

PERSPECTIVE

Sustainable commodity sourcing requires measuring and governing land use change at multiple scales

Erasmus KHJ zu Ermgassen¹  | Cécile Renier¹  | Andrea Garcia¹  |
Tomás Carvalho²  | Patrick Meyfroidt^{1,3} 

¹Earth and Life Institute, UCLouvain,
Louvain-la-Neuve, Belgium

²Stockholm Environment Institute,
Stockholm, Sweden

³Fonds de la Recherche Scientifique F. R.
S.-FNRS, Brussels, Belgium

Correspondence

Erasmus K.H.J. zu Ermgassen, Earth and
Life Institute, UCLouvain, Place Pasteur 3,
1348 Louvain-la-Neuve, Belgium. Email:
erasmus.zuermgassen@uclouvain.be

Funding information

Norway's International Climate and
Forest Initiative, Grant/Award Numbers:
QZA-21/0156, BRA-22/0017; Quadrature
Climate Foundation, Grant/Award
Number: 01-21-000098; Biodiversa+
FNRS Grant n° PINT MULTI/BEJ,
Grant/Award Number: R.8002.20; Gordon
and Betty Moore Foundation,
Grant/Award Number: 7703.01

Abstract

The increased availability of remote sensing products and new legislative agendas are driving a growing focus on farm-level traceability and monitoring to tackle commodity-driven deforestation. Here, we use data on land use change in Brazil (1985–2021) from Mapbiomas to demonstrate how analyses of the drivers of deforestation are sensitive to the scale of analysis: while pixel- or property-level analyses identify proximate drivers of deforestation, analyses at larger scales (subnational regions or countries) capture more complex land use dynamics, including indirect land use change. We argue that initiatives which seek to monitor and address commodity-driven deforestation—such as the European Union's deforestation due-diligence regulation and the World Business Council on Sustainable Development's Greenhouse Gas Protocol—must be conscient of these wider land use dynamics. Only by measuring progress and defining success at multiple scales can initiatives for sustainable commodity sourcing create the right mix of incentives for addressing deforestation.

KEYWORDS

deforestation, governance, greenhouse gas accounting, land use change

1 | INTRODUCTION

Agricultural expansion is the driver of more than 90% of deforestation across the tropics (Pendrill et al., 2022), a major source of anthropogenic carbon emissions and biodiversity loss (Alroy, 2017; Friedlingstein et al., 2022). Establishing who is responsible for this expansion—which crops, which companies, and which consumers—is, however, not a straightforward task. The “driver” of deforestation may be determined either by evaluating which products are expanding in planted area or by evaluating which products are being grown on recently deforested

land (Bellfield et al., 2023). The former, product expansion approach (also known as “land balance”), is typically based on agricultural statistics reported at the national or subnational scale (Pendrill et al., 2019) while the latter, “spatially explicit” approach, is typically based on remote sensing products detecting land use change at the level of individual farms or pixels, with the resolution of data ranging from 250 m to 1 km for MODIS data down to 30 cm for products such as WorldView-3.

In recent years, falling costs of remote sensing has led to a boom in high-resolution land use data, which tips the scale in favor of land use accounting and governance

This is an open access article under the terms of the [Creative Commons Attribution](https://creativecommons.org/licenses/by/4.0/) License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2024 The Authors. Conservation Letters published by Wiley Periodicals LLC.

efforts at fine scale (Moran et al., 2020). In this article, we caution that this shift in scale belies also a shift in focus, which prioritizes the “proximate” or “direct” drivers of deforestation over “indirect” or “underlying” drivers, which are captured by analyses and monitoring implemented at coarser scales.

Finally, we reflect on the implications for initiatives, such as the World Business Council for Sustainable Development’s Greenhouse Gas Protocol and the European Union’s deforestation due-diligence (EU, 2023; WRI & WBCSD, 2022a), which prioritize monitoring land use change at the farm level. We argue that to be successful in reducing deforestation, sustainable sourcing initiatives should see pixel- or farm-level monitoring as only one component within a bundle of monitoring and action at multiple scales of resolution (i.e. from plots and farms to subnational regions or at national scale).

We make our case using remote sensing data for Brazil from Mapbiomas v7.1 (11). Mapbiomas offers a uniquely detailed (i.e., crop-specific), long-term mapping of all land uses in the country, thereby capturing the land use dynamics of multiple commodities in a harmonized methodology across 36 years (1985–2021). Specifically, we compare the drivers of deforestation which are identified when aggregating and analyzing the original data (30 × 30 m) at five different observational scales: at the level of individual pixels, properties, municipalities, states, and the country as a whole. By using a single common data source for our analyses, we isolate the role of the scale of analysis (rather than the type of underlying data, i.e., agricultural statistics vs. remote sensing products) in attributing deforestation to different drivers. Mapbiomas’ time series includes changes in agriculture (including soybeans, pasture, sugarcane, coffee, cotton, rice), tree plantations, and natural vegetation types (forests, savanna, and grasslands, and other nonforest natural formations). We use the term “deforestation” as a shorthand when referring to the conversion of natural vegetation, though they are not all strictly forested. We note that pasture expansion is not only motivated by its use for cattle ranching but also land speculation, as pasture is one of the cheapest land uses to establish post-deforestation. The soybean class does not distinguish between fields with one or multiple harvests—soybeans are often double-cropped with maize or cotton. Where the post-deforestation land use (i.e., crops, pasture) could not confidently be determined, pixels are classified as a “Land Use Mosaic.”

When the data are aggregated beyond the pixel resolution, we identify the driver of deforestation using the “product expansion” approach, as commonly adopted in other studies and accounting standards for land use change emissions (BSI, 2012; Pendrill et al., 2019; WRI & WBCSD, 2022b). In the Supporting Information, we compare our results across alternative approaches (Figure S1).

Product expansion attributes the loss of native vegetation to expanding products based on their share of expansion (Equation 1).

$$PAF_{r,p} = \frac{A_{r,p,y_1} - A_{r,p,y_0}}{\sum_p (A_{r,p,y_1} - A_{r,p,y_0})}, \quad (1)$$

where $PAF_{r,p}$ is the “product allocation factor,” the proportion of agricultural expansion across the study time period (y_0, y_1) which was due to each product p , in each region r (where $A_{r,p,y}$ is the area of product p , in region r , in year y). We ran the analyses for 1985–2021 and 2000–2021 for all regions, and for 2008–2021 when comparing property and pixel-level results in Mato Grosso in the period after the establishment of the Soy Moratorium. To convert $PAF_{r,p}$ from a proportion (0–1) of agricultural expansion into an area of deforestation (in hectares), $PAA_{r,p}$, we multiplied it by the area of native vegetation (NV) converted in each region r (Equation 2).

$$PAA_{r,p} = PAF_{r,p} \times (NV_{r,y_1} - NV_{r,y_0}) \quad (2)$$

We calculated $PAA_{r,p}$ separately for several scales of region (property, municipality, state, and country) before summing and comparing results at the national level (PAN_p , as a percentage of the total deforestation; Equation 3).

$$PAN_p = \frac{\sum_r PAA_{r,p}}{\sum PAA_{r,p}} \times 100 \quad (3)$$

The state-level results, for example, were calculated separately for each of Brazil’s 27 states to capture the land use dynamic within each state, before being summed to build a picture at the national level. For the calculation at the scale of land management units (hereafter, “Property”), we intersected Mapbiomas data with polygons of different land tenure (Sparovek et al., 2019) to calculate $PAF_{r,p}$ in all polygons and land tenure classifications. Though we use the shorthand “Property” to describe this scale of analysis, we note that these data include polygons of multiple land tenure types, including individual private properties, legal reserves, undesignated public lands, and indigenous territories. All analyses were done in R 4.1.3 (R Core Team, 2022) and Google Earth Engine (Gorelick et al., 2017).

2 | HOW SCALE AFFECTS THE ATTRIBUTION OF LAND USE CHANGE TO DIFFERENT DRIVERS

Though pasture is typically considered the main driver of deforestation in Brazil (Barreto, 2021; Häggli et al., 2023), across both time periods (1985–2021 and 2000–2021), its



FIGURE 1 Agricultural expansion in Brazil, 1985–2021 (A); the percentage of deforestation attributed to each expanding land use from 1985–2021 (B) and 2000–2021 (C). Plot A is reproduced as an area plot in Figure S2.

relative importance decreases as the scale of analysis gets more coarse (Figure 1B and C). Mirroring this, the proportion of deforestation attributed to soybeans is 3–4 times greater when calculated at national- rather than pixel scale (36% vs. 14% for 1985–2021 and 55% vs. 14% for 2000–2021). Sugarcane and forest plantations also emerge as major drivers of deforestation at national scale (Figure 1B and C). Analyses at coarser scales capture interactions and competition between land uses, including indirect land use change (WRI & WBCSD, 2022a)—where the expansion of one land use (the “indirect” driver) displaces another, which is the “proximate” or “direct” driver of deforestation (Arima et al., 2011; Bhan et al., 2021; Gasparri & de Waroux, 2014; Hänggli et al., 2023). In this example, though the net area of pasture in Brazil has been stable or declining since the mid-2000s (Figure 1A), cattle pasture across the south and central Brazil has been displaced by the expan-

sion of soy, sugarcane, and tree plantations; pasture has shifted notably northward, expanding, in particular, at the expense of forests in the Amazon biome (Andrade de Sá et al., 2013; Arima et al., 2011; Barona et al., 2010; Barreto, 2021; McManus et al., 2016).

3 | HOW SCALE AFFECTS THE SOLUTIONS TO LAND USE CHANGE

In recent decades, a series of governance efforts have emerged to tackle deforestation. Prior to the 1990s, governance of land use was the domain of domestic governments (Cashore, 2002), who set constraints on land use, including the establishment of protected areas, recognition of indigenous territories, and rules for conservation on private land—such as Brazil’s Forest Code, established in

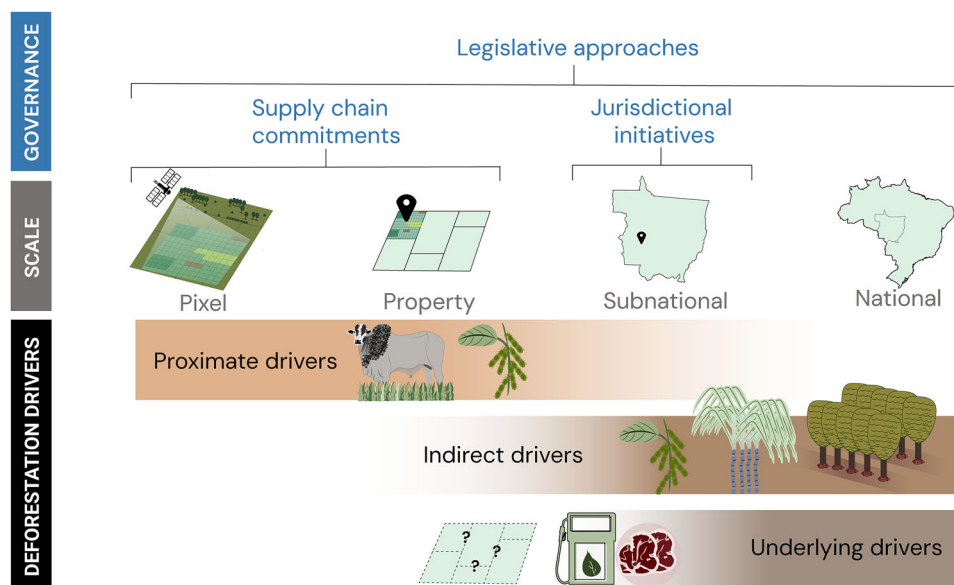


FIGURE 2 Governance approaches (top) are implemented at different scales and so address different drivers of land use change (bottom), depending on the scale at which the drivers manifest. Proximate drivers include cattle ranching and soybean expansion in the Brazilian Amazon. Indirect drivers include the expansion of soybeans, sugarcane, and tree plantations across Brazil. Underlying drivers include land tenure uncertainty, which incentivizes land grabbing, and the demand for and investment in land-intensive products, such as meat and biofuels.

1965 (Rajão et al., 2021). As globalization accelerated, production and consumption became increasingly distanced; with domestic policy seemingly failing to deliver products with the standards demanded by international agendas (e.g., on deforestation, farmer incomes, pollution, forced labor), governance shifted toward nonstate actors and from being place-based to flow-based (Sikor et al., 2013), with a variety of voluntary governance initiatives organized around global value chains. Examples include the rise of certification schemes, company standards, and zero deforestation commitments (Lambin et al., 2018). In the 2000s, various subnational approaches to governing land use emerged—REDD+ projects to incentivize subnational action on climate change and biodiversity loss, and then jurisdictional sourcing initiatives, which seek to expand the horizons of companies, to look beyond their supply chains and account for impacts in their sourcing regions (Boshoven et al., 2021; Boucher & Elias, 2013; IDH, 2021; Meyer & Miller, 2015). Most recently, flow-based legislative efforts have also emerged, with the European Commission's recently adopted due-diligence regulation seeking to ensure that products imported into the EU do not come from recently deforested land (EU, 2023).

These different governance structures seek to address land use change at different levels and so target different land use change processes (Figure 2). Supply chain commitments focus on pixels (e.g., the Amazon Soy Moratorium; Gibbs et al., 2015; Heilmayr et al., 2020) or properties (e.g., zero deforestation commitments in the cattle sector;

Gibbs et al., 2016), and so address “direct” or “proximate” drivers of deforestation. The difference between pixel- and property-level assessments and policy focus is well illustrated by the implementation of the Soy Moratorium. The Moratorium prohibits the planting of soybeans on land deforested after 2008 in the Amazon biome, though it is monitored at the pixel level; farmers may thus plant soybeans on pasture and then clear land elsewhere within their property (Gollnow et al., 2018). When comparing soybean expansion in the state of Mato Grosso (the main soybean producer in the Amazon) since 2008, the proportion of deforestation attributed to soybeans is almost double when analyzed at the property rather than the pixel level (20.3% vs. 11.4%). Jurisdictional or landscape efforts help capture regional and cross-commodity land use dynamics (Boshoven et al., 2021), while legislative approaches can govern land use change at multiple levels. They may target areas at the pixel level (e.g., regulations prohibiting clearing in riparian areas), constrain land use within properties or protected areas, and enact regional land use planning. For example, expansion of sugarcane in the Amazon has been constrained by the Sugarcane Agroecological Zoning, launched in 2009 and lifted in 2019 (Hernandes et al., 2021). This policy prevented sugarcane from becoming a proximate driver of deforestation, but did not address its indirect role through the displacement of other agricultural land uses (Hernandes et al., 2021). Finally, national policies can also address the “underlying” drivers of deforestation, which ultimately fuel the proximate and indirect

drivers of deforestation. Underlying drivers include land tenure uncertainty (Azevedo-Ramos et al., 2020), capital surpluses invested in agricultural frontiers (Richards & Arima, 2018), and demand for land-intensive products, such as livestock products and sugarcane ethanol biofuels. Governments can address land tenure issues through land titling programs and assigning undesignated land to conservation, reduce capital booms in agriculture through taxes on windfall profits or redirecting investments to other sectors, and modulate demand for land-intensive products through nutritional and public procurement guidelines, subsidies, quotas, and taxes.

4 | ACTION AT DIFFERENT SCALES IS COMPLEMENTARY—AND NECESSARY

Because of their different characteristics, pixel, property, jurisdictional, and national efforts can be complements in governing land use change. Indeed, this complementarity is seen as a strength of polycentric governance more generally (Ekroos et al., 2017; Ostrom, 2010). We caution, however, that the growing emphasis on supply chain sustainability initiatives risks narrowing attention to property-level and proximate drivers of deforestation (Figure 2). Two important recent initiatives which prioritize monitoring and action at property-scale are the European deforestation due-diligence regulation and the Greenhouse Gas Protocol (EU, 2023; WRI & WBCSD, 2022a). The European Union due-diligence regulation, passed in May 2023, requires that companies importing deforestation-risk products (cocoa, coffee, beef, leather, soybeans, palm oil, wood, and rubber) into the European Union demonstrate that these products do not arise from land deforested after December 31, 2020. A cornerstone of the regulation is the requirement for plot-level traceability, launching a race for companies to trace and measure compliance at the farm-scale (see Supporting Information for more details). The race is also on for companies to set climate mitigation targets using property-level data. The Greenhouse Gas Protocol is the most widely adopted greenhouse gas accounting standard for companies. The protocol's draft Land Sector and Removals Guidance (i.e., the guidance on accounting of land use change) distinguishes between “direct land use change,” which is measured at farm or land management unit level, and “statistical land use change” (such as the product expansion methodology shown here) which is calculated across sourcing regions (see Supporting Information for more details). Though the protocol acknowledges the complementarities of these two metrics, it currently requires companies to select a single metric for scope 3 (i.e., supply chain emissions) reporting, with a clear tendency

for companies to switch to reporting direct land use change emissions wherever traceability is sufficient (WRI & WBCSD, 2022a).

The deforestation due-diligence regulation and Greenhouse Gas Protocol are agenda-setting, defining for years-to-come what success looks like for governments' and companies' efforts to reduce deforestation and carbon emissions—and they must therefore be conscient of the incentives they create for action at different scales.

While the deforestation due-diligence regulation includes text which calls for “cooperation [with producer countries to] promote the development of integrated land use planning processes, relevant legislation of producer countries, multi-stakeholder processes, fiscal or commercial incentives and other pertinent tools to improve forest and biodiversity conservation”—that is, coordinated action at landscape or jurisdictional level—the implementation of this article remains uncertain (FERN, 2023). The European Union has thus far only committed to “develop a comprehensive Union strategic framework for such engagement”—still forthcoming at the time of writing in February 2024. Our results suggest that this framework is urgent and essential to ensure that property-level traceability and monitoring are also complemented by action at larger scales. Jurisdictions (either countries or subnational regions) could be incentivized to adopt land use planning and other landscape-level tools by counting landscape-level efforts toward the European Union's risk benchmarking, which will be used to determine the level of checks on imports from those regions (Supplementary Information). Similarly, the Greenhouse Gas Protocol could elevate statistical land use change to an obligatory metric given equal importance with direct land use change emissions. This would hold companies partially accountable for land use change in the jurisdictions where they source, and could accelerate corporate engagement in landscape-level initiatives. These landscape initiatives have been already identified as one of four pillars of sustainable sourcing by the companies of the Consumer Goods Forum (Forest Positive Coalition of Action, 2021) and multi-stakeholder platforms such as the Cocoa and Forests Initiative, though investment and action so far lags behind the Corporate Sustainability Reporting (CSR) rhetoric (zu Ermgassen et al., 2022).

Support for landscape-level action is all the more important because the feasibility and reliability of large-scale traceability remains unproven. The traceability required for farm-level monitoring is extremely challenging, particularly in commodity-producing landscapes where diffuse smallholder production, informal trading relationships, multi-tier-supply chains, corruption, and illegality are common (zu Ermgassen et al., 2022). It remains to be seen whether reliable traceability systems can be set up which

capture all commodity production, closing loopholes (mislabeling, laundering, fraud), which allow nonconformant products to enter “green” supply chains (Grant et al., 2021).

5 | CONCLUSION

The increased availability of remote sensing products and new legislative agendas are driving a growing focus on farm-level traceability and monitoring to tackle commodity-driven deforestation. Here, we used land use change data for Brazil from 1985–2021 to demonstrate that analyses of the drivers of deforestation are sensitive to the scale of analysis—while property-level analyses identify proximate drivers of deforestation, analyses at larger scales (subnational regions or countries) capture more complex land use dynamics, including indirect land use change. We argue that initiatives which seek to address commodity-driven deforestation must be conscient of this. Only by measuring progress and defining success at multiple scales can initiatives for sustainable commodity sourcing create the right mix of incentives for addressing deforestation.

ACKNOWLEDGMENTS

We thank Valentin Guye for helpful comments and Sandra Milena Bonilla Becerra for support on artwork. The work is a contribution to the Global Land Programme (www.glp.earth). This research benefitted from funding from Norway's International Climate and Forest Initiative (BRA-22/0017 & QZA-21/0156), the Gordon and Betty Moore Foundation (7703.01), Quadrature Climate Foundation (01-21-000098) and the Fonds de la Recherche Scientifique—FNRS (Grant n°PINT MULTI/BEJ—R.8002.20 BiodivERsA SUSTAIN-COCOA project, under the BiodivClim ERA-Net COFUND programme).

DATA AVAILABILITY STATEMENT

The data and code required to reproduce our results have been deposited in a public Zenodo repository (10.5281/zenodo.10671587).

ORCID

Erasmus KHJ zu Ermgassen  <https://orcid.org/0000-0002-9168-6057>

Cécile Renier  <https://orcid.org/0000-0002-8235-1183>

Andrea Garcia  <https://orcid.org/0000-0003-0315-0189>

Tomás Carvalho  <https://orcid.org/0000-0002-1125-5370>

Patrick Meyfroidt  <https://orcid.org/0000-0002-1047-9794>

REFERENCES

- Alroy, J. (2017). Effects of habitat disturbance on tropical forest biodiversity. *PNAS*, *114*, 6056–6061.
- Andrade de Sá, S., Palmer, C., & di Falco, S. (2013). Dynamics of indirect land-use change: Empirical evidence from Brazil. *Journal of Environmental Economics and Management*, *65*, 377–393.
- Arima, E. Y., Richards, P., Walker, R., & Caldas, M. M. (2011). Statistical confirmation of indirect land use change in the Brazilian Amazon. *Environmental Research Letters*, *6*, 024010.
- Azevedo-Ramos, C., Moutinho, P., Arruda, V. L. D. S., Stabile, M. C. C., Alencar, A., Castro, I., & Ribeiro, J. P. (2020). Lawless land in no man's land: The undesignated public forests in the Brazilian Amazon. *Land Use Policy*, *99*, 104863.
- Barona, E., Ramankutty, N., Hyman, G., & Coomes, O. T. (2010). The role of pasture and soybean in deforestation of the Brazilian Amazon. *Environmental Research Letters*, *5*, 024002.
- Barreto, P. (2021). *Políticas para desenvolver a pecuária na Amazônia sem desmatamento*. Imazon, Belém, PA.
- Bellfield, H., Pereira, O., Gardner, T., & Siqueira Lino, J. (2023). *Risk benchmarking for the EU deforestation regulation: Key principles and recommendations (Policy briefing)*. Trase & Proforest.
- Bhan, M., Gingrich, S., Roux, N., Le Noë, J., Kastner, T., Matej, S., Schwarzmüller, F., & Erb, K.-H. (2021). Quantifying and attributing land use-induced carbon emissions to biomass consumption: A critical assessment of existing approaches. *Journal of Environmental Management*, *286*, 112228.
- Boshoven, J., Fleck, L. C., Miltner, S., Salafsky, N., Adams, J., Dahl-Jørgensen, A., Fonseca, G., Nepsted, D., Rabinovitch, K., & Seymour, F. (2021). Jurisdictional sourcing: Leveraging commodity supply chains to reduce tropical deforestation at scale. A generic theory of change for a conservation strategy, v 1.0. *Conservation Science and Practice*, *3*, e383.
- Boucher, D., & Elias, P. (2013). From REDD to deforestation-free supply chains: The persistent problem of leakage and scale. *Carbon Management*, *4*, 473–475.
- BSI. (2012). *PAS 2050-1:2012 Assessment of life cycle greenhouse gas emissions from horticultural products* (No. ISBN 978 0 580 75725 9).
- Cashore, B. (2002). Legitimacy and the privatization of environmental governance: How non-state market-driven (NSMD) governance systems gain rule-making authority. *Governance*, *15*, 503–529.
- Ekroos, J., Leventon, J., Fischer, J., Newig, J., & Smith, H. G. (2017). Embedding evidence on conservation interventions within a context of multilevel governance. *Conservation Letters*, *10*, 139–145.
- EU. (2023). *Regulation (EU) 2023/1115 of the European Parliament and of the Council of 31 May 2023 on the making available on the Union market and the export from the Union of certain commodities and products associated with deforestation and forest degradation and repealing Regulation (EU) No 995/2010*.
- FERN. (2023). *An EU strategic framework for working with countries to achieve deforestation-free production*. FERN.
- Forest Positive Coalition of Action. (2021). *Nurturing transparency: The path to forest positive*. Consumer Goods Forum.
- Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Gregor, L., Hauck, J., Le Quéré, C., Luijckx, I. T., Olsen, A., Peters, G. P., Peters, W., Pongratz, J., Schwingshackl, C., Storch, S.,

- Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S. R., Alkama, R., ... Zheng, B. (2022). Global Carbon Budget 2022. *Earth System Science Data*, 14, 4811–4900.
- Gasparri, N. I., & de Waroux, Y. L. P. (2014). The coupling of South American soybean and cattle production frontiers: New challenges for conservation policy and land change science: The coupling of soy and cattle frontiers. *Conservation Letters*, 8, 290–298.
- Gibbs, H. K., Munger, J., L'Roe, J., Barreto, P., Pereira, R., Christie, M., Amaral, T., & Walker, N. F. (2016). Did ranchers and slaughterhouses respond to zero-deforestation agreements in the Brazilian Amazon? *Conservation Letters*, 9, 32–42.
- Gibbs, H. K., Rausch, L., Munger, J., Schelly, I., Morton, D. C., Noojipady, P., Soares-Filho, B., Barreto, P., Micol, L., & Walker, N. F. (2015). Brazil's Soy Moratorium. *Science*, 347, 377–378.
- Gollnow, F., Hissa, L. D. B. V., Rufin, P., & Lakes, T. (2018). Property-level direct and indirect deforestation for soybean production in the Amazon region of Mato Grosso, Brazil. *Land Use Policy*, 78, 377–385.
- Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., & Moore, R. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment, Big Remotely Sensed Data: tools, applications and experiences*, 202, 18–27.
- Grant, J., Freitas, B., & Wilson, T. (2021). *Traceability systems: Potential tools to deter illegality and corruption in the timber and fish sectors?* TNRC Topic Brief, World Wildlife Fund for Nature.
- Hänggli, A., Levy, S. A., Armenteras, D., Bovolo, C. I., Brandão, J., Rueda, X., & Garrett, R. D. (2023). A systematic comparison of deforestation drivers and policy effectiveness across the Amazon biome. *Environmental Research Letters*, 18, 073001.
- Heilmayr, R., Rausch, L. L., Munger, J., & Gibbs, H. K. (2020). Brazil's Amazon soy moratorium reduced deforestation. *Nature Food*, 1, 801–810.
- Hernandes, T. A. D., Duft, D. G., dos Santos Luciano, A. C., Leal, M. R. L. V., & Cavalett, O. (2021). Identifying suitable areas for expanding sugarcane ethanol production in Brazil under conservation of environmentally relevant habitats. *Journal of Cleaner Production*, 292, 125318.
- IDH. (2021). SourceUp—Supply chain sustainability [WWW Document]. URL <https://www.idhsustainabletrade.com/approach/sourceup/>
- Lambin, E. F., Gibbs, H. K., Heilmayr, R., Carlson, K. M., Fleck, L. C., Garrett, R. D., Waroux, L. P. de, McDermott, C. L., McLaughlin, D., Newton, P., Nolte, C., Pacheco, P., Rausch, L. L., Streck, C., Thorlakson, T., & Walker, N. F. (2018). The role of supply-chain initiatives in reducing deforestation. *Nature Climate Change*, 8, 109–116.
- McManus, C., Barcellos, J. O. J., Formenton, B. K., Hermuche, P. M., Carvalho, Jr, O. A. D., Guimarães, R., Gianezini, M., Dias, E. A., Lampert, V. D. N., Zago, D., & Neto, J. B. (2016). Dynamics of cattle production in Brazil. *PLoS ONE*, 11, e0147138.
- Meyer, C., & Miller, D. (2015). Zero deforestation zones: The case for linking deforestation-free supply chain initiatives and jurisdictional REDD+. *Journal of Sustainable Forestry*, 34, 559–580.
- Moran, D., Giljum, S., Kanemoto, K., & Godar, J. (2020). From satellite to supply chain: New approaches connect earth observation to economic decisions. *One Earth*, 3, 5–8.
- Ostrom, E. (2010). Polycentric systems for coping with collective action and global environmental change. *Global Environmental Change*, 20th Anniversary Special Issue, 20, 550–557.
- Pendrill, F., Gardner, T. A., Meyfroidt, P., Persson, U. M., Adams, J., Azevedo, T., Bastos Lima, M. G., Baumann, M., Curtis, P. G., De Sy, V., Garrett, R., Godar, J., Goldman, E. D., Hansen, M. C., Heilmayr, R., Herold, M., Kuemmerle, T., Lathuillière, M. J., Ribeiro, V., ... West, C. (2022). Disentangling the numbers behind agriculture-driven tropical deforestation. *Science*, 377, eabm9267.
- Pendrill, F., Persson, U. M., Godar, J., Kastner, T., Moran, D., Schmidt, S., & Wood, R. (2019). Agricultural and forestry trade drives large share of tropical deforestation emissions. *Global Environmental Change*, 56, 1–10.
- R Core Team. (2022). *R version 4.1.3 R: A language and environment for statistical computing*. R Foundation for Statistical Computing.
- Rajão, R., Del Giudice, R. R., van der Hoff, R., & Carvalho, E. B. (2021). *Uma breve história da legislação florestal brasileira: Contém a lei nº 12.651, de 2012, com comentários críticos acerca da aplicação de seus artigos*. Expressão.
- Richards, P., & Arima, E. (2018). Capital surpluses in the farming sector and agricultural expansion in Brazil. *Environmental Research Letters*, 13, 075011.
- Sikor, T., Auld, G., Bebbington, A. J., Benjaminsen, T. A., Gentry, B. S., Hunsberger, C., Izac, A.-M., Margulis, M. E., Plieninger, T., Schroeder, H., & Upton, C. (2013). Global land governance: From territory to flow? *Current Opinion in Environmental Sustainability*, 5, 522–527.
- Sparovek, G., Reydon, B. P., Guedes Pinto, L. F., Faria, V., de Freitas, F. L. M., Azevedo-Ramos, C., Gardner, T., Hamamura, C., Rajão, R., Cerignoni, F., Siqueira, G. P., Carvalho, T., Alencar, A., & Ribeiro, V. (2019). Who owns Brazilian lands? *Land Use Policy*, 87, 104062.
- WRI & WBCSD. (2022a). *Land Sector and Removals Guidance, Draft for Pilot Testing and Review, Part 1: Accounting and Reporting Requirements and Guidance*.
- WRI & WBCSD. (2022b). *Land Sector and Removals Guidance, Draft for Pilot Testing and Review, Part 2: Calculation Guidance*.
- zu Ermgassen, E. K. H. J., Bastos Lima, M. G., Bellfield, H., Dontenville, A., Gardner, T., Godar, J., Heilmayr, R., Indenbaum, R., Dos Reis, T. N. P., Ribeiro, V., Abu, I., Szantoi, Z., & Meyfroidt, P. (2022). Addressing indirect sourcing in zero deforestation commodity supply chains. *Science Advances*, 8, eabn3132.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: zu Ermgassen, E. K. H. J., Renier, C., Garcia, A., Carvalho, T., & Meyfroidt, P. (2024). Sustainable commodity sourcing requires measuring and governing land use change at multiple scales. *Conservation Letters*, e13016. <https://doi.org/10.1111/conl.13016>