about the origin (e.g., the supplier list) is commonly not provided until after a purchase is made (10).

Moreover, there is a strong economic logic for traders to source via local intermediaries. Intermediaries reflect specialisation in the supply chain. Local middlemen specialise in product sourcing and aggregation while traders specialise in the logistics of export, international trade, and other aspects of commodity trading, including speculation on commodity futures and currency movements, arbitrage, and investing in financial instruments and private equity (23). For example, the variation in reliance on indirect sourcing among palm oil traders (Figure 2) reflects differences in business strategy. Companies, such as Wilmar, which have invested heavily in palm oil refinery capacity and focus on the export of higher value products such as refined palm oil have a greater reliance on indirect sourcing than companies, such as Sinar Mas, which is focused on growing, milling, and exporting crude palm oil (11,23). In the cattle sector, production is further fragmented - farmers specialise in the production of calves, calf-rearing, or fattening, which introduces extra intermediaries between the location where cattle are born and traders’ direct suppliers (Figure 2). For traders, intermediaries who aggregate products from hundreds or thousands of individual producers
thus help reduce their transaction costs. While still a significant share of the market, the level of indirect sourcing is notably lower for soy supply chains, where farming is often large-scale, than for oil palm, cocoa, and cattle, which commonly come from smaller, less capitalised producers. It would be more costly for traders to form individual contracts with hundreds of thousands of farmers than to buy from a smaller number of local intermediaries who each aggregate supply from multiple farms. In some cases, the physical characteristics of the commodity lends itself to aggregation early in the supply chain. Fresh oil palm fruit bunches are perishable and must be processed within 48 hours to avoid spoilage. They are therefore aggregated and processed locally before long distance distribution in the more stable form of crude palm oil. Finally, from the farmer’s perspective, they may also gain market power when selling as a group through a cooperative compared to individually negotiating contracts with traders - a critical concern when considering the imbalanced power dynamics between multinational purchasing companies and individual farmers.

**The challenge that indirect sourcing poses to zero deforestation commodity sourcing.** It is simpler for companies to identify, engage with, and exert influence over their direct suppliers, with whom they have contractual relations, than actors more than one tier removed from them (7, 24). Mirroring this market reality, trading companies have been slower to engage with and take responsibility for the actions of their indirect suppliers. In 2009, under civil society pressure, major Brazilian meatpackers, including Minerva (which both slaughters and exports cattle), committed to zero deforestation in their supply chains in the Amazon biome. As a result of these so-called ‘Cattle Agreements’, meatpackers implemented systems for monitoring their direct suppliers. Over the following years, the blind spot of indirect suppliers was highlighted repeatedly (25, 26), though it was not until 2020 that Minerva and other companies in the sector announced they would expand monitoring to include indirect suppliers in the Amazon and Cerrado biomes (27). Key details of this monitoring remain unclear, including the mechanisms of implementation and cut-off dates. In the soy sector, Cargill is mapping the location of direct supplier farms, but for indirectly sourced soy it so far reports only mapping the points of procurement (i.e., farmer cooperatives or silos) (28). In some cases, companies explicitly exclude their indirect suppliers from sustainable sourcing commitments. COFCO, the fifth largest soy trader, specifies that its sustainable sourcing policy applies only to direct suppliers (29). Similarly, cocoa industry efforts to increase traceability do not include indirect sourcing through traitants. The Cocoa & Forests Initiative (CFI), a multi-stakeholder initiative signed by the governments of Côte d’Ivoire and Ghana and leading cocoa companies, is a case in point. Companies participating in the Cocoa & Forests Initiative, including eight trading companies active in Côte d’Ivoire, have set targets for mapping cocoa sourced via cooperatives, but are notably silent about mapping or addressing sustainability risks in cocoa sourced via other intermediaries (30) - which makes up 20-70% all cocoa sourced by each trader (Figure 2).

Unfortunately, deforestation and related risks are often higher in precisely the parts of the supply chain over which companies have the least visibility (Figure 4). In the Côte d’Ivoire cocoa sector, for example, we mapped localised indirect sourcing through cooperatives for six traders. For four of these six, the relative deforestation risk (hectares/kton cocoa) of cocoa sourced through cooperatives (‘localised indirect’) was lower than for the remaining cocoa, sourced indirectly through traitants (Figure 4A). In the Brazilian cattle sector, indirect suppliers to slaughterhouses with zero deforestation commitments are 1.72 times more likely to deforest than direct suppliers (31). Deforestation risks among indirect suppliers also translate into hidden legal risks. A study of beef exports from the Brazilian states of Mato Grosso and Pará found that 48% of exports were contaminated with potentially illegal deforestation when considering meatpackers’ indirect suppliers - in comparison with 12% contamination when looking only at their direct suppliers (32). A similar
pattern emerges when evaluating confirmed cases of illegality: in Brazil, properties with non-compliant deforestation may be placed on a list of embargoed areas, from which it is not permitted to purchase goods. We assessed live cattle traders' cattle purchases and found that, for companies who have adopted zero deforestation commitments, embargoed areas are 1.2-1.6 times more common among indirect than direct suppliers (Figure 4B and Supplementary text).

[Insert Figure 4 about here]

Indirect suppliers can pose higher deforestation risks through several pathways (Supplementary text). Of particular concern, however, is that a focus on direct suppliers creates leakage, where non-compliant production is not eradicated but displaced from direct to indirect suppliers. After meatpackers began monitoring their direct suppliers in the Brazilian Amazon, the cattle ranches that they bought directly from did reduce deforestation (26). Laundering of cattle from non-compliant indirect suppliers to compliant direct suppliers is, however, widespread (9, 25), and the meatpackers commitments have had little effect on overall deforestation rates (33). Similarly, one of the success stories of corporate environmental efforts, the Soy Moratorium is also at risk of being undermined by unverified indirect sourcing (Supplementary text). The Soy Moratorium is a multi-stakeholder, landscape initiative to avoid the purchase of soy planted on recently deforested land in the Amazon. Between 2006 and 2016, the moratorium is estimated to have avoided 18,000 ± 9,000 km² of deforestation (34), though compliance is still not 100%. In 2018, 882.34 km² of soy were planted on land cleared after the moratorium cut-off date, making up 4.8% of the deforestation in the monitored area (35). A key mechanism through which non-compliant soy reaches the market is indirect sourcing, as only 45% of traders specify cut-off dates and compliance with the Moratorium in contracts for their indirectly-sourced soy (36).

Discussion

Prospects for eliminating deforestation from commodity supply chains. Here, we have focused on one part of agricultural commodity supply chains, from farmers to traders, showing that [i] indirect sourcing via local intermediaries is common, [ii] traders have been slow to address their indirect sourcing, and [iii] sustainability risks are often higher through indirect sourcing. These three observations, when taken together, expose systemic limitations of current sustainable procurement efforts. Below we identify six approaches (Table 1) that traders currently adopt, to varying degrees, to ensure their sourcing complies with sustainability commitments. This list is not intended to be exhaustive or definitive; we focus on common approaches and assess how each addresses the challenge of ensuring sustainability in indirectly sourced products. These different sustainable procurement approaches are interdependent and not used in isolation. Certification can be implemented at multiple levels - at farms, cooperatives, or landscapes; companies may source through a landscape initiative while also requiring traceability and cascading compliance from their tier-1 suppliers; and there can also be no transparency of supply chain connections without first establishing traceability.

[Insert Table 1 about here]

Direct sourcing: Where companies face sustainability risks, they may seek to simplify their supply chains and increase direct sourcing or vertical integration to have more control over the supply chain tier where risks occur (37, 38). This shift is seen in the soy sector. As part of a multi-stakeholder
initiative, the Soft Commodities Forum, traders have increased their direct sourcing in ‘priority’
municipalities where 70% of soy expansion into native vegetation takes place (Table S2). Eliminating
indirect sourcing is, however, not an effective, scalable or necessarily equitable solution. Indirect
suppliers are local actors, and efforts to eliminate them from supply chains exacerbate existing
inequalities in global value chains (39). Commodity trading is otherwise dominated by a small
number of mostly international companies who yield great market power. Though intermediaries are
sometimes villainized as capturing value from farmers, in reality their share of the global value chain
is small. Across the cocoa supply chain only 3-5% of net margins are captured by actors involved in
the collection and export of cocoa, of which the local traitants will take only a share (40). In some
cases, eliminating indirect sourcing is also physically impossible. The movement of cattle between
farms is a feature of livestock farming in all parts of the world, as farms specialise in different parts
of the cattle lifecycle, whether cow-calf production or fattening.

**Cascading compliance:** Cascading compliance approaches are where a focal company delegates
responsibility for sustainable procurement to their direct (‘tier-1’) suppliers, in the expectation that
they in turn implement codes of conduct with their (‘tier-2’) suppliers (41). Cascading compliance
can be a sustainability multiplier where tier-1 suppliers are required to ensure their entire supply base
meets sustainability standards, not just the part delivering products to the focal company. One risk
of cascading compliance approaches is that focal companies pass on the burden of enforcing
sustainable procurement onto potentially lower-capacity local suppliers (42). In practice, firms may
choose hybrid approaches, engaging with or monitoring both direct and indirect suppliers (43, 44).
Palm oil traders making No Deforestation, No Peat and No Exploitation (NDPE) commitments,
for example, take steps to educate supplier mills about these policies, but then also invest in building
local capacity (e.g., farmer training in farm management and conservation) and use satellite
monitoring to independently detect forest loss on their direct suppliers’ declared suppliers (45).

**Certification:** By design, certification can address the challenges of indirect sourcing by providing
standardized information which does not require the trader to monitor or know the producer and
successive intermediaries. The penetration of certification varies across commodities - from close to
zero for cattle products to 23-38% of global cocoa - with uncertainty around the exact figures
because of products being double or triple certified by competing standards (46). Certification labels
allow brands to communicate the sustainability credentials of products directly to consumers,
though evidence of the effectiveness of certification is mixed (47). Certification has the potential to
include smallholder farmers into sustainable procurement initiatives, but access to certification is not
uniform, and the additionality of certification depends on the context and is not guaranteed (48).
Globally, certified farms are disproportionately located in places with good market access, not
necessarily where they are needed for biodiversity conservation and poverty alleviation (49). Many
certification programs struggle to reach independent smallholders not organised into cooperatives or
company schemes (50). The positive impacts of certification may also be undermined by other
changes in the surrounding landscape. Certification under the Roundtable for Sustainable Palm Oil
(RSPO) has reduced illegal deforestation on certified plantations, but had little impact on overall
deforestation rates as farmers clear more in other areas (51). Similarly, there is no evidence that
RSPO certification has reduced fire or peatland clearance (51, 52). Arguably, many of the challenges
of certification stem from price premiums being set too low. Certification still mostly relies on cost-
minimizing mass-balance or book-and-claim systems, where certified products are mixed with non-
certified products or divorced from actual product flows entirely. Under book-and-claim systems,
downstream companies pay a premium depending on how much certified product they want to buy,
but they do not know to what degree the products they procure are actually compliant with their sourcing standards.

**Traceability:** Many companies are investing heavily in efforts to improve traceability back to farm, both to increase knowledge of their supply chain and assess the risks associated with their procurement. In 2020, the palm oil trader Musim Mas, for example, reported 66% traceability back to the plantation for its fresh fruit bunches, up from 49% in 2019 (53). Traceability is inherently easier for direct than for indirect sourcing. The Brazilian soy trader Amaggi reports 100% traceability to farm for its direct sourcing but only 22% traceability for its indirect sourcing (54). For indirect sourcing, traceability may require mapping back to more producers than a company actually sources from, given the lack of segregation in most commodity supply chains. In many contexts, particularly where the supply chain is not formally organised, traceability efforts are only just starting and will be challenging to scale up. Under the Cocoa & Forests Initiative, for example, participating companies have so far mapped only a fraction (<46%) of their supply chain (Figure S3). The reliability of farm-level mapping efforts are uncertain because of their partial coverage and fluidity of trading relationships. So far, companies in the Cocoa & Forests Initiative have only mapped farms registered in cooperatives, though membership of cooperatives is fluid, with farmers signing up and dropping out seasonally (55). In addition, most farmers have 2-3 cocoa plots, though they usually only report a single one to the trading companies and it is not unheard of for cooperatives to ‘top up’ their production with cocoa sourced from non-member farmers (56).

Given the costs and challenges of improving traceability, some companies have limited efforts to high-risk regions. This is in practice what soy traders are doing as part of the Soft Commodities Forum, which focuses on sourcing in 61 priority municipalities in Brazil. In focusing on a subset of the supply chain, hotspot approaches inevitably ignore risks in other regions. As much as one third of soy-associated vegetation clearing in the Cerrado occurs outside the Soft Commodities Forum’s priority municipalities (57). Hotspots are also a moving target - the deforestation frontier is dynamic and constantly shifting (58). This requires governance efforts to also be dynamic - ideally proactive - in identifying landscapes where the implementation of sustainable sourcing standards is prioritized.

Finally, traceability must also be externally demonstrable. Companies may use third-party audits for external validity of their traceability efforts, but these audits often only include a fraction of the supply chain. Minerva’s audits of their cattle procurement in the Amazon cover only 10% of their purchases (59), and allegations of non-compliant sourcing continue (60). These concerns can be addressed through transparency - where companies make public data about their supply chains.

**Transparency:** Corporate disclosures and transparency allow corporate claims of traceability and good production practices to be verifiable and discourage greenwashing (3, 61, 62). The information which companies disclose, however, is rarely aligned with reporting norms such as the Accountability Framework initiative - a consensus-based framework for the type and quality of supply chain information that companies should report (63). This can be seen from the variety of data sources required in this study to piece together each trader’s direct and indirect sourcing (Table 2), despite the Accountability Framework’s specification that ‘companies should report on the proportion of supply chain volume that is traceable to specific direct or indirect suppliers at each supply stage’ (63). Transparency is most powerful where a norm is established, and supply chain information disclosed across an entire sector. If traceability and transparency are optional and implemented only by lead firms, as is currently the case (64), then it risks market bifurcation, whereby products with traceable and transparent supply chains cover only a subset of the market.
Though some supply chains may be “clean”, such partial efforts can fail to deliver net positive impacts as non-compliant products are simply diverted into less discerning parts of the market (65).

Governments can play a key role in facilitating a level playing field by either mandating company disclosure or facilitating access to key data sets on supply chains to help reveal direct and indirect sourcing patterns. In Brazil, the animal movement permits used in this study to track indirect sourcing are public documents according to legal assessments (60), though government ministries have moved to discourage their use (66). Access to property ownership information from the Brazilian rural cadaster - a key resource for monitoring and tracing commodities back to farm - is also variable from state to state. In Côte d’Ivoire, the coffee and cocoa board, CCC, operates an online database for tracking production from the first buyer (the cooperative or pisteur/traitant) to the port, and a paper-based system of receipts for tracking cocoa from each farmer to the first buyer. Making the database public would allow all trading companies to trace their cocoa back to local regions (‘sous-prefectures’); digitizing and publishing the system of receipts would facilitate complete traceability all the way back to farmers for all companies regardless of their resources (56). The coffee and cocoa board are also actively GPS mapping the locations of cocoa farms (67). Who will have access to these data is not yet clear, but making these types of data public would remove the burden from individual companies and side-steps companies’ concerns about releasing competition-sensitive data. Importantly, it allows collaboration in problem solving. All companies can see where their sourcing overlaps and build coalitions which can reduce costs by working together (68).

Regardless of the level of transparency, not all commodity-driven deforestation can be linked to commodity supply chains using available data. Illegal commodity production is notoriously hard to trace. In Côte d’Ivoire, for example, 18% of cocoa is grown inside protected areas (69), though few companies admit to purchasing this cocoa, much of which enters their supply chains through indirect sourcing. There can also be a temporal mismatch between deforestation and supply chain monitoring. Cocoa and oil palm, for example, take 2-5 years to first harvest. Areas are cleared speculatively by ‘future farmers’ - the majority of the expansion of cocoa farms in Côte d’Ivoire, for example, is linked to recent migrants (70), who are not reached by ongoing corporate sustainability programs and not included in current traceability efforts (50). Data quality also limits accountability at the farm-level. In cattle supply chains in the Brazilian Amazon, state-of-the-art supply chain mapping is only able to track the purchase and sale of cattle from properties responsible for 29% of deforestation and 50% of the pasture area (9). Mismatches in property ownership information and cattle movement records mean that the remaining 71% of deforestation and 50% of pasture cannot be linked to specific companies' supply chains (9). Addressing these sources of deforestation requires looking beyond supply chains, working at the landscape level.

**Landscape and jurisdictional approaches:** Commodity-centric landscape governance efforts are multi-stakeholder initiatives addressing sustainability issues associated with commodity production within specific landscapes (biomes or subnational jurisdictions) (71). Across our focus contexts, landscape approaches include the Amazon Soy Moratorium, Cerrado Working Group, Soft Commodity Forum’s priority municipalities, RSPO’s jurisdictional approach, and the Cocoa & Forests Initiative’s priority regions. By having a lens larger than a specific supply chain and incorporating all actors and land uses within the focal area, landscape approaches offer the potential to ‘internalize’ systemic challenges such as hard-to-trace indirect or illegal sourcing and the drivers of deforestation over which supply chain-focused approaches have limited reach, such as speculative land clearing (50, 72). Landscape approaches can thereby reduce costs and redundancies of investing
in farm-level traceability, transparency, and certification. Though landscape approaches have the advantage of being able to find solutions across commodities, all too often they are focussed on only one target commodity. Among the Soft Commodity Forum’s priority municipalities, for example, only 21% of native vegetation loss is for soy (73). The other 79% is converted to other uses - notably cattle ranching. Approaches which bring together the cattle and soy sectors will be key in reducing inter-commodity leakage and breaking the link between agriculture and deforestation (2).

To be successful, landscape approaches require buy-in from farmers, financial commitment from companies, and support from local or national government. The business case for sustainable commodity production can be made at a local level by including a strong focus on the welfare of local communities alongside the monitoring of sustainability risks such as deforestation. Companies can provide financial incentives through ‘jurisdictional sourcing’ efforts, where they commit to preferential sourcing from verified sourcing areas - jurisdictions which implement time-bound landscape conservation plans (74–76). Jurisdictional sourcing efforts are highlighted by the SourceUp initiative (75), but committed buyers remain few and far between. Notably, the Consumer Goods Forum’s Forest Positive Coalition of Action, a collection of the world’s largest brands (including Carrefour, Mars, Mondeléz, Nestlé and Unilever), has identified landscape approaches as one of four key pillars of their sustainable sourcing efforts, alongside trader engagement, transparency and accountability, and government and stakeholder engagement (77). Their annual investment in landscape programs amounts, however, to only nine million dollars (77) – a sum less than 0.0128% of the annual profit of participating companies (Table S7).

The corporate sustainability agenda, accelerated by the emergence of importer-country due diligence legislation, presents a fundamental challenge to traditional commodity trading, which has historically focused on financial and logistic considerations, and much less so on where products came from and how they were produced (22). This study shows that indirect sourcing is prevalent if not dominant in many key agricultural commodity supply chains, constituting a sizable blind spot for traders’ monitoring and sustainability commitments.

We focus here on major forest-risk commodities, though our insights are relevant also to other supply chains and sustainability issues. The patterns which make indirect sourcing common (commodities traded in bulk originating from large numbers of often small-scale producers) apply to other agricultural commodities such as coffee, rice, rubber, and orange juice concentrate, and sectors including mining or apparel (73, 74). Moreover, indirect sourcing presents a sustainability blind spot not just for traders but also downstream buyers. Across 449 publicly listed companies in the food, textile, and wood-products sectors, where companies have supplier codes of conduct, these are in most cases (60.5%) limited to their direct suppliers (79). Indirect suppliers have similarly been identified as a disproportionate source of risk exposure for companies in the automotive, electronics, pharmaceutical and consumer goods sectors (80). Addressing deforestation in indirect supply chains already poses a significant challenge; the problem becomes even greater for issues such as pesticide contamination or social issues which cannot be mapped using broad coverage earth observation data (42). This imbalance is seen in the published grievances against palm oil companies - where social issues, including wage disputes, forced labour, and violence, are underreported relative to deforestation (78).

Despite more than a decade of corporate sustainable sourcing commitments, commodity-driven deforestation continues (1, 2). To deliver on promises to eliminate deforestation from commodity supply chains, sectoral sustainability initiatives, such as the Cocoa & Forests Initiative, Amazon Soy
Moratorium, and Cattle Agreements, need to acknowledge, monitor, and report on indirect sourcing - and ultimately ensure it doesn’t remain a barrier to delivering on sustainability goals. The on-the-ground reality of commodity production – widespread indirect sourcing, smallholder production, informal supply chain relationships, and multiple interacting drivers of deforestation in commodity-producing landscapes – means, however, that no single intervention is sufficient to break the link between commodity production and deforestation. Rather, there needs to be a broadening of responsibility for ensuring greater transparency and accountability - as well as more equitable sharing of benefits - across the supply chain, including indirect sourcing. Interventions by multiple actors are needed to help achieve this. Efforts to trace commodities from farm to fork should be enabled by producer government policies which prioritise transparency and unlock data on supply chains. Trading companies must invest in sustainable procurement efforts which extend beyond their own direct supply chains, and policies from consumer countries, such as on mandatory due diligence, need to account for the prevalence of indirect sourcing and informal production and trade. Only by layering these policies with inclusive land use governance, rule enforcement, green finance, and other corporate sustainability efforts (79), may we create the necessary mix of incentives for sustainable development within production landscapes.

Materials and Methods

Quantifying the prevalence of indirect sourcing
We used detailed shipping data from 2018-2019 from the Trase initiative (https://trase.earth/) to identify the commodity trading companies handling the top 60% of exports of our four focus commodities: soy from South America (2018 data on trader market share across Brazil, Argentina, and Paraguay), cocoa from Côte d'Ivoire (2019), palm oil from Indonesia (2018), and live cattle exports from Brazil (2019). These data include exports both as a raw commodity (e.g. cocoa beans) and processed products (e.g. cocoa butter or paste). When reporting market share per trader, all volumes were converted into ‘raw product equivalents’ (e.g. the volume of cocoa beans required to produce cocoa butter exports), by multiplying these product volumes by standard conversion coefficients (80).

We reviewed corporate annual, sustainability and traceability reports to identify and extract the percentage of each trader’s sourcing which was direct and indirect in each producer country, and the identity of the direct and indirect suppliers (whether their own plantations or farms, etc). Where these figures were not reported, we used context-specific supply chain data to estimate direct and indirect sourcing (Table 2). Details of the assessments for each commodity are provided below.

South American soy: Several soy traders report the proportions of direct and indirect sourcing for only part of their supply chain: Bunge only for priority municipalities included in the Soft Commodities Forum, Viterra only for the Cerrado, and COFCO only for Mato Grosso and Matopiba. The percentages sourced directly/indirectly were then combined with Trase’s trade data (i.e., exported volumes in per region) to show the overall sourcing patterns. The remaining volumes were recorded as ‘unknown’. In corporate disclosures, traders do not differentiate between soy sourced via cooperatives and other aggregators. In Figure 2 we therefore use a color gradient to reflect this uncertainty in the type of indirect sourcing used. Where trading companies have undergone a name change, we report the current name (i.e. ‘Glencore Agriculture’ is named as Viterra throughout the manuscript).
Côte d’Ivoire cocoa: Trading companies (and cocoa processors) do not directly disclose the volumes sourced from cooperatives or other local intermediaries, though many do disclose which cooperatives they buy from, and the number of farmers per cooperative (Supplementary text). For each cooperative, we estimate the volume sold to their customer traders by multiplying the number of reported member farmers by cocoa production per farm. For 440/710 cooperatives linked to a known trading company, the number of supplying farms was reported by the trading company. For the remaining 270 cooperatives, the number of farmers was estimated by taking 1000 Monte Carlo samples (with replacement) from the known cooperative sizes (median: 591 farmers/cooperative, mean: 766 farmers/cooperative). Production per farmer (ton/year) was also estimated using Monte-Carlo resampling from production data from 441 cocoa farmers across Côte d’Ivoire (81). The Monte Carlo simulation produced relatively narrow confidence intervals (Figure S2), and so we focus on the mean values per trader in this manuscript. More details on the uncertainty, data sources, and methods are available in (80). Finally, the percentage of cocoa purchased via cooperatives (localised indirect sourcing) was calculated as the sum of the cocoa bean sourcing from each cooperative, divided by the trader’s total procurement in Côte d’Ivoire. Two of our focal traders, S3C and Africa Sourcing, do not disclose their cooperative suppliers, and so their sourcing is listed as unknown.

We also estimate the percentage of each trader’s cocoa sourcing which has been mapped to farm-level. We extracted the number of farms mapped from statistics listed in each company’s 2019/2020 Cocoa & Forests Initiative reports. This was again converted to a cocoa volume using Monte Carlo sampling of farmer production data. Where trading companies reported farms mapped both ‘through direct investment’ and ‘on behalf of clients’, we used the sum of these two figures as the total number of cocoa farms mapped in Côte d’Ivoire.

Indonesian palm oil: All assessed palm oil traders provide information on the percentage of products sourced from their third-party and own-company mills, though in a non-standardized manner.

Sinar Mas report that 39% of their sourcing comes from their own mills (82), of which 70% is from ‘nucleus plantations’ (vertically integrated direct sourcing), 20% from ‘plasma smallholders’ (direct sourcing), and 10% from ‘independent smallholders & third party producers’ (localised indirect sourcing) (82). The remaining 61% comes from third-party mills. In order to conservatively estimate ‘indirect sourcing’ through third-party mills, we assumed that all palm oil sourced via third-party mills which was traceable to plantation came from mills’ own plantations (i.e., was direct sourcing), rather than originating from independent smallholders or other aggregators. This assumption is based on the fact that fresh fruit bunches sourced from a mill’s own plantation are more readily traceable (mills are often located on site) than fruit sourced via intermediaries. Traceable volumes are extracted from each refinery’s traceability summary reports, and the overall proportion traceable was calculated by weighting the sourcing of each facility by its refinery capacity (Table S4). As a check of the validity of using processing capacities to estimate sourcing volumes per facility, we verified that this method gave a similar estimate of sourcing via third-party mills to Sinar Mas’ self-reported numbers (57% vs 61%).

Musim Mas’ report that “The bulk of our supply - 90% - comes from external sources, meaning third-party mills outside Musim Mas control. These mills receive FFB either from their own plantations (equivalent to 40% of our supply) or independent smallholders (50%)” (45). Of the 10%
of sourcing via their own mills, 70.2% comes from Musim Mas plantations, 3% from scheme smallholders, 0.1% from independent smallholders, and 26.7% from other third parties (45).

Wilmar reports each refinery’s sourcing (%) from Wilmar’s own mills and third-party mills, but they don’t report overall volumes. We calculated volumes using each refinery’s processing capacity (Table S4). In 2021, Wilmar also disclosed the origin of fresh fruit bunches for its own mills 40.4% from Wilmar plantations, 4% from scheme smallholders and the remaining 55.5% from third-party sources (84). For purchases through third-party mills, as above, we assumed that all traceable volumes sourced came from mills’ own plantations (direct sourcing), and untraceable volumes were sourced through other intermediaries (indirect sourcing).

When reporting the sourcing of Royal Golden Eagle, we focus on their subsidiary Apical Group, which operates refineries responsible for more than 86% of Royal Golden Eagles palm oil exports. In December 2020, Apical reported that they source 100% from third-party mills and that “29.4% is sourced from third party supplier mills’ own plantations while 70.6% is sourced from third party plantations” (85). Here, Apical count Asian Agri (another company within the Royal Golden Eagle conglomerate) as a third-party supplier. Since Apical does not report what percentage of its direct sourcing comes from Asian Agri mills, in Figure 2 we use a colour gradient when reporting their direct/vertically integrated sourcing.

**Brazilian live cattle exports:** The market share of live cattle traders was calculated from Trase’s shipping data. For 20% of trade, the trading company was not listed, market shares were therefore calculated based on the remaining 80% of trade where the trader was known. We quantified each trader’s indirect sourcing as the percentage of their cattle purchases (2017-2019) which came from direct suppliers who in turn bought in cattle. For this, we used a database of cattle movements, known as the Guia de Trânsito Animal (GTA). The GTA is a legally required document detailing the movement of batches of cattle between properties in Brazil, including the date of each movement, the identity of the farm, slaughterhouse, or trader sending and receiving cattle, and the number of cattle. Altogether, the dataset used in this analysis includes 33 million records of cattle movements across 23 states in Brazil, processed and cleaned according to (12).

Direct suppliers were identified as the farms moving cattle to a property owned by the trader (identified by the first 8-digits of the CNPJ, which is unique to each company, Table S5). Direct sourcing (i.e. purchases from ‘complete cycle’ cattle farms who do not buy in cattle but produce and rear their own cattle) was classified using a cut-off of 20 cattle bought-in across 2017-2019. i.e., If a property bought in 20 or fewer cattle, it was considered as part of the trader’s direct sourcing. This cut-off allows for small-scale movement of cattle for purposes such as breeding. For comparison, the average herd size in the state of Pará, the main source of live cattle exports, is 148 cattle/property (16). Our results are not sensitive to this cut-off (Table S6). In cases where farmers both produce calves on farm (complete-cycle) and buy in some cattle, where their purchases exceed our 20 cattle threshold, all cattle from that property are considered as being in the indirect supply chain. There is no widely adopted system for tracking individual cattle in Brazil, and so from a trader’s perspective, when they purchase from a direct supplier they do not have any mechanism of assessing whether the cattle was born on that farm or elsewhere. Similarly, though traders could map the spatial location of their direct suppliers - we do not, however, count their indirect sourcing as ‘localised’, because direct suppliers in turn source cattle from a wide region: 62-66% of cattle purchases are from municipalities other than where the direct supplier is itself located.
**Assessing deforestation risks in indirect sourcing**

To illustrate how deforestation risks are distributed across direct and indirect sourcing, we present analyses for Côte d’Ivoire cocoa and Brazilian live cattle exports. Similar calculations are not possible for palm oil and soy traders, because data are not available to spatialise where companies source directly vs indirectly. To do so would require soy traders to disclose the locations and volumes of their supplier farms and silos, and palm oil traders to disclose for each of their supplier mills the mix of supply which come from mills’ own plantations, rather than smallholders or local aggregators.

**Côte d’Ivoire cocoa:** We estimate the deforestation risk of cocoa traders based on the cocoa-driven deforestation in the départements from which they sourced. This calculation requires three steps. First, identifying the volumes sourced by traders from each département through their ‘localised’ and indirect supply chains. Second, identifying the area of cocoa-driven deforestation (in hectares) per département. And third, the production of cocoa (in ktons) per département. Step one is explained above; steps two and three are discussed in more detail below.

Cocoa-driven deforestation (in hectares) was identified by intersecting remote sensing products of cocoa (69) and forest loss (17) to identify the area of cocoa production in 2019 which was planted on land that was converted between 2000-2015. The cocoa land cover map was 20-m² resolution, based on Sentinel-1 and Sentinel-2 satellite images. The land cover map was based on 30-m² resolution Landsat imagery, processed by the UN-FAO and Côte d’Ivoire’s BNETD (National Bureau of Technical Studies and Development) as part of the monitoring efforts for the implementation of REDD+ programs in the country. As such, we use an allocation period of 15 years (forest cleared between 2000-2015) and a time lag of 4 years (2015-2019) to allocate deforestation risk to cocoa harvested in 2019. This time lag reflects that land cleared in 2015 (or earlier) and planted with cocoa trees takes 3-5 years to become productive. The total area of cocoa-driven deforestation for the Côte d’Ivoire was 289.1 Kha (Figure S1).

The area of cocoa-driven deforestation per département was then divided by cocoa production (in ktons), to estimate the deforestation risk per département (ha/kton), which was linked to trader flows.

Since there is no official, publicly-available subnational data on cocoa production in Côte d’Ivoire, cocoa production per département was calculated using the remote-sensing map of cocoa area and a cocoa suitability map (86) to weight the cocoa area in each département by its relative suitability for cocoa production.

The ‘relative suitable area’ (RSA) for cocoa in each département was calculated as:

\[ RSA_d = \sum_{n=1}^{i} area_n \times suitability_n \]

Where \( d \) represents all départements, \( n \) represents all pixels under cocoa, \( area_n \) the area covered by each pixel, and \( suitability_n \) the suitability index (0-1) of each pixel.

Cocoa production (in tonnes) per unit of RSA was calculated as:

\[ pRSA = \frac{production_{ICCO}}{\sum_{d=1}^{l} RSA_d} \]
Where $production_{ICCO}$ is the total cocoa production volume (kg) of the Côte d'Ivoire (from ICCO statistics). Finally, we calculated cocoa production per département:

$$production_d = RSA_d * pRSA$$

The confidence intervals in the deforestation risk of each trader’s sourcing (Figure 4) reflects the uncertainty in the estimation of volumes sourced by each trader from each cooperative.

**Brazilian live cattle exports:** We crossed lists of each traders’ suppliers against properties embargoed by the Brazilian environmental enforcement agency, Ibama, to identify risks among traders’ direct and indirect suppliers.

Properties are embargoed by Ibama for environmental crimes - illegal deforestation, preventing reforestation, as well as other acts including illegal hunting, polluting, and building without permission in natural areas. We focus on embargoes as a simple demonstration of sustainability risks in meatpackers’ direct and indirect supply chains. Embargoes are, however, only the tip of the iceberg - less than 1% of the Amazon’s illegal deforestation goes on to be embargoed (92).

We identified cattle movements from embargoed properties as cases where: [1] the tax identifier (CPF, Cadastro de Pessoas Físicas in Portuguese) of the property transferring cattle in the GTAs matched a CPF in the embargo list; [2] the property was listed in the same municipality as the embargo, and [3] the transport date in the GTAs came after the date that the property was placed on the embargo list (The ‘Data de Inserção na Lista’, in Portuguese). We then report the number of embargoed suppliers as a percentage of each trader’s suppliers for which the CPF was listed in the GTA data (Supplementary text).

**References**

1. P. G. Curtis, C. M. Slay, N. L. Harris, A. Tyukavina, M. C. Hansen, Classifying drivers of global forest loss. *Science*. **361**, 1108–1111 (2018).
2. E. K. H. J. zu Ermgassen, B. Ayre, J. Godar, M. G. B. Lima, S. Bauch, R. Garrett, J. Green, M. J. Lathuilière, P. Löfgren, C. MacFarquhar, P. Meyfroidt, C. Suavet, C. West, T. Gardner, Using supply chain data to monitor zero deforestation commitments: an assessment of progress in the Brazilian soy sector. *Environ. Res. Lett.* (2019), doi:10.1088/1748-9326/ab6497.
3. C. Folke, H. Österblom, J.-B. Jouffray, E. F. Lambin, W. N. Adger, M. Scheffer, B. I. Crona, M. Nyström, S. A. Levin, S. R. Carpenter, J. M. Anderies, S. Chapin, A.-S. Crépin, A. Dauriach, V. Galaz, L. J. Gordon, N. Kautsky, B. H. Walker, J. R. Watson, J. Wilen, A. de Zeeuw, Transnational corporations and the challenge of biosphere stewardship. *Nat. Ecol. Evol.*, 1–8 (2019).
4. M. Serdijn, A. Kolk, L. Fransen, Uncovering missing links in global value chain research – and implications for corporate social responsibility and international business. *Crit. Perspect. Int. Bus.*, 1742–2043 (2020).
5. Directorate-General for Environment, Proposal for a regulation on deforestation-free products (2021; https://ec.europa.eu/environment/publications/proposal-regulation-deforestation-free-products_en).
6. J. Grabs, S. L. Carodenuto, Traders as sustainability governance actors in global food supply chains: A research agenda. *Bus. Strategy Environ.* **30**, 1314–1332 (2021).
7. E. M. Tachizawa, C. Yew Wong, Towards a theory of multi-tier sustainable supply chains: a systematic literature review. *Supply Chain Manag. Int. J.* **19**, 643–663 (2014).
8. E. Koberg, A. Longoni, A systematic review of sustainable supply chain management in global supply chains. *J. Clean. Prod.* **207**, 1084–1098 (2019).

9. M. F. Skidmore, F. Moffette, L. Rausch, M. Christie, J. Munger, H. K. Gibbs, Cattle ranchers and deforestation in the Brazilian Amazon: Production, location, and policies. *Glob. Environ. Change.* **68**, 102280 (2021).

10. C. Wiggs, B. Kuepper, M. Piotrowski, “Spot Market Purchases Allow Deforestation-Linked Palm Oil to Enter NDPE Supply Chains” (Chain Reaction Research, 2020), p. 11.

11. S. Glenday, J. Yusurum, Suharno, A. Safford, “Central Kalimantan’s Oil Palm Value Chain: Opportunities for Productivity, Profitability and Sustainability Gains” (A CPI, PILAR & GreenWorks Asia Working Paper, CPI, PILAR & GreenWorks Asia, 2015), p. 29.

12. E. K. H. J. zu Ermgassen, J. Godar, M. J. Lathuillère, P. Löfgren, T. Gardner, A. Vasconcelos, P. Meyfroidt, The origin, supply chain, and deforestation risk of Brazil’s beef exports. *Proc. Natl. Acad. Sci.* **117**, 31770–31779 (2020).

13. E. D. Goldman, M. Weisse, N. Harris, M. Schneider, Estimating the Role of Seven Commodities in Agriculture-Linked Deforestation: Oil Palm, Soy, Cattle, Wood Fiber, Cocoa, Coffee, and Rubber. *Glob. For. Watch* (2020), doi:https://doi.org/10.46830/writn.na.00001.

14. FAO, FAOSTAT: Statistical databases (2020), (available at http://faostat.fao.org/).

15. X.-P. Song, M. C. Hansen, P. Potapov, B. Adusei, J. Pickering, M. Adami, A. Lima, V. Zalles, S. V. Stehman, C. M. D. Bella, M. C. Conde, E. J. Copati, L. B. Fernandes, A. Hernandez-Serna, S. M. Jantz, A. H. Pickens, S. Turubanova, A. Tuukavina, Massive soybean expansion in South America since 2000 and implications for conservation. *Nat. Sustain.*, 1–9 (2021).

16. IBGE, Censo Agropecuário 2017. *IBGE - Censo Agro 2017* (2017), (available at https://censoagro2017.ibge.gov.br//resultados-censo-agro-2017.html).

17. FAO, Le Secrétariat Exécutif Permanent REDD+, “Données forestières de base pour la REDD+ en Côte d’Ivoire” (FAO, Abidjan, CI, 2017).

18. K. G. Austin, A. Mosnier, J. Pirker, I. McCallum, S. Fritz, P. S. Kasibhatla, Shifting patterns of oil palm driven deforestation in Indonesia and implications for zero-deforestation commitments. *Land Use Policy.* **69**, 41–48 (2017).

19. Direktorat Jenderal Perkebunan, “Statistik perkebunan unggulan nasional 2019-2021” (Statistical of National Leading Estate Crops Commodity, Direktorat Jenderal Perkebunan Kementerian Pertanian, Republik Indonesia, 2021), p. 1056.

20. J. W. Molenaar, M. Persch-Orth, S. Lord, C. Taylor, J. Harms, “Diagnostic Study on Indonesia Oil Palm Smallholders. Developing a Better Understanding of their Performance and Potential” (International Finance Corporation, Washington, DC, 2013), p. 96.

21. J. Fernando, R. Kelly, How Commodities Work. *Investopedia* (2021), (available at https://www.investopedia.com/terms/c/commodity.asp).

22. S. Freidberg, Trading in the secretive commodity. *Econ. Soc.* **46**, 499–521 (2017).

23. R. Pirard, N. Schulz, J. Benedict, R. Heilmayr, F. Ramada, B. Ayre, H. Bellfield, “Corporate ownership and dominance of Indonesia’s palm oil supply chains” (Trase, 2020).

24. J. H. Grimm, J. S. Hofstetter, J. Sarkis, Critical factors for sub-supplier management: A sustainable food supply chains perspective. *Int. J. Prod. Econ.* **152**, 159–173 (2014).

25. P. Barreto, R. Pereira, A. Brandão Jr, S. Baima, “Os frigoríficos vão ajudar a zerar o desmatamento da Amazônia?” (Imazon & ICV, Belém, PA; Cuiabá, MT, 2017), p. 162.

26. H. K. Gibbs, J. Munger, J. L’Roe, P. Barreto, R. Pereira, M. Christie, T. Amaral, N. F. Walker, Did Ranchers and Slaughterhouses Respond to Zero-Deforestation Agreements in the Brazilian Amazon? *Conserv. Lett.* **9**, 32–42 (2016).
27. Minerva Foods, Minerva deve lançar ferramenta para monitorar fornecimento indireto de gado na Amazônia e no Cerrado | Minerva (2021), (available at https://www.minervafoods.com/noticias/minerva-deve-lancar-ferramenta-para-monitorar-fornecimento-indireto-de-gado-na-amazonia-e-no-cerrado/).

28. Cargill, “South American Soy - Progress Report Mid-year update 2020” (2020), (available at https://www.cargill.com/doc/143216466608/soy-progress-mid-year-report-2020-en.pdf).

29. COFCO, “Sustainable Soy Sourcing Policy” (Version 01, 2019), (available at https://www.cofcointernational.com/media/1330/sustainable-soy-sourcing-policy.pdf).

30. S. Carodenuto, M. Buluran, The effect of supply chain position on zero-deforestation commitments: evidence from the cocoa industry. J. Environ. Policy Plan. 0, 1–16 (2021).

31. M. Skidmore, thesis, The University of Wisconsin - Madison, United States -- Wisconsin (2020).

32. R. Rajão, B. Soares-Filho, F. Nunes, J. Börner, L. Machado, D. Assis, A. Oliveira, L. Pinto, V. Ribeiro, L. Rausch, H. Gibbs, D. Figueira, The rotten apples of Brazil’s agribusiness. Science. 369, 246–248 (2020).

33. J. Alix-Garcia, H. K. Gibbs, Forest conservation effects of Brazil’s zero deforestation cattle agreements undermined by leakage. Glob. Environ. Change. 47, 201–217 (2017).

34. R. Heilmayr, L. L. Rausch, J. Munger, H. K. Gibbs, Brazil’s Amazon Soy Moratorium reduced deforestation. Nat. Food. 1, 801–810 (2020).

35. Agrosatélite, ABIOVE, INPE, Grupo de Trabalho da Soja, “Soy Moratorium - crop year 2018/19” (2020), (available at https://abiove.org.br/wp-content/uploads/2020/04/Report_Soy_Moratorium_2018-19_en.pdf).

36. Soja na Linha, Transparência. Soja Na Linha (2021), (available at https://www.sojaalinha.org/index/transparency).

37. M. J. Murcia, R. Panwar, J. Tarzijan, Socially Responsible Firms Outsource Less: Bus. Soc. (2020), doi:10.1177/0007650319898490.

38. A. Orsdemir, B. Hu, V. Deshpande, Ensuring Corporate Social and Environmental Responsibility Through Vertical Integration and Horizontal Sourcing. Manuf. Serv. Oper. Manag. 21, 417–434 (2019).

39. J. Grabs, F. Cammelli, S. A. Levy, R. D. Garrett, Designing effective and equitable zero-deforestation supply chain policies. Glob. Environ. Change. 70, 102357 (2021).

40. FAO, BASIC, “Comparative study on the distribution of value in European chocolate chains” (Paris, FR, 2020).

41. R. Narula, Enforcing higher labor standards within developing country value chains: Consequences for MNEs and informal actors in a dual economy. J. Int. Bus. Stud. 50, 1622–1635 (2019).

42. M. Wilhelm, C. Blome, V. Bhakoo, A. Paulraj, Sustainability in multi-tier supply chains: Understanding the double agency role of the first-tier supplier. J. Oper. Manag. 41, 42–60 (2016).

43. L. Huang, J.-S. J. Song, R. Swinney, “Managing Social Responsibility in Multitier Supply Chains” (SSRN Scholarly Paper ID 2837332, Social Science Research Network, Rochester, NY, 2020), doi:10.2139/ssrn.2837332.

44. C. Mena, A. Humphries, T. Y. Choi, Toward a Theory of Multi-Tier Supply Chain Management. J. Supply Chain Manag. 49, 58–77 (2013).

45. Musim Mas, “Paving the way for a responsible supply base. Sustainability Report 2019” (Musim Mas Holdings Pte Ltd, Sustainability Report 2019, 2020), (available at https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwi4-
46. J. Lernoud, J. Potts, G. Sampson, B. Schlatter, G. Huppe, V. Voora, H. Willer, J. Wosniak, D. Dang, “The State of Sustainable Markets 2018 - Statistics and Emerging Trends.” (International Trade Centre (ITC), International Institute for Sustainable (IISD), Research Institute of Organic Agriculture (FiBL), Geneva, CH, 2018), p. 202.

47. E.-M. Meemken, C. B. Barrett, H. C. Michelson, M. Qaim, T. Reardon, J. Sellare, Sustainability standards in global agrifood supply chains. *Nat. Food*, 1–8 (2021).

48. T. Dietz, J. Grabs, Additionality and Implementation Gaps in Voluntary Sustainability Standards. *New Polit. Econ.* 0, 1–22 (2021).

49. C. Tayleur, A. Balmford, G. M. Buchanan, S. H. M. Butchart, C. Corlet Walker, H. Ducharme, R. E. Green, J. C. Milder, F. J. Sanderson, D. H. L. Thomas, L. Tracewski, J. Vickery, B. Phalan, Where are commodity crops certified, and what does it mean for conservation and poverty alleviation? *Biol. Conserv.* 217, 36–46 (2018).

50. H. Bakhtary, E. Matson, C. Streek, *Engaging Smallholders in Cocoa & Palm Oil Supply Chains* (2020).

51. R. Heilmayr, K. M. Carlson, J. J. Benedict, Deforestation spillovers from oil palm sustainability certification. *Environ. Res. Lett.* 15, 075002 (2020).

52. K. M. Carlson, R. Heilmayr, H. K. Gibbs, P. Nooijipady, D. N. Burns, D. C. Morton, N. E. Walker, G. D. Paoli, C. Kremen, Effect of oil palm sustainability certification on deforestation and fire in Indonesia. *Proc. Natl. Acad. Sci.*, 201704728 (2017).

53. Musim Mas, NDPE Roadmap. *Musim Mas* (2021), (available at https://www.musimmas.com/sustainability/ndpe-roadmap/).

54. Amaggi, “Progress report 2019: towards a deforestation and native vegetation conversion free chain” (Amaggi, 2020), p. 29.

55. Barry Callebaut, “Barry Callebaut 2018-2019 Annual CFI Progress Report” (Barry Callebaut, Zürich, CH, 2020), (available at https://www.barry-callebaut.com/sites/default/files/2020-04/CFI%20Progress%20Report_Barry%20Callebaut.pdf).

56. Nitidae, “Feasibility assessment: Traceability and transparency of cocoa supply chains in Côte d’Ivoire and Ghana” (REDD+ Facility of the European Forest Institute, 2021), p. 43.

57. WBCSD, “Soft Commodities Forum progress report: towards deforestation-free soy” (World Business Council for Sustainable Development, 2021), p. 26.

58. P. Pacheco, K. Mo, N. Dudley, A. Shapiro, N. Aguilar-Amuchastegui, P. Y. Ling, C. Anderson, A. Marx, “Deforestation fronts: Drivers and responses in a changing world.” (WWF, Gland, Switzerland, 2021), p. 125.

59. BDO, “Minerva S.A. Third-party audit report to meet ‘undertaking to adopt minimum criteria for industrial-scale operations with cattle and beef products in the Amazon biome’” (São Paulo, Brazil, 2020), p. 19.

60. Global Witness, “Beef, Banks and the Brazilian Amazon” (Global Witness, London, UK, 2020), p. 64.

61. T. A. Gardner, M. Benzie, J. Börner, E. Dawkins, S. Fick, R. Garrett, J. Godar, A. Grimard, S. Lake, R. K. Larsen, N. Mardas, C. L. McDermott, P. Meyfroidt, M. Osbeck, M. Persson, T. Sembres, C. Suavet, B. Strassburg, A. Trevisan, C. West, P. Wolvekamp, Transparency and sustainability in global commodity supply chains. *World Dev.* 121, 163–177 (2019).

62. Y. Wu, K. Zhang, J. Xie, Bad Greenwashing, Good Greenwashing: Corporate Social Responsibility and Information Transparency. *Manag. Sci.* 66, 3095–3112 (2020).
63. Accountability Framework, “Operational Guidance on Reporting, Disclosure, and Claims” (Accountability Framework version 1.0, 2019), (available at https://accountability-framework.org/operational-guidance/reporting-disclosure-and-claims/).

64. A. Bateman, L. Bonanni, What Supply Chain Transparency Really Means. Harv. Bus. Rev. (2019), (available at https://hbr.org/2019/08/what-supply-chain-transparency-really-means).

65. M. G. Bastos Lima, M. Persson, P. Meyfroidt, Leakage and boosting effects in environmental governance: A framework for analysis. Environ. Res. Lett. (2019), doi:10.1088/1748-9326/ab4551.

66. MAPA, “Nota Técnica nº 4/2019/CTOA/DSA/SDA/MAPA” (PROCESSO Nº 21000.026775/2017-31, Ministério da Agricultura, Pecuária e Abastecimento, 2019), (available at https://www.gov.br/agricultura/pt-br/acesso-a-informacao/dadosabertos/arquivos-raiz/SEI_MAPA7022860NotaTecnica_SDA.pdf).

67. Conseil Café Cacao, “Sadre du dialogue politique entre la Côte d’Ivoire et l’Union Européenne pour un cacao durable” (Conseil Café Cacao, CCC, Abidjan, CI, 2021), p. 8.

68. M. Boström, A. Jönsson, S. Lockie, A. Mol, P. Oosterveer, Sustainable and responsible supply chain governance: Challenges and opportunities. J. Clean. Prod. 107 (2014), doi:10.1016/j.jclepro.2014.11.050.

69. I. O. Abu, Z. Szantoi, A. Brink, M. Robuchon, M. Thiel, Detecting cocoa plantations in Côte d’Ivoire and Ghana and their implications on protected areas. Ecol. Indic. 129, 107863 (2021).

70. B. Yao Sadaïou Sabas, K. Gislain Danmo, K. Akoua Tamia Madeleine, B. J. A, Cocoa Production and Forest Dynamics in Ivory Coast from 1985 to 2019. Land. 9, 524 (2020).

71. M. G. Bastos Lima, U. M. Persson, Commodity-Centric Landscape Governance as a Double-Edged Sword: The Case of Soy and the Cerrado Working Group in Brazil. Front. For. Glob. Change. 3 (2020), doi:10.3389/ffgc.2020.00027.

72. H. Deans, M. A. F. Ros-Tonen, M. Derkyi, Advanced Value Chain Collaboration in Ghana’s Cocoa Sector: An Entry Point for Integrated Landscape Approaches? Environ. Manage. 62, 143–156 (2018).

73. World Business Council for Sustainable Development, “Soft Commodities Forum progress report. Building transparent and sustainable supply chains. December 2020.” (World Business Council for Sustainable Development (WBCSD), 2020), (available at https://www.wbcsd.org/Programs/Food-Land-Water/Food-Land-Use/Soft-Commodities-Forum).

74. J. Boshoven, L. C. Fleck, S. Miltner, N. Salafsky, J. Adams, A. Dahl-Jørgensen, G. Fonseca, D. Nepsted, K. Rabinovitch, F. Seymour, Jurisdictional sourcing: Leveraging commodity supply chains to reduce tropical deforestation at scale. A generic theory of change for a conservation strategy, v 1.0. Conserv. Sci. Pract. 3, e383 (2021).

75. IDH, SourceUp - Supply chain sustainability (2021), (available at https://www.idhsustainabletrade.com/approach/sourceup/).

76. Accountability Framework, Achieving Commitments Through Collaboration. Account. Framev. (2020), (available at https://accountability-framework.org/operational-guidance/achieving-commitments-through-collaboration/).

77. Forest Positive Coalition of Action, “Nurturing Transparency: The Path to Forest Positive” (Consumer Goods Forum, 2021), p. 55.

78. EIA, “Promises in Practice: The Limited Reliability of Voluntary ‘No Deforestation’ Commitments in Papua’s Palm Oil Plantations” (EIA UK, London, UK, 2019), p. 20.
79. P. R. Furumo, E. F. Lambin, Policy sequencing to reduce tropical deforestation. *Glob. Sustain.* 4 (2021), doi:10.1017/sus.2021.21.

80. Trase, “SEI-PCS Côte d’Ivoire Cocoa v1.1.0 documentation” (Trase, 2021), (available at https://schema-cms-api-pages127df1a-1100pd61xro1g.s3.amazonaws.com/280/blocks/1044/2021-04-07-civ_cocoa_seipcs_method_doc-rebrand.pdf).

81. R. Bymolt, A. Laven, M. Tyszler, “Demystifying the cocoa sector in Ghana and Côte d’Ivoire - Sustainable Economic Development” (KIT - Royal Tropical Institute, 2018), (available at https://www.kit.nl/sed/project/demystifying-cocoa-sector/).

82. GAR, “GAR Announces 100% Traceability to the Plantation for Owned Mills” (Golden Agri-Resources Ltd, 2019), p. 2.

83. Golden Agri-Resources, GAR-Owned Mills (2021), (available at https://goldenagri.mediacites.id/sustainability-dashboard/gar-owned-mills).

84. Wilmar, Traceability back to Mill (2021), (available at https://www.wilmar-international.com/sustainability/traceability/traceability-back-to-mill).

85. Apical Group, Traceability & Working with Suppliers (2021), (available at https://www.apicalgroup.com/sustainability/working-with-suppliers/).

86. G. Schroth, P. Läderach, A. I. Martinez-Valle, C. Bunn, L. Jassogne, Vulnerability to climate change of cocoa in West Africa: Patterns, opportunities and limits to adaptation. *Sci. Total Environ.* 556, 231–241 (2016).

87. Glencore Agriculture, “Soft Commodities Forum Progress Report, June 2019: Building transparent and traceable soy supply chains in Brazil’s Cerrado region” (2019), (available at https://www.glencoreagriculture.com/dam/jcr:1af6336a-cb5d-4933-b827-1eb9f703f3c/SCF%20June%202019Report_Glencore_Agriculture_Final.pdf).

88. Glencore Agriculture, “Soft Commodities Forum Progress Report, June 2020: Building transparent and traceable soy supply chains” (2020), (available at https://www.viterra.com/dam/jcr:2db7604f-a97d-4b7f-a695-cc18a2701eb6/SCF%20Glencore_Agriculture_Jun_2020.pdf).

89. Greenpeace International, “Destruction: Certified” (2021), p. 61.

90. Minerva, “2020 Sustainability report” (2021), (available at https://www.minervafoods.com/wp-content/uploads/2021/04/RS2020__MinervaFoods_EN.pdf).

91. Mapbiomas, “Relatório Anual do Desmatamento no Brasil 2019” (São Paulo, Brazil, 2020), p. 49.
Fig. 1. The supply chains of our four focal commodity contexts. Grey boxes are a trader’s direct suppliers. Traders’ direct sourcing is shown in purple, and indirect sourcing in orange/brown; black lines can contain a mix of both direct and indirect sourcing. ‘Direct
sourcing: vertical’ (dark purple) refers to vertically integrated traders who operate their own farms. Supply chains are simplified to showcase the different sourcing strategies and intermediaries. Soybeans, for example, may be crushed into soybean meal and oil before export, and farmers may own multiple farms.

Fig. 2. Market share of trading companies. Traders responsible for the top 60% of exports across our four focal contexts: South American soy, Côte d’Ivoire cocoa, Indonesian palm oil, and Brazilian live cattle.
Fig. 3. The prevalence of different sourcing strategies. The proportion of commodities which are indirectly (orange) and directly (purple) sourced in by major traders exporting soy from South America, cocoa from Côte d’Ivoire, palm oil from Indonesia, and live cattle from Brazil. For soy traders and Royal Golden Eagle we were not able to distinguish between their different types of indirect and direct sourcing, respectively (see Methods), and a colour gradient is used to reflect this uncertainty.
Fig. 4. Deforestation risks are higher in the parts of the supply chain over which companies have the least visibility. A) For 4/6 cocoa traders whose sourcing through cooperatives (localised indirect sourcing) is known, deforestation risks (ha/kton cocoa) are higher in the indirect supply chain. Error bars are 95% confidence intervals, reflecting uncertainty in the estimation of volumes sourced by each trader from each cooperative (SI Appendix). B) Embargoed properties are more common among indirect (orange) than direct (purple) suppliers for live cattle traders which have adopted zero deforestation commitments; the opposite pattern holds for Bull Log Trading which had not made a commitment.
Table 1. Common approaches taken by companies to ensure that sourcing complies with sustainability commitments. Includes summary of how each approach addresses risks in indirect sourcing as well as their strengths and weaknesses in delivering more sustainable commodity sourcing.

| Sustainable sourcing strategy | How addresses risks in indirect sourcing | Strengths | Weaknesses | Inter-dependencies | Examples |
|------------------------------|-----------------------------------------|-----------|------------|--------------------|---------|
| Increased direct sourcing    | Reduces indirect sourcing                | Reduces transaction costs and information asymmetries as focal company has direct contract with (or owns) the properties producing raw materials (44) | Increases market concentration; can exclude local actors; may increase costs if companies outstretch their core competencies; impact of sustainable procurement efforts are limited to own supply chain; can result in bifurcated supply chains if buyers shift supply to low risk regions | Requires transparency or certification of on-farm activities (e.g., zero deforestation) to be externally demonstrable | Between 2018 and 2019, the soy trader Viterra increased direct sourcing in 'priority municipalities' in Brazil's Matopiba region from 42.9% to 64.9% (87-88) |
| Cascading compliance         | Requires direct suppliers to in turn engage with their suppliers and communicate sustainable procurement requirements | Low cost for focal company (41) | Passes burden of enforcing compliance to actors with (in many cases) lower capacity (41); impact remains limited to actors in own supply chain | Requires transparent third-party audits or certification to be externally demonstrable (41) | Few examples by agricultural commodity traders; more commonly used by downstream companies, e.g., Consumer Goods Forum Forest Positive Coalition of Action members that pass compliance requirements onto traders and other suppliers (77) |
| Certification                | Provides evidence that producer meets certification standard without requiring the trader to monitor or have direct relationship with producers | Recognized by consumers; downstream companies do not necessarily need to identify product origin when buying certified products; mass-balance or book-and-claim approaches keep costs low | Low additionality (48); risks market bifurcation; book-and-claim and mass-balance approaches hinder traceability and create disconnect between product labels and content (89); low transparency leads to questions over audit quality | Can be implemented at multiple scales (farm, cooperative, or landscape), though usually implemented at farm or cooperative level | Rainforest Alliance/UTZ and Fairtrade for cocoa, RSPO for palm oil, RTRS for soy |
| Traceability                 | Seeks to track all sourcing back to farm | Increases focal company’s understanding of their supply chain and sourcing risks; makes engagement between trader and producers possible (e.g., around zero deforestation requirement, preferable contracts, market access) | Requires segregation for commodities that are traditionally stored and processed in bulk; because of costs, often limited to direct supply chains only or to ‘high-risk’ regions (57); where optional, it risks market bifurcation; doubts over reliability of some farm-level mapping exercises (9, 56) | In itself, traceability does not affect the mode of production of a commodity; thus requires cascading compliance or communication of sourcing standards to induce a change at the farm level; requires transparency or certification for sustainability claims to be externally demonstrable | Between 2019 and 2020, the oil palm trader Musim Mas increased traceability back to the plantation from 49% to 66% (53); in 2020, Minerva monitored 3770 direct suppliers in Brazil for deforestation (90) |
| Transparency | Open communication of progress (e.g., on traceability, risks, implementation measures, outcomes) and challenges implementing sustainable procurement practices in direct and indirect sourcing | Allows companies to communicate with consumers about product origins and demonstrate progress against sustainability targets; discourages greenwashing and malpractice (61) | Data disclosures are non-standardized; where optional, it risks market bifurcation (61); limited by data availability (e.g., may only focus on the direct supply chain) | A prerequisite for transparency is knowledge of both the focal company's supply chain (e.g., through traceability, certification, or information on suppliers) as well as on-the-ground impacts (e.g., through independent or own satellite monitoring) (61) | Leading cocoa traders have disclosed which cooperatives they source from in Côte d'Ivoire (55) |
| --- | --- | --- | --- | --- | --- |
| Landscape approaches | Internalises all production practices - among both direct and indirect suppliers - within the landscape where commodity originates | The only approach which captures land use dynamics outside of monitored supply chains; seeks to build capacity and identify solutions across sectors (74); avoids redundancy between overlapping certification or corporate sustainability programs; jurisdictional sourcing efforts reward jurisdictions which implement sustainable land use plans (75) | Challenging to create inclusive, consensus-led initiatives in regions that often have weak governance; for additionality, must go beyond high/low risk rating systems; need committed buyers to support jurisdictional sourcing and expand beyond a small number of target landscapes | Requires certification and/or transparent monitoring and evaluation to be externally demonstrable | Amazon Soy Moratorium, RSPO jurisdictions; SourceUp initiative links agri-commodity companies with multi-stakeholder initiatives in producing regions |
**Table 2. Data sources.** Summary of data sources used to quantify the prevalence of indirect sourcing in each commodity context.

| Context                      | Data sources used to quantify the prevalence of indirect sourcing                                                                 |
|------------------------------|-------------------------------------------------------------------------------------------------------------------------------|
| South American soy           | Trase data on traded volumes; corporate reports; Soft Commodities Forum progress reports                                         |
| Cocoa in Côte d’Ivoire       | Trase data on traded volumes; company self-disclosures of the location and size of supplier cooperatives; cocoa production per cooperative estimated from the number of cooperative members and farm production data |
| Indonesian palm oil          | Trase data on traded volumes; corporate reports; capacity of individual processing facilities                                     |
| Live cattle in Brazil        | Trase data on traded volumes; animal transport permits                                                                           |
Supplementary Materials

South American Soy: variable transparency
Discussions around the sustainability of soy in South America have tended to focus on deforestation in the Brazilian Amazon (1), though soy is a driver of forest loss across the continent (2). In line with this focus, while all (7/7) traders disclosed some information about direct and indirect sourcing within Brazil, 5/7 traders sourcing soy in Argentina and 4/6 traders sourcing soy in Paraguay do not provide similar information for these contexts. Sourcing is marked ‘unknown’ in these cases.

Mechanisms of indirect suppliers’ deforestation risk
The elevated deforestation risk among indirect suppliers can arise through multiple processes. First, they may reflect intrinsic differences in the characteristics (including land management and agricultural practices) of farmers who sell directly to traders, through cooperatives, or via other local intermediaries. Second, it may reflect the efficacy of sustainable sourcing initiatives which are focused on direct suppliers or cooperatives. Third, the exclusion of indirect suppliers creates a loophole where risks are not reduced among indirect suppliers. Lastly, the focus on direct suppliers also creates the opportunity for leakage, where non-compliant production is displaced from direct to indirect suppliers.

Risk of cattle purchases from embargoed properties/holdings
We crossed lists of each traders’ suppliers against properties embargoed by the Brazilian environmental enforcement agency, Ibama, to identify risks among traders’ direct and indirect suppliers. Our method treats (multiple) properties linked to the same CPF in the same municipality as a single holding. These properties are often adjacent - according to (12), 40% of multi-property cases are located less than 0.01 km apart, with a median distance between properties of 0.4 km. In practice, farmers manage their cattle across these properties as a single herd, though when monitoring their zero deforestation commitments, traders tend to treat each property separately. We therefore checked whether the embargoes we identify in traders’ direct supply chains are cases where the embargoed area is on a sister property to the one listed as supplying cattle. We matched the supplier and embargo lists not only on the CPF and municipality (as above), but also the property name. 75.8% of our identified embargoes included a farm name, and of these, no embargoed areas were found on the properties directly supplying traders with zero deforestation commitments (Figure S4) – rather, embargoed areas were on other properties within the same holding. Among tier-1 indirect suppliers, embargoed areas were both detected on the properties (in 4-21% of cases) and holdings (in 79-96% of cases) selling cattle to the traders’ direct suppliers. These results suggest that traders are successfully filtering out embargoes from their direct suppliers when assessed at the property-level, but not at the level of holdings, and that their monitoring is also not addressing embargoes among indirect suppliers, both at the property- and holding-level. Our findings mirror other work (12), also highlighting that traders’ property-level monitoring creates a loophole for cattle from embargoed areas to enter their supply chains from their direct suppliers’ sister properties within the same holding.
**Fig. S1.**
The area of cocoa-driven deforestation per département in Côte d'Ivoire, calculated as the area of cocoa in 2019 which was detected on areas of forest cleared between 2000-2015.
Fig. S2.
Mean estimate and 95% confidence intervals for the percentage of cocoa sourced from cocoa cooperatives (cf. traitants) for major cocoa traders in Côte d'Ivoire.
Fig. S3.
Comparison of the number of farms mapped in Côte d'Ivoire, as reported under the Cocoa & Forests Initiative, against Monte Carlo estimates of the number of farms in each trader's supply chain. Error bars are 95% confidence intervals. S3C and Africa Sourcing do not participate in the CFI and so no farm numbers are listed.
Figure S4.
For companies making a zero deforestation commitment (ZDC), all embargoed areas among their direct suppliers were detected within their direct supplier’s holding (sister properties registered to the same owner, within the same municipality), rather than the specific property from which the trader purchased cattle. Among traders’ tier-1 indirect suppliers (i.e. their direct suppliers’ suppliers), 4-21% of embargoed areas were in the properties whose names match the name of properties from which the cattle movement was recorded.
Table S1.
How the terms ‘direct’ and ‘indirect’ suppliers or sourcing have been used in different commodity contexts. While in the soy sector, for example, indirect procurement is usually taken to mean any soy not purchased from the farmer who produced it, in crops produced by smallholders, such as cocoa or oil palm, the term ‘direct supplier’ has been used to refer to purchases from the first actor who aggregates products within a given local area - e.g. a farmer cooperative in cocoa, or a mill in oil palm (oil palm's fresh fruit bunches are easily perishable and so are processed at local mills before being sold to other companies). In this manuscript we present a unified framework for direct and indirect sourcing (see main text). Note: in supply chain management, the separate term ‘indirect procurement’ is used to refer to purchases which do not add to a business's bottom line, e.g. buying office supplies or acquiring services.

| Sector       | Terminology used                                                                 | Examples where this is referred to as such                                                                 |
|--------------|----------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------|
| Brazil beef  | “Direct suppliers are farms which sell cattle directly to meatpackers, while indirect suppliers are farms which sell or transfer cattle to other farms or intermediaries.” | Grupo de Trabalho dos Fornecedores Indiretos na Pecuária Brasileira: https://gtfi.org.br/cadeia-da-carne-no-brasil/ |
| Brazil soy   | Indirect sourcing: soy not purchased directly from farmers, instead purchased from cooperatives or aggregators who operate silos (storage facilities) to which multiple farmers contribute soybeans. | Soft Commodities Forum progress report, December 2019: https://docs.wbcsd.org/2019/12/WBCSD_Soft_Commodities_Forum_progress_report.pdf. |
| Brazil soy   | “Direct: soy sourced directly from a farmer.”                                     | Louis Dreyfus company (2020) Soy Sustainability - Focus on Brazil & Argentina. Transparency Update: Sourcing Profile and Deforestation/Conversion Risks https://www.ldc.com/wp-content/uploads/Brazil-and-Argentina-Deforestation-Risk-Profile_24.6.2020_final.pdf |
| West Africa cocoa | The term “direct supply chain” is used to refer to cocoa beans purchased through cooperatives or producer groups. | Cocoa & Forests Initiative reports CFI reports, e.g. https://www.worldcocoafoundation.org/wp-content/uploads/2018/08/WCF_Report_14.6_051420.pdf |
| Indonesian Oil palm | Direct sourcing is where the mill or cooperatives (of smallholders) are known. | Cargill Supplier Engagement: https://www.cargill.com/sustainability/palm-oil/palm-supplier-engagement |
|---------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|
|                     | Indirect sourcing is where palm oil is purchased from local traders and refineries, or from independent smallholders, or “mills with whom we do not have a direct commercial relationship”. |                                                                                                   |
| Indonesian Oil palm | “Indirect mills listed represent mills supplied to Wilmar's third-party refineries, traders and/or bulkers.” | Wilmar Traceability Summary: https://www.wilmar-international.com/docs/default-source/default-document-library/sustainability/supply-chain/traceability-report-q3-2019---q2-2020/indonesia/mna-kualatanjung_201022.pdf?sfvrsn=2bb7b41d_2 |
| Indonesian Oil palm | “Direct supply: sourced directly from third-party mills.” “Indirect supply: procured from trading partners who in turn source oil from their own operations or third-parties.” | Bunge: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwjc5sb4trTuAhvN6OKHTVIB7AQFjAAegQIBRAC&url=https%3A%2F%2Fbungeloders.com%2Fassets%2F2020-05%2FBunge_Sustainable_Palm_Oil_Sourcing_Policy.pdf&usg=AOvVaw3pRI044nQnar1EZHzh4Veg |

Table S2.
Percentage of direct sourcing of the top soy traders in Brazil, comparing nationwide values vs. the initial 25 priority municipalities target as part of the Soft Commodities Forum (SCF). *Bunge only reports direct sourcing in priority municipalities (responsible for 23.4% of their soy sourcing in Brazil). COFCO reports their direct sourcing percentage only for Mato Grosso and Matopiba (70%), which together make up 39.6% of their soy sourcing in Brazil. Viterra reports their direct sourcing percentage only for the Cerrado (60.4%). The Cerrado makes up 42% of their soy in Brazil.

| Company | % direct sourcing, across Brazil | % direct sourcing in 25 priority municipalities - June 2019 report | % direct sourcing in 25 priority municipalities - December 2020 report | Change in direct sourcing from 2019-2020 reports |
|---------|---------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|-----------------------------------------------|
| Bunge   | Not disclosed*                  | 98%                                                           | 98.4%                                                         | Increase                                      |
| ADM     | 63                              | 93.4%                                                         | 88%                                                           | Decrease                                      |
| Cargill | 69                              | 96.6%                                                         | 97%                                                           | Increase                                      |
| COFCO   | Not disclosed*                  | 84%                                                           | 95.9%                                                         | Increase                                      |
| Viterra | Not disclosed*                  | 57.10%                                                        | 64.9%                                                         | Increase                                      |
| LDC     | 47                              | 100%                                                          | 100%                                                          | Increase                                      |
| Amaggi  | 79                              | Does not participate in SCF                                    | Does not participate in SCF                                   | Not applicable                                |
Table S3
Pixel classes used to identify cocoa-driven deforestation.

| Code | Classification                  |
|------|---------------------------------|
| 221  | Forest loss 2000-2015           |
| 212  | Forest-agriculture transitions  |
Table S4.
The mill-level sourcing and capacity of Wilmar’s palm oil processing facilities. Where a facility included statistics for crude palm oil, lauric acid, or kernel crushing separately, we report figures for crude palm oil. The figures for different products were similar and include overlapping mill suppliers. Source: (11).

| Company          | Processing facility                      | Mill type         | Percent supply per processing facility | Capacity (MT/year) |
|------------------|------------------------------------------|-------------------|----------------------------------------|--------------------|
| Wilmar           | PT Wilmar Nabati Indonesia, Padang       | Own mills         | 25.98                                  | 858000             |
| Wilmar           | PT Wilmar Nabati Indonesia, Padang       | Independent mills | 74.026                                 | 858000             |
| Wilmar           | PT Wilmar Nabati Indonesia, Gresik        | Own mills         | 5.79                                   | 3036000            |
| Wilmar           | PT Wilmar Nabati Indonesia, Gresik        | Independent mills | 94.21                                  | 3036000            |
| Wilmar           | PT Wilmar Nabati Indonesia, Balikpapan    | Own mills         | 0.00                                   | 950000             |
| Wilmar           | PT Wilmar Nabati Indonesia, Balikpapan    | Independent mills | 100.00                                 | 950000             |
| Wilmar           | PT Wilmar Nabati Indonesia, Pelintung     | Own mills         | 25.32                                  | 1980000            |
| Wilmar           | PT Wilmar Nabati Indonesia, Pelintung     | Independent mills | 74.67                                  | 1980000            |
| Wilmar           | PT Wilmar Cahaya Indonesia, Pontianak     | Own mills         | 51.80                                  | 214500             |
| Wilmar           | PT Wilmar Cahaya Indonesia, Pontianak     | Independent mills | 48.19                                  | 214500             |
| Wilmar           | PT Sinar Alam Permai, Kumai              | Own mills         | 1.80                                   | 990000             |
| Wilmar           | PT Sinar Alam Permai, Kumai              | Independent mills | 98.20                                  | 990000             |
| Wilmar           | PT Multi Nabati Sulawesi, Bitung         | Own mills         | 0.00                                   | 594000             |
| Wilmar           | PT Multi Nabati Sulawesi, Bitung         | Independent mills | 100.00                                 | 594000             |
| Wilmar           | PT Multimas Nabati Asahan, Pulo Gadung   | Own mills         | 0.00                                   | 82500              |
| Wilmar          | Plant Location                      | Type of Mill       | Percentage | Revenue (KRW) |
|----------------|-------------------------------------|--------------------|------------|---------------|
| Wilmar          | PT Multimas Nabati Asahan, Pulo Gadung | Independent mills | 100.00     | 82500         |
| Wilmar          | PT Sinar Alam Permai, Palembang     | Own mills          | 27.30      | 693000        |
| Wilmar          | PT Sinar Alam Permai, Palembang     | Independent mills  | 72.70      | 693000        |
| Wilmar          | PT Multimas Nabati Asahan, Kuala Tanjung | Own mills        | 12.71      | 1914000       |
| Wilmar          | PT Multimas Nabati Asahan, Kuala Tanjung | Independent mills | 87.29      | 1914000       |
| Wilmar          | PT Multimas Nabati Asahan, Paya Pasir | Own mills          | 0.00       | 450000        |
| Wilmar          | PT Multimas Nabati Asahan, Paya Pasir | Independent mills | 100.00     | 450000        |
| Wilmar          | PT Wilmar Nabati Indonesia, Dumai    | Own mills          | 26.53      | 1353000       |
| Wilmar          | PT Wilmar Nabati Indonesia, Dumai    | Independent mills  | 73.47      | 1353000       |
To identify the network of farms supplying each trader, we queried animal movement data (GTA) based on the suppliers to the following business registry numbers (CNPJ, Cadastro Nacional da Pessoa Jurídica in Portuguese), which were used to handle live cattle exports by each company.

| Trader                | CNPJs assessed                                      |
|-----------------------|-----------------------------------------------------|
| Minerva Global Foods  | 67620377000890                                      |
| Agroexport Trading    | 25333824000538, 25333824000376, 25333824000457, 25333824000961 |
| Bull Log Trading      | 20819178000176, 20819178000338                       |
| Mercurio Alimentos    | 11831785000160                                      |
Table S6
The percentage of live cattle traders’ sourcing which is classified as ‘direct’, depending on the cut-off used to define direct sourcing: either <20 or <100 cattle may be bought by a direct supplier, before it is considered part of the indirect supply chain.

| Trader                | Max 20 cattle bought by traders’ direct suppliers | Max 100 cattle bought by traders’ direct suppliers |
|-----------------------|--------------------------------------------------|--------------------------------------------------|
| Minerva Global Foods | 2.55%                                            | 3.59%                                            |
| Agroexport Trading    | 3.62%                                            | 6.48%                                            |
| Bull Log Trading      | 6.03%                                            | 12.10%                                           |
| Mercurio Alimentos    | 1.15%                                            | 2.77%                                            |
The 2020 profit of companies involved in landscape initiatives, as listed in the Consumer Goods Forum’s Forest Positive Coalition of Action 2021 annual report. We contrast the $70.6 billion that these companies declared in profit against the $9 million they invested in landscape programs (ca. 0.0128% of annual profit). This number excludes figures for Mars, for whom no public data on profit are available, because they are a privately-owned company. CR = conversion rate to USD, based on currency values in January 2022.

| Company              | Net Profit | Currency | CR  | USD (billion s) | Source:                                                                 |
|----------------------|------------|----------|-----|-----------------|-------------------------------------------------------------------------|
| Carrefour            | 6.41E+08   | EUR      | 1.13| 0.72433         | https://www.retaildetail.eu/en/news/food/carrefour-sees-record-performance-2020 |
| Colgate-Palmolive    | 1.02E+10   | USD      | 1   | 10.17           | https://www.macrotrends.net/stocks/charts/CL/colgate-palmolive/gross-profit |
| Danone               | 2.23E+09   | USD      | 1   | 2.234           | https://www.macrotrends.net/stocks/charts/DANOVY/danone/net-income      |
| General Mills        | 3.14E+09   | USD      | 1   | 3.14            | https://www.statista.com/statistics/261177/operating-profit-of-general-mills-worldwide/ |
| Grupo Bimbo          | 9.11E+09   | MEX      | 0.04| 0.42817         | https://www.statista.com/statistics/796990/net-income-bimbo-worldwide/    |
| Jerónimo Martins     | 3.12E07    | EUR      | 1.13| 0.35256         | https://econews.pt/2021/03/03/jeronimo-martins-posts-a-net-profit-of-e312m-in-2020/ |
| Mars                 | NA         | USD      | 1   | NA              |                                                                         |
| Mondelxz             | 1.04E+10   | USD      | 1   | 10.466          | Net revenue: https://ir.mondelezinternational.com/news-releases/news-release-details/mondelez-international-reports-q3-2021-results |
| Nestlé               | 1.22E+10   | CHF      | 1.09| 13.298          | https://www.statista.com/statistics/268889/net-profit-of-the-nestle-group-worldwide/ |
| PepsiCo              | 7.00E+09   | USD      | 1   | 7               | https://www.statista.com/statistics/242288/global-net-income-of-pepsico/  |
| Reckitt              | 1.20E+09   | GBP      | 1.33| 1.59999         | https://finbox.com/LSE:RKT                                               |
| Tesco                | 9.73E+08   | GBP      | 1.33| 1.29409         | https://www.tescopl.com/investors/reports-results-and-presentations/financial-performance/five-year-record/ |
| Company   | Value   | Currency | Price | Percentage | Link                                               |
|-----------|---------|----------|-------|------------|----------------------------------------------------|
| Unilever  | 6.38E+09 | USD      | 1     | 6.375      | https://www.macrotrends.net/stocks/charts/UL/unilever/net-income |
| Walmart   | 1.35E+10 | USD      | 1     | 13.51      | https://www.macrotrends.net/stocks/charts/WMT/walmart/net-income  |