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LETTER

Balancing detail and scale in assessing transparency to improve the governance of agricultural commodity supply chains

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Abstract

To date, assessments of the sustainability of agricultural commodity supply chains have largely relied on some combination of macro-scale footprint accounts, detailed life-cycle analyses and fine-scale traceability systems. Yet these approaches are limited in their ability to support the sustainability governance of agricultural supply chains, whether because they are intended for coarser-grained analyses, do not identify individual actors, or are too costly to be implemented in a consistent manner for an entire region of production. Here we illustrate some of the advantages of a complementary middle-ground approach that balances detail and scale of supply chain transparency information by combining consistent country-wide data on commodity production at the sub-national (e.g. municipal) level with per shipment customs data to describe trade flows of a given commodity covering all companies and production regions within that country. This approach can support supply chain governance in two key ways. First, enhanced spatial resolution of the production regions that connect to individual supply chains allows for a more accurate consideration of geographic variability in measures of risk and performance that are associated with different production practices. Second, identification of key actors that operate within a specific supply chain, including producers, traders, shippers and consumers can help discriminate coalitions of actors that have shared stake in a particular region, and that together are capable of delivering more cost-effective and coordinated interventions. We illustrate the potential of this approach with examples from Brazil, Indonesia and Colombia. We discuss how transparency information can deepen understanding of the environmental and social impacts of commodity production systems, how benefits are distributed among actors, and some of the trade-offs involved in efforts to improve supply chain sustainability. We then discuss the challenges and opportunities of our approach to strengthen supply chain governance and leverage more effective and fair accountability systems.

1. Introduction

Internationally traded agricultural commodities—such as soy, oil palm and beef—are a multi-billion-dollar segment of the global economy, driving development in both producer and consumer countries as they move along complex international supply chains into nearly every economic sector. But production of these commodities, especially in developing countries throughout the tropics, is often linked to heavy social and environmental impacts. In response, governments, consumers, investors and companies themselves are demanding greater levels of sustainability in the production and trade of these commodities, increasingly in the form of zero deforestation 2020 commitments (e.g. UN 2014). One of the greatest obstacles to progress on such commitments is the poor state of supply chain transparency with the places and actors that make up complex supply chains remaining hidden. Without a rapid step-change in understanding the web of supply chain connections, and how these connections can be coupled with recent improvements in monitoring of impacts on the ground, the achievement of deforestation-free supply chains will be put at serious risk and will be seen as unrealistic, and the vital political momentum around the 2020 commitments could be lost (Bregman *et al* 2015).

Despite the urgency of this challenge, the existing toolkit of approaches for assessing the sustainability of agricultural commodity supply chains is insufficient for guiding practical decision making around commodity production, sourcing and investment—either because they are not designed for this purpose (e.g. coarse-grained conventional footprint accounting) or because they are too expensive or complex to scale-up in a consistent manner to entire regions or commodities (e.g. life-cycle analyses (LCA) and detailed traceability systems).

For example, globally applicable national-level footprint measures that estimate the environmental impacts of consumption, such as the ecological footprint (Wackernagel *et al* 1999, Kissinger 2013) and the water footprint (Mekonnen and Hoekstra 2011, Ewing *et al* 2012) have proven very effective in raising awareness about the displaced impacts of the consumption of nations. However, they have limited practical utility for guiding the management of specific supply chains because of their coarse-grained resolution of production and supply chain dynamics. Footprints typically assess the environmental impacts of the consumption of traded commodities at the scale of an entire country, and thus only provide aggregate proxies of impact that mask sub-national heterogeneity and often require regionally distinct environmental impacts to be combined into single indices (Finger 2013, Giampietro and Saltelli 2014). In addition footprints have traditionally attributed most of the impacts of production, transport and processing to the end consumers, bypassing the role played by intermediate actors (Lenzen *et al* 2007, Sonnino *et al* 2014), many of which may be more influential in transforming supply chains than individual end consumers (e.g. such as traders; WWF 2012).

In contrast to macro-level consumption footprint analyses there are a number of more targeted approaches to understanding the sustainability implications of a commodity supply chain such as company and product-specific life cycle analyses (LCA and social LCA: Curran 2012, Rocha *et al* 2014, Mol and Oosterveer 2015) and full chain-of-custody traceability systems (Beske *et al* 2014, O'Rourke 2014). Such approaches are highly variable yet are capable of providing a lot more detail regarding both the types of environmental and social impact that are associated with different stages of a product's life cycle (through product specific LCA) as well as the specific localities of production (through detailed traceability systems). LCAs are not focused on a complete global commodity chain but rather on inputs from samples or averages of the several pathways that are characteristic of given type of supply chain, and therefore are unable to capture the diversity of links between places, actors and impacts. Chain of custody traceability systems, like many LCAs, are also commonly limited by high costs (Menrad *et al* 2012, Waldman and Kerr 2014), and their bespoke nature—meaning that they are very unlikely to provide a feasible and adequate solution for assessing multiple supply chains as related to a specific commodity, actors or production region. Indeed, to date the high cost of dedicated traceability systems has limited their use to a small number of flagship enterprises driven by front-runners with financial capital and willingness to act (Nikolakis and Innes 2014). Moreover, the fact that such systems do not, by definition, encompass the majority of the trade in a given commodity makes it impossible to track the levels of risk and performance associated with an entire sector (e.g. Brazilian soy), undermining confidence in the utility of such data given the risks of leakage and the need to deliver net positive lasting impacts on the ground, irrespective of the performance, size or sustainability policies of the particular actors involved.

Here we propose a middle-ground approach which balances detail and scale in transparency information by combining the untapped potential of customs data, with emerging methods to analyze global trade material flows (Kastner *et al* 2011, Henders *et al* 2015) and high-resolution production data to trace producer to consumer linkages in a consistent and cost-effective manner across entire countries and commodity sectors. This inherently jurisdictional approach is complementary to existing approaches to assessing the sustainability of commodity supply chains and can help provide actionable information, for example to improve sourcing and production practices, without requiring costly dedicated tracking systems for each individual supply chain.

We present the data and methods that illustrate the advances offered by this approach together with brief examples from major agricultural commodities in South America (soy, coffee) and Indonesia (palm oil). We then discuss how such advances can increase understanding of (i) the environmental and social impacts of commodity production systems; (ii) the ways in which both the impacts and benefits associated with commodity production can be attributed to different actors involved in the production, trade and consumption of that commodity; and (iii) the trade-offs involved in any attempt to improve the sustainability of the system. Finally, we draw on these observations to discuss challenges and opportunities of using these kinds of commodity transparency and performance data to help deliver a genuine step-change in the adoption of more effective and fair accountability and due diligence systems.

2. Balancing detail and scale in supply chain transparency: connecting places to actors

The rise in publically available or purchasable data on sub-national (districts, provinces) production systems, national customs and export data, and earth observation remote-sensing systems (see SI text and table SI1 for data sources), provides the basis for a step-change in our understanding of producer to consumer linkages and associated impacts at a scale that is relevant to supply chain management. This largely unexplored middle-ground between national-scale footprints and resource-intensive LCA or traceability systems depends upon advances in two important areas:

(i) Enhanced spatial resolution of supply chain connections, allowing for a more accurate consideration of geographic differences in risk and performance that are associated with different regions of production.

(ii) Identification and mapping of supply chain actors, helping to identify coalitions of actors that have a shared stake in a particular region, and that together could be capable of delivering a more cost-effective and coordinated response to sustainability concerns.

We present emerging methods for progressing in these two areas to deliver enhanced material flow analyses. We illustrate the potential for a more detailed understanding of the key locations and actors that make up a commodity supply chain through the use of detailed production, demand, customs and international bilateral trade data in the SEI-PCS tool (Godar *et al* 2015). SEI-PCS is a material-flow method to trace physical quantities of the commodity of interest along the supply chain, from a specific sub-national production region (e.g. municipalities or provinces) to the country of first consumption (Kastner *et al* 2011). When input with detailed custom declarations it traces the place of production, exporter company, shipping company, importer company, country of first import and the country of first consumption. In countries where all the necessary data are not available spatial allocation modeling is used to connect ports and sub-national production regions, allowing for a flexible and nested approach depending on data availability (see SI text for more details and table SI1 for datasets used here).

A key advantage of enhanced material flow approaches, such as SEI-PCS, is their capacity to trace material flows (e.g. in tones) while also retaining information on the involvement of specific supply chain actors (e.g. exporters, importers), for example using individual shipment customs data. As such they have particular utility for companies, governments and investors who play a direct role in the governance of international supply chains. Volumes of the original commodity embedded further down the supply chain can be traced by combining with material flow analyses of those subsequent supply chains, or potentially by additional modeling such as through input–output economic models (Hubacek and Feng 2016).

2.1. Enhanced spatial resolution of supply chain connections

Deciding on the level of spatial disaggregation, including the location of production regions necessary to adequately assess the sustainability of a supply chain, involves balancing the effort required to acquire finer-scale data with the spatial scale of heterogeneity in production practices and measures of sustainability risk and performance. For example for the case of Brazil, which is one of the world's leading exporters of farming commodities as well as the host to some of the world's highest levels of biological and socio-cultural diversity, mapping the municipal sourcing of globally consumed soy for different countries reveals key differences in risks and performance associated to different supply chain actors (figures 1(a) and (b)). For example, Chinese consumption of Brazilian soybeans in 2012 (24.6 Mt of soybean equivalents) was more concentrated in the south and southeast regions and in western Cerrado, while EU consumption (11.5 Mt of soybean equivalents) depended more on soy from the rapidly deforested northern Cerrado and along the Cerrado–Amazon frontier in Mato Grosso and the southern Amazon. The EU consumes most of the soy produced in the central and eastern Amazon, where soy expansion on forested land is limited by the Amazon soy moratorium (Gibbs *et al* 2015). Achieving this higher level of spatial resolution is necessary to unlock the huge potential of recent advances in earth observation data (e.g. http://globalforestwatch.org, http://earthengine.google.com) and spatially explicit information on socio-economic conditions and governance systems (e.g. Medina *et al* 2015).

2.2. Identification and mapping of supply chain actors

The role of different actors in a supply chain can often be identified directly from commercially available imports and exports documents (e.g. custom declarations and bills of lading[6]) or other sources such as sectorial reports and national customs databases summarizing trade information (e.g. from commercial invoices and certificates of origin). These

[6] A legal document between the shipper of a good and the carrier detailing the type, quantity and destination of the good being carried. The bill of lading is a receipt of shipment when the good is delivered to the predetermined destination. This document must accompany the shipped goods, no matter the form of transportation, and must be signed by an authorized representative from the carrier, shipper and receiver (http://investopedia.com/terms/b/billoflading.asp). This information is commercially available for various countries.

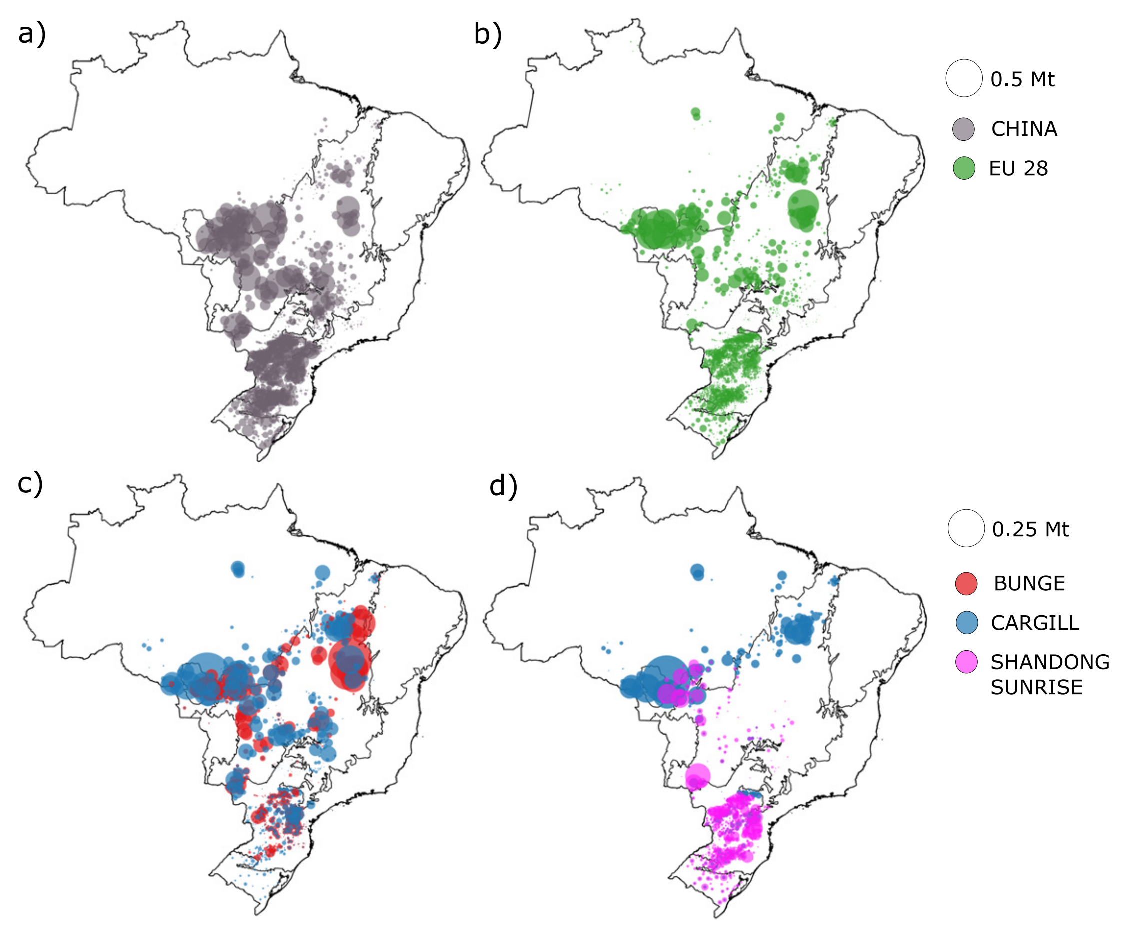

Figure 1. Estimated municipal origin of the Brazilian soy produced in 2012 that is (a) consumed in China, (b) consumed in the European Union (28) (c) exported by the two main traders (d) imported by two of the main global traders. Circle areas are proportional to quantity traded and consumed. The six Brazilian biomes are delineated to illustrate the differential sourcing from areas with very different environmental characteristics. All values are in soybean equivalents, encompassing exports of soybeans, soy cake, soy oil and soy sauce. The two main exporters (c) and two of the main importers (d) are drawn from a total of over 300 companies based on detailed exports declarations.

standardized datasets can be supplemented by additional information from intermediaries, such as multinational traders, who usually record the details of their trades, as well as from governments recording traceability data for various purposes (e.g. taxes, health and food security). See table SI1 for a list of databases used in the examples. Information on the spatial location of production regions and the identity of actors can be combined to reveal patterns associating different actors with different places. For example, in the Brazilian soy sector, older and more consolidated traders (such as Bunge, currently the largest exporter of Brazilian soy in 2012) are better established in the southern regions, whilst relative latecomers (e.g. Cargill) have a more dominant role in the Amazonian frontier (figure 1(c)). Infrastructure facilities are key in driving the development of specific supply chains, e.g. as linked to the port of Santarem in the Amazon river which is owned by Cargill, underpinning their dominance in the central Amazon as well as areas supplying that port (e.g. western Mato Grosso and Rondônia through the Madeira river). Revealing these connections can help identify associations between key places and actors and the potential leverage points that such associations present, such as the particular relevance of the Amazon soy moratorium to Cargill.

Companies may operate solely as exporters in the country of production, as shipping companies or as global importers of goods, or be involved in operations at several or all of these stages. Two of the main global importers of Brazilian soy (figure 1(d)) sourced from distinct regions in 2012. Nearly two-thirds of the Brazilian soy imported to other countries by Cargill is also exported from Brazil by Cargill, and sourced mostly from the Amazon biome and the States of Mato Grosso, Paraná and Maranhão. However most of Cargill's exports (68%) are sold to a total of 59 other importers, many of which are in China or elsewhere in Asia. Dependency between major players is often complex, e.g., although Shandong Sunrise—one of the biggest global soy importers—sources its soy mainly from long-settled soy areas in south and southeast Brazil, distinct from those areas where Cargill imports from, Shandong Sunrise has Cargill as its main single provider of soy (14.5% of its imports in 2012).

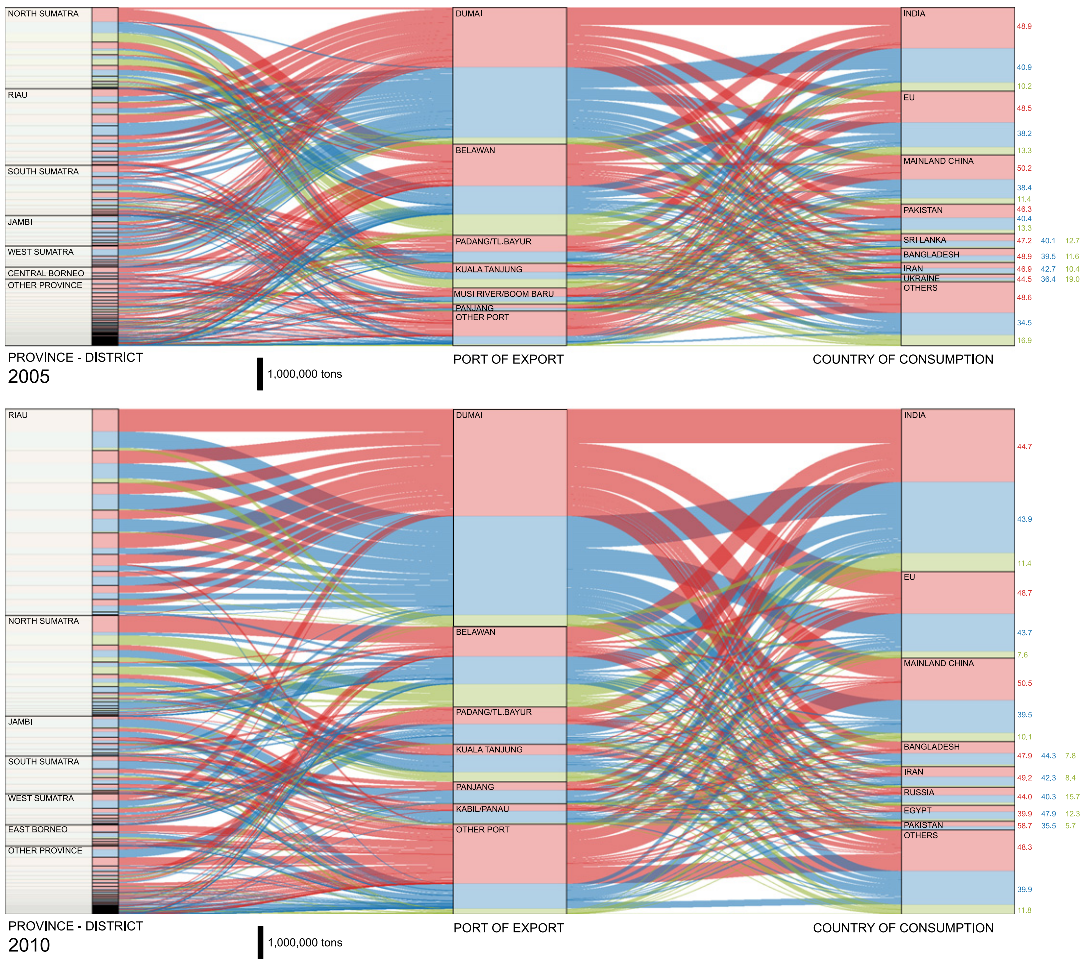

Figure 2. Simplified supply chain of Indonesian palm oil in 2005 and 2010, detailing the ownership of the oil palm plantations (red: private enterprises, blue: smallholders, green: state-owned) in all 121 districts producing oil palm, and how they are connected to 125 ports and other export facilities, and countries of consumption. Numbers at the right indicate the percentage of consumption in each country supplied by the three forms of plantation ownership.

It is also possible to visualize changes in connections between supply chain actors and places over time (and therefore exposure of those actors to geographic differences in production practices and environmental and social risks). In the case of Indonesian palm oil it is possible to see, for example, that India, China and the EU considerably increased both their total imports (by 94%, 70% and 36%, respectively) and share of sourcing from smallholder farmers (by 3%, 1.1% and 5.5 % respectively) between 2005 and 2010 (figure 2). By contrast palm oil exports from East Borneo come mainly from private company's landholdings and are exported predominantly to China and other Asian countries. 47% of the palm oil in 2010 was shipped through the ports of Dumai, Belawan and Kuala Tanjung, all situated in northeastern Sumatra, indicating the potential for locally targeted monitoring systems to make a significant contribution to the transparency and governance of the Indonesian oil palm sector.

Analyzing the example of trade in Colombian coffee from the demand side (figure 3), it is possible to see that the top 20 global importers comprised 33% of total exports in 2010 and 46% in 2014, achieving increasing market consolidation over time. Imports into the United States, the major buyer of Colombian coffee, are consolidated in the hands of few corporations, with 20 importers accounting for 67% of total imports, whilst by contrast the EU relies on a much larger number of traders (the same 20 top importers account for just 26%). Once again it is possible to identify key shifts in sourcing patterns over time. For example, the European-based Rothfos conglomerate was the main importer of Colombian coffee in 2010, but was replaced by Starbucks in 2014—which greatly diversified its procurement, including from many small cooperatives in line with its commitments to responsible sourcing. Despite the spatial-temporal complexity of these coffee supply chains, some dominant producer–consumer linkages stand out, connecting, for example in 2014, the Nariño province, the exporter Carcafe Ltda and importer Starbucks to the US through the port of Seattle. Identifying such connections is a key step in simplifying what can otherwise be an overwhelmingly complex system, helping to

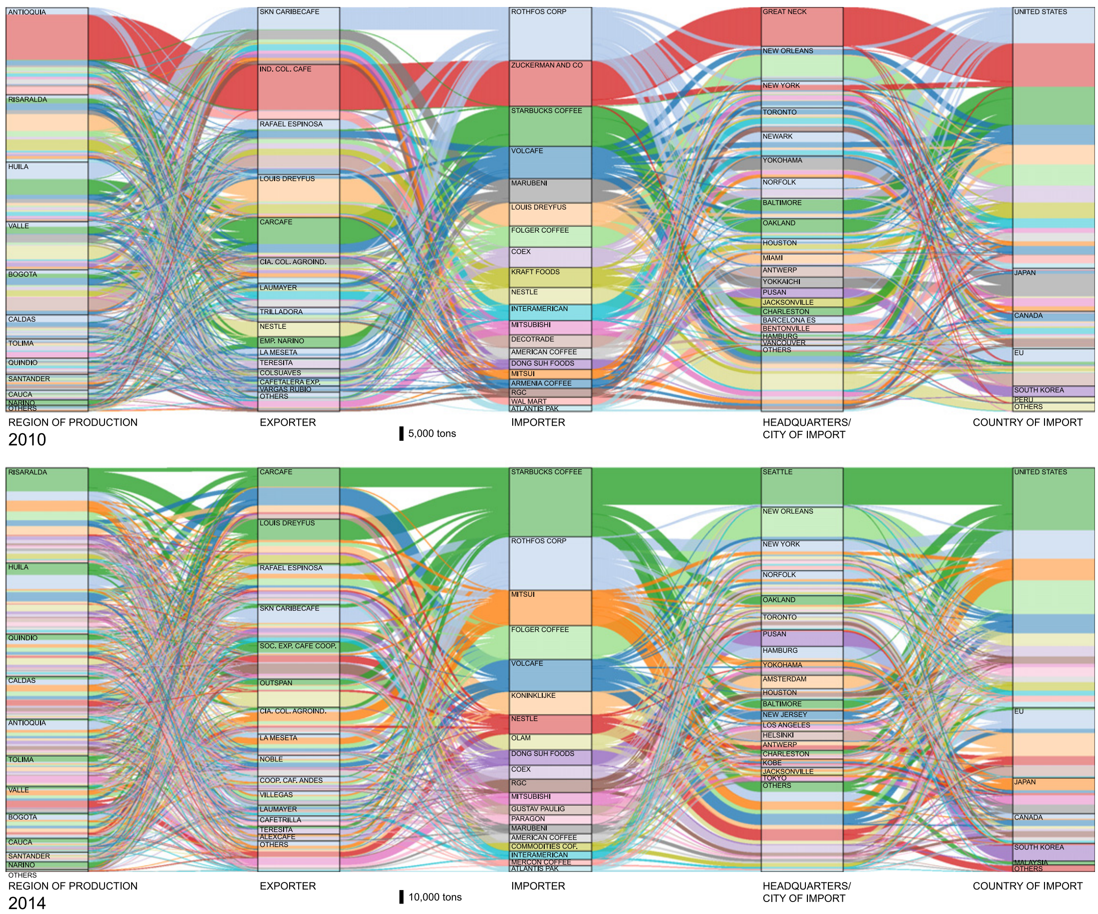

Figure 3. Simplified description of the supply chain of the 20 largest importers of Colombian coffee in 2010 and 2014, illustrating connections between the region of production, export and import companies, and the city and country of import. Colors of flows correspond to the coffee that is handled by different importers.

reveal potentially critical entry points and coalitions of supply chain actors that can work together to improve regional governance.

3. Balancing detail and scale in supply chain transparency: applications and limitations

Achieving a more fine-grained mapping of the links between entire production regions and supply chain actors, whilst avoiding the need for the kind of highly detailed traceability work that is necessary to separately link individual producers to specific downstream actors, provides a powerful basis for better understanding opportunities to improve the sustainability governance of supply chains. Here we illustrate three opportunities for such an improved understanding: (i) a more accurate assessment of the environmental and social risks that are embedded in the consumption and trade of agricultural commodities; (ii) revealing differences in the impacts and benefits associated with the production and trade of commodities by specific supply chain actors; and (iii) improving the understanding of the trade-offs associated with interventions to improve the governance of commodity supply chains.

3.1. More accurate large scale assessments of the environmental and social risks embedded in the production of traded commodities

Accurate assessments of the environmental and social risks and performance associated with the production of internationally traded agricultural commodities are central to ongoing debates regarding the sustainability of different land uses, e.g. biofuels (Gerbens-Leenes *et al* 2009, Hoefnagels *et al* 2010). Having the capacity to scan and discriminate different levels of social and environmental impact that are associated with different production regions of a given commodity, and in turn represent different levels of risk exposure for the supply chain actors and consumers that are connected to those regions, is critical to the design of more sustainable sourcing strategies, e.g. by traders and consumer nations. Beyond improving the accuracy of national footprint assessments by accounting for spatial heterogeneity in a country's socio-environmental dimensions (Godar *et al* 2015), high levels of sub-national variability in environmental impacts (e.g. illegal deforestation) mean that actors connected to different production regions can be exposed to very different levels of risk. The middle-ground approach to assessing supply chain transparency that is put

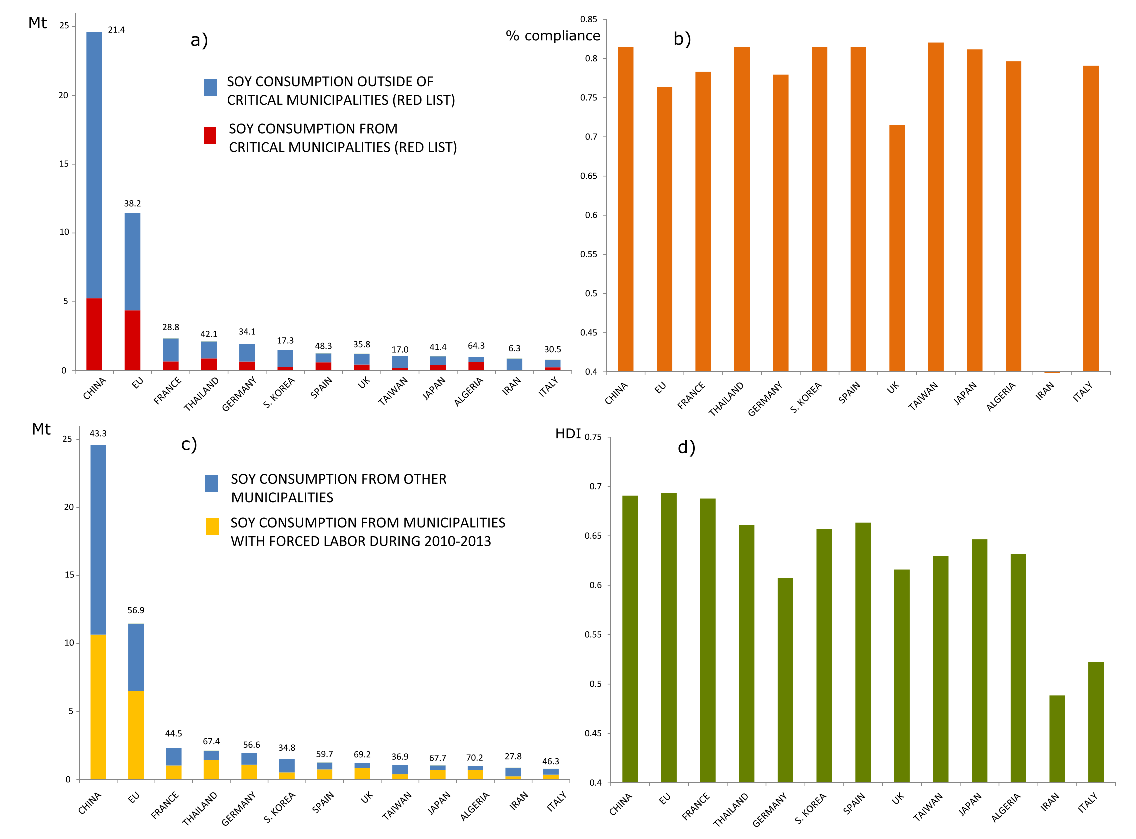

Figure 4. Example indicators of the environmental and social performance of municipalities producing the soy consumed by the main global consumers of Brazilian soy in 2012. (a) Total soy consumption and share sourced from the critical deforestation list by the Brazilian Ministry of the Environment by 2012. (b) Average compliance with the Rural Environmental Registry System (CAR) (percentage of compliant area versus total), calculated only for the State of Pará due to data availability, weighted by the proportion of soy sourced from each municipality. (c) Total soy consumption and share sourced from municipalities with records of forced labor between 2010 and 2013. (d) Average human development index in the municipalities from which soy is sourced, weighted by the proportion of soy sourced from each municipality. Data from the Brazilian Statistics Institute (IBGE).

forward in this paper offers a major step forward in filtering this complexity.

For example, in 2012 the EU sourced more Brazilian soy from municipalities included in the list of critical deforestation municipalities established by the Brazilian Ministry of the Environment (38.2% of EU's total imports), compared to China (21.4%) or any other of the top consumer countries (figure 4(a)). EU consumption also depended on municipalities with lower average levels of compliance with the Brazilian Rural Environmental Registry (CAR in Pará State, figure 4(b)) and a higher proportion of official records of forced labor infractions (figure 4(c)). By contrast, however, the EU also sourced from municipalities with better than average development conditions than most other consumer countries, as measured by the human development index that combines measures of life expectancy, education, per capita income. These contrasts highlight the complexity of such impact and risk assessments, the need to zoom in to the highest available spatial resolution, and to consider multiple indicators of territorial performance to guide decision making.

3.2. Revealing the benefits and risks associated with commodity production and trade by specific supply chain actors

Different actors benefit differently from the production and trade of a given commodity, and are varyingly capable of influencing how that supply chain, and any environmental and social risks that may be associated with it, are governed (West *et al* 2014). Untangling the differentiated levels of benefit (e.g. through differences in monetary gain) and risk experienced by different supply chain actors can help guide approaches to addressing sustainability concerns. More specifically, efforts to unpack the ways in which a broad range of actors participate in a supply chain, beyond just producers or final consumers, can play a pivotal role in raising awareness, identifying entry points for effective interventions and fostering a more coordinated, polycentric approach to supply chain governance (Ostrom 2010). The data and methods described in this paper greatly increase our ability to identify the actors involved in a given supply chain. These insights provide a critical first step towards discriminating differences in the types and levels of benefit enjoyed by each actor, and in turn how different levels of benefit

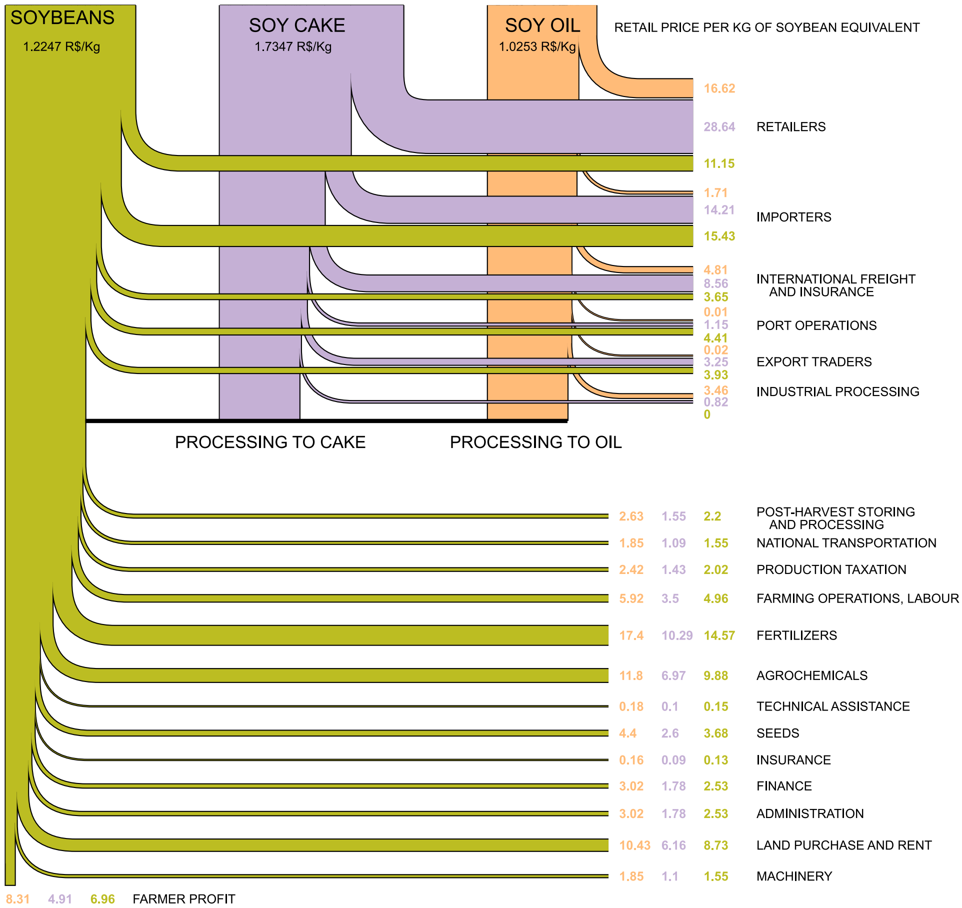

Figure 5. Income distribution analysis revealing the different actors and sectors along the supply chain that benefitted from the production of Brazilian soy in 2012. Numbers to the right represent the percentage of each step in the supply chain of the final retail price per original kilogram of soybeans needed to create the final product. The income received by each beneficiary is only a proxy of the monetary benefits as costs have not been accounted for. Retail and importers income, together with production costs, account for the majority of the price gap between the final retail price and the price at which farmers sell the harvested soy. The data corresponds to specific illustrative pathways of traded soybeans, and do not reflect the proportions of soybeans that were transformed into cake or soybeans in 2012.

are aligned with differences in the levels of impact and risk that can be associated with the activities of the same actors.

A simple, illustrative approach to estimating differences in the levels of benefit enjoyed by different actors is to approximate the share of total income generated by the production and trade of a commodity that is received by different actors along that supply chain. Other non-monetary dimensions could also be used to attribute different levels of benefit to actors, including proxies for corporate or regulatory influence such as dominance in certain steps of the supply chain (e.g. monopolistic or monopsonistic positions), market share, or volume of investments, in addition to co-benefits created for other actors, e.g. through job creation or tax revenue. We illustrate a simple income distribution analysis by discriminating the gross income received by different actors through a value chain analysis (Fitter and Kaplinksy 2001, Rueda and Lambin 2013), using databases on both costs (e.g. production cost, transportation, storing and processing), and prices (e.g. farm gate sales, free on board, cost insurance and freight, wholesale and retail prices) along a selected subset of the Brazilian soy supply chain in 2012 (figure 5 and SI text). While merely illustrative, this analysis offers a powerful and complementary lens to material flow analyses (e.g. figures 2 and 3) in describing the diversity of actors that benefit from the production and trade of a given commodity and in providing a first appreciation of the level of income received by each actor.

The kind of enhanced material flow analyses presented here also underpins a marked improvement in our ability to associate different supply chain actors with different levels of environmental and social impacts, and hence potential risks and responsibilities in regions of production. For example, associating the amount of deforestation in municipalities producing soy to the actors trading this soy makes it possible to identify different levels of exposures of companies and other actors to risks of trading or consuming soy that may in some way be associated with deforestation (figure 6). For example, Cargill is potentially submitted to a high level of risk because of its high level of

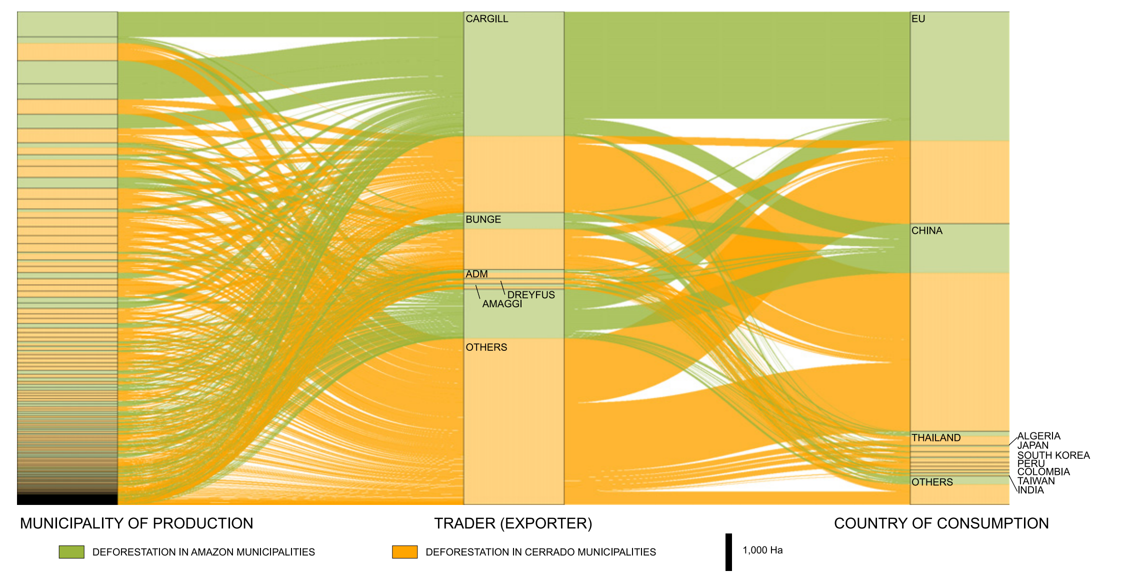

Figure 6. Risk exposure to Amazonian and Cerrado deforestation of exporters and consumer countries involved in the Brazilian soy supply chain, 2012. Flows represent km^2 of deforestation in the production municipalities, calculated from the proportions of volumes traded/consumed by companies and countries per municipality of production. Deforestation data obtained from INPE (2015) for the Amazon, and LAPIG (2015) for the Cerrado.

involvement in the Amazon biome, although this risk is mitigated by the soy moratorium (Gibbs *et al* 2015). In the Cerrado biome, where soy expansion is a main driver of current deforestation, linking different traders to different regions of production can reveal very different levels of risk exposure. For example, in the municipalities of the Cerrado from which Cargill exports soy the deforestation risk per ton of soy exported is four times larger than for municipalities from which Bunge sources soy. This crude analysis should only be seen as a risk scanning exercise and does not in any way imply direct attribution. Analyzing the attribution of risks to different actors requires accounting for other land-uses and drivers of deforestation, as well as the role of all other actors (Davis *et al* 2014, Henders *et al* 2015), which is a logical extension of our approach out of the scope of this paper.

3.3. Improved understanding of multiple impacts, trade-offs and opportunities in the management of commodity production systems

Spatially explicit information linking specific places and supply chain actors to the range of specific environmental and social risks, impacts and benefits, current sustainability governance systems, and socio-economic development characteristics of individual production regions provides for more locally and management relevant analyses (figures 4 and 6). Such analyses can, in turn, help guide efforts to improve the sustainability of commodity production systems, e.g. by providing a benchmark for assessments of alternative investments and management decisions, and helping identify trade-offs and opportunities regarding where and how commodities are produced. For example, shifting production away from carbon-rich areas where clearance of native vegetation produces high emissions may result, unexpectedly, in greater impacts on biodiversity—as is the case of soy expansion in the Brazilian Cerrado, which has less above-ground biomass than the Amazon but is a more threatened ecosystem. By contrast, targeting increased production to areas that are already cleared may appear a logical solution, but outcomes depend on the relative prevalence of good management practices (e.g. certified properties), conditions for rural development (e.g. access to infrastructure and services), potential for leakage and other dimensions that together can help foster more sustainable development pathways.

3.4. Challenges in developing an operational supply-chain transparency system for the production and trade of forest-risk commodities globally

There are at least four major challenges to operationalizing and scaling up the enhanced material flow analyses presented in this paper which are shared by any supply chain transparency system: the resources required; the mapping of domestic supply chains; the ability to track potential leakage and indirect effects; and the coupling of supply chain mapping data with data on environmental and social impacts in regions of production.

The data necessary to develop a global supply chain transparency system, building on the kind of enhanced material-flow analyses approaches presented in this paper (critically, sub-national production data and customs declarations), can be acquired for at least tens of producer countries. These countries include many of the larger production and export countries and account for the majority of global trade for many of the world's most important farming commodities (e.g. soy, beef, palm oil). For at least those countries data can potentially be acquired for virtually any commodity. Yet, variability in data formats, relatively high acquisition costs and in some cases the time necessary to compile relevant secondary data sets for model development and validation constitute noteworthy barriers to implementation. That said, these barriers are marginal compared with the enormous costs of the myriad bespoke traceability systems currently being developed by in isolation by hundreds of companies and certification bodies, not to mention the complexity of scaling up those systems to provide comparable coverage of different actors and commodities for entire countries or regions.

The modeling approach presented here—an extended version of the SEI-PCS model of Godar *et al* (2015)—is focused on exported commodities. In the case of commodities where domestic consumption is of comparable or greater importance to exports, such as Brazilian beef, additional information and approaches are necessary, such as increasingly available data on national taxation, national shipments, sanitary and disease controls of transported goods and transaction data of private enterprises.

A general challenge of any supply-chain transparency and traceability system is that interventions to improve the sustainability of production practices in a specific location may only lead to a diversion of products originating from that place to other buyers, or to a displacement of undesired impacts (e.g. deforestation) to other locations (i.e. leakage), thus limiting or negating any overall net benefits (Meyfroidt and Lambin 2009). In contexts where all production is fully fungible and buyers source their products indifferently from one place to another, tracing the flows and actors down to the very local level may have limited usefulness for mitigating overall impacts, which primarily depend on the overall level of consumption of a given product. Yet in most cases, there is a certain degree of inertia in trade relations (Villoria and Hertel 2011), and producers are at least partly tied to a particular set of buyers, so that interventions from downstream actors can have a meaningful impact on production practices. The kind of enhanced material flow approach presented here can help improve our understanding of patterns of relative inertia in trade relations (Godar *et al* 2015), including, for example, by providing information on production and corporate dynamics for a full set of inter-linked supply chains (e.g. to detect leakage and understand transboundary dynamics of soy production and trade in Brazil, Paraguay, Argentina and Bolivia considered as a whole, (le Polain *et al* 2016)).

Finally, the practical relevance of any supply chain mapping exercise for addressing sustainability concerns is determined, in part, by the coupling of commodity flows between actors and places with data on environmental and social features that characterize those places. This challenge is lessoned by the boom in availability of near real-time earth observation data and other statistical data on environmental and social risks (e.g. deforestation and land-use change, water scarcity, biodiversity significance, carbon emissions, food security and employment and revenue opportunities), but requires further research on methodologies and standards to credibly attribute different impacts in specific jurisdictions to different actors.

4. Discussion

Despite the ongoing development of different approaches to assess the sustainability of international commodity supply chains, the governance of these systems continues to be severely hindered by a lack of clear and feasible implementation strategies to deliver on aspirational sustainability goals at scale. This situation is manifest in zero deforestation and zero degradation supply chain commitments made by some multinational companies and governments (e.g. the New York Declaration on Forests (UN 2014)). For most commodities, the persistent uncertainty around the nature of the connections between producer to consumer systems and socio-environmental concerns casts significant doubt over the feasibility of these commitments. Moreover, these uncertainties may undermine the effort of front-runners, thereby eroding the credibility and power of the market to leverage private and public sector action. Current approaches to understanding supply chain connections, and embedded social and environmental impacts and risks, are insufficient to adequately address the scale of this challenge.

Here we advocate the complementary benefits of a new approach to assessing the sustainability of international trade in agricultural commodities based on enhanced material flow analyses and hitherto untapped data on sub-national production and international trade. This 'middle-ground' approach has the advantage of being able to specify individual production regions and supply chain actors that is not possible through macro-economic footprint analyses or standard material flow methods, while remaining more feasible and cost-efficient to deliver at scale than highly detailed commodity and user-specific LCAs and supply chain traceability systems.

The kinds of transparency information and methods illustrated here can underpin a strengthened jurisdictional approach that can be used to leverage improvements in the sustainability of supply chain governance on multiple, inter-related levels.

First, they can support private and public sector procurement decisions, as well as decisions over financial investments, by identifying exposure of different actors to broad categories of risk associated with the production system—including reputational risks, regulatory compliance, and other social and environmental risks that could undermine the viability of long-term business models.

Second, this kind of middle-ground approach that balances detail and scale can greatly facilitate the involvement of a wider range of actors in efforts to improve the sustainability of production systems. Our approach and data encompasses all production regions and traders irrespective of volumes produced and traded or levels of commitment to achieve sustainability goals, and does so without depending on confidential data of individual private sector actors. Regional jurisdictions constitute a meaningful scale to connect producer–trader–consumer relationships with sustainability concerns for multiple reasons, including the limited availability of data at finer spatial scales (e.g. individual properties), the need for cost-efficient approaches to scanning risks and triaging areas that demand more detailed analyses, and the importance of aligning private and public sector efforts to strengthen territorial and supply chain governance. Efforts to identify synergies with policies beyond the narrow realm of supply chains, such as pro-poor and food security policies, conservation, national development policies (employment, health, education), and local and traditional knowledge systems, can further reduce operating costs of all actors and strengthen public–private partnerships that connect supply chain actors with broader public policy agendas around land-use sustainability in that jurisdiction.

Third, the approach we present here can also provide a powerful basis to support the monitoring, reporting and verification activities of private, public or civil society actors involved in a supply chain. By encompassing the total production of a given region and commodity, as well as the participation of all actors involved in the export of that commodity, such a middle-ground approach provides a feasible, standardized, comprehensive and rapidly deployable framework for tracking changes in the overall performance of key territories, and the way in which key actors are associated with such changes.

A transparency and territorial performance platform that combines supply chain mapping capabilities with information not only on environmental and social risks in production regions but also information on the performance of different actors (e.g. levels of certification) and enabling conditions for good governance more generally, would provide a key decision support capability that complements and helps upscale the supply chain tracking and traceability systems currently under development. An online transparency platform (Transformative Transparency Platform, https://ttp.sei-international.org/) is under development as a program to help address this need and visualize and process the kinds of data and middle ground approach presented in this paper (Gardner *et al* 2015, Suavet 2016).

Whilst important, the advances and opportunities presented in this paper constitute only one component of a broader framework of conditions and capabilities needed for improved supply chain sustainability. Better transparency is merely a key precondition for better supply chain governance, meaning that such a framework also needs to facilitate the uptake and use of transparency information to foster more fair and effective accountability and due diligence systems, and identify the additional factors that are necessary to deliver practical advances in land-use and supply chain sustainability. A significant amount of work is needed to develop this framework and to understand more broadly how the governance of commodity supply chains can be re-envisaged to support a more sustainable stewardship of natural resources and improved access to benefits for the more marginalized communities of producers. The unprecedented opportunity presented by recent zero deforestation commitments from private and public actors in response to rapidly depleting tropical forests means that this work could not be more urgent.

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