Mapping and Monitoring Zero-Deforestation Commitments

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A growing number of companies have announced zero-deforestation commitments (ZDCs) to eliminate commodities produced at the expense of forests from their supply chains. Translating these aspirational goals into forest conservation requires forest mapping and monitoring (M&M) systems that are technically adequate and therefore credible, salient so that they address the needs of decision makers, legitimate in that they are fair and unbiased, and scalable over space and time. We identify 12 attributes of M&M that contribute to these goals and assess how two prominent ZDC programs, the Amazon Soy Moratorium and the High Carbon Stock Approach, integrate these attributes into their M&M systems. These programs prioritize different attributes, highlighting fundamental trade-offs in M&M design. Rather than prescribe a one-size-fits-all solution, we provide policymakers and practitioners with guidance on the design of ZDC M&M systems that fit their specific use case and that may contribute to more effective implementation of ZDCs.

Keywords: agroecosystems, land use management, monitoring and mapping, remote sensing, tropical ecosystems

Tropical deforestation is largely driven by the production of agricultural commodities including oil palm, beef, and soy (Curtis et al. 2018). Production of these commodities is increasingly linked to growing demand from wealthy and emerging economies around the world (DeFries et al. 2010, Pendrill et al. 2019). In recognition of these links, many companies have developed sustainable supply chain initiatives that address the environmental and social consequences of commodity production (NYDF Assessment Partners 2020). By 2018, over 400 companies had established sustainable commodity commitments, and more than 70 companies had pledged to eliminate deforestation from their supply chains (Rothrock et al. 2019). Several multistakeholder coalitions and sectoral standards aim to harmonize the definition, design, and execution of these zero-deforestation commitments (ZDCs; Brown and Zarin 2013, Lambin et al. 2018, Accountability Framework 2019). These include, for example, the Soy Moratorium in the Brazilian Amazon, the Roundtable on Sustainable Palm Oil (RSPO), Colombia's National Zero Deforestation Agreements, the Cocoa and Forests Initiative in Ghana and Cote d'Ivoire, and the High Carbon Stock Approach (HCSA).

Despite such diverse efforts, the rates of tropical primary forest loss have increased each year since the signatories to the 2014 New York Declaration on Forests pledged to halve deforestation by 2020 (NYDF Assessment Partners 2020). Some analysts have attributed the continued deforestation to the substantial implementation gap between high-level ambition and the concrete actions needed to eliminate deforestation from commodity supply chains (Rogerson et al. 2019). Because less than one-third of companies with ZDCs were monitoring and reporting on the progress of their commitments in the year 2019 (Rothrock et al. 2019), our ability to determine whether and to what extent these pledges are being put into action and delivering on their stated goals is limited (Godar et al. 2016).

Across contexts ranging from community-based forest management to national Reduced Emissions from Deforestation and Forest Degradation (REDD+) programs, mapping and monitoring systems are recognized as crucial components of effective resource governance (Ostrom and Nagendra 2006, Herold and Skutsch 2011, Andersson et al. 2014). In the context of ZDCs, mapping and monitoring systems can improve effectiveness by encouraging compliance with commitments and enabling adaptive management to refine ZDC interventions (Rasmussen and Jepsen 2018, Garrett et al. 2019). Mapping and monitoring system outputs (e.g., mapped locations of deforestation) also inform decision-making across a range of stakeholder groups. They

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help purchasing companies and consumers make informed choices about what they buy and whom they buy from, support producers to demonstrate that they are adopting or adhering to a set of standards that would allow market access and enable third parties to track and enforce the standards and requirements laid out in ZDCs (Gardner et al. 2019).

There is a broad range of information that should be mapped or monitored to gauge ZDC progress, including company actions designed to meet ZDC standards and requirements (e.g., procurement and investment decisions), traceability data that links supply chain actors to places of production, and the impacts of commodity cultivation on forest cover (Haupt et al. 2018, Gardner et al. 2019, Accountability Framework 2019). In the present article, we focus on data collection and analysis methods for mapping and monitoring forested areas identified under ZDCs. We acknowledge that mapping and monitoring encompasses a range of needs including internal monitoring to support operations and formal audits designed for public reporting and external evaluation.

Despite the importance of mapping and monitoring systems for fulfilling ZDCs, there has been limited research investigating which system characteristics best support ZDC effectiveness (Accountability Framework 2019, Garrett et al. 2019). Our research fills this gap by answering three questions: What attributes are likely to contribute to effective ZDC mapping and monitoring systems? How are these attributes integrated into leading zero deforestation approaches? And what are the trade-offs between desirable attributes?

There is no one-size-fits-all solution to achieving effective ZDC mapping and monitoring, but rather, the situation requires a tailored configuration of system attributes unique to different contexts across committed actor, commodity, and geography. We therefore defined key system attributes that can be used to guide the development of ZDC mapping and monitoring systems that encourage buy-in from supply chain actors, government entities, and civil society, and contribute to more effective implementation of ZDC commitments.

Study approach and case study ZDC programs

To develop a typology of priority ZDC mapping and monitoring system attributes, we convened experts for a 2-day October 2019 workshop supported by the Science for Nature and People Partnership (https://snappartnership.net) based in Santa Barbara, California. Participants were selected on the basis of their work researching, realizing, or monitoring multistakeholder ZDC initiatives including the Amazon Soy Moratorium (SoyM) in Brazil and palm oil ZDCs in Indonesia. The group included representatives from academia (*n* = 9 individuals), the private sector (*n* = 2), and environmental civil society organizations (*n* = 6). We sought to include diverse international perspectives on features of ZDC mapping and monitoring systems valued by a relatively broad range of stakeholders, convening experts from Indonesia (*n* = 4), Brazil (*n* = 2), Singapore (*n* = 1), Europe (*n* = 2), Australia (*n* = 1), and the United States (*n* = 7). All of the participants additionally contributed to this article as authors.

We based our assessment on the premise that the effectiveness of ZDCs will depend, at least in part, on operational mapping and monitoring systems which enable and encourage users to act on their stated commitments. Throughout this article, we define users as all possible users of the data including supply chain actors (e.g., downstream purchasers, upstream suppliers, investors), government entities, civil society organizations, local communities, and consumers. We further argue that users will be enabled to make better-informed decisions if the mapping and monitoring system achieves a set of criteria, including credibility (users perceive the methodology and outputs to be technically adequate), saliency (outputs are relevant to and address the needs of users), legitimacy (users perceive systems and processes of generating information as fair and unbiased according to societal or ethical standards), and scalability (systems are economically feasible at large spatial scales and across multiple years).

The first three criteria in this list, modified from Cash and colleagues (2003), are well-established conditions for environmental indicators to be used by decision-makers in the design and evaluation of environmental policies (Cash et al. 2003, Clark et al. 2016). Others have modified and refined these criteria to accommodate various science–policy interfaces (e.g., Sarkki et al. 2015, van Voorn et al. 2016). We included a fourth dimension—scalability—to address the need to extend ZDC mapping and monitoring systems in space and time (Cash et al. 2006, Vervoort et al. 2012). These criteria are also informed by efforts to define characteristics of effective monitoring systems for REDD+ (IPCC 2003, Herold and Johns 2007).

We identified key mapping and monitoring system attributes that contribute to one or more of these overarching criteria. To illustrate how these attributes have been integrated in the design of existing mapping and monitoring systems, we reviewed Brazil's SoyM monitoring system and the HCSA as used in support of ZDCs in Indonesia's oil palm sector. We chose these two case studies because their mapping and monitoring systems have been elaborated to a greater degree than in many other geographic and commodity contexts. We examined the extent to which each initiative has incorporated our selected attributes into the design and development of their mapping and monitoring systems. For each system, we scored attributes on a scale of 1 (attribute has not been addressed) to 3 (attribute has been achieved), according to a rubric (table 1). This scoring system provides a systematic way to compare the technical approaches to mapping and monitoring between the two cases, and investigate potential trade-offs between attributes.

Soy moratorium in the Brazilian Amazon. In 2018, Brazil produced roughly one-third of global soybeans (FAOSTAT 2020). From 2001 to 2006, soy cultivation expanded by more than 1 million hectares (ha) in the Amazon biome, and nearly

Table 1. ZDC mapping and monitoring (M&M) system criteria, definitions, contributing attributes, description, and scoring rubric used in the assessment of existing and proposed systems.

			Indicative score		
Criterion	**Attributes**	**Description**	**0**	**1**	**2**
Credibility (Users perceive methods and outputs as technically adequate)	Technical rigor	M&M protocols provide reliable assessments of the location of forests and deforestation, and methods and outputs are evaluated by qualified experts	No information provided on methods	Methods and outputs available but have not been evaluated by qualified experts	Methods and outputs have been evaluated by qualified experts
	Consistency	The methods and procedures for M&M are comparable and consistent across time and space	Methods are specific to individual study sites, do not conform to a standard protocol, or are not replicable	Methods are specific to individual study sites, but conform to a standard protocol and are replicable over time	Methods are consistent and comparable across time and space
	Accuracy	M&M results correctly reflect forest cover attributes and deforestation occurrence	Results are not validated, or are not validated in the specific area of interest	Accuracy does not always meet the standards agreed in each ZDC context	Accuracy always meets standards agreed in each ZDC context
Salience (Outputs are relevant to and address the needs of users)	Geographic scope	M&M covers the area where companies with ZDCs source their products	Does not cover the area where the commodity is sourced	Covers a subset of the area where the commodity is sourced	Covers all potential areas where the commodity is sourced
	Categorical detail	M&M technical approaches are designed to discriminate land cover types and land cover changes relevant to a ZDC initiative	Does not distinguish forest types relevant to the ZDC	Discriminates some forests types relevant to the ZDC initiative	Discriminates all forest categories relevant to the ZDC initiative
	Monitoring Frequency	Monitoring frequency aligns with user decision making cycles	Monitoring is not conducted	Monitoring occurs regularly but at intervals greater than 1 year	Monitoring occurs at least annually, and is rapidly provided to users
Legitimacy (Users perceive systems and processes of generating information as fair and unbiased)	Transparency	The methodologies of and outputs from M&M systems are publicly available and accessible	Methods and data are not publicly available and accessible	Methods and data are available and accessible to ZDC companies only	Methods and data are publicly available in an easily accessible format
	Independence	The results of M&M are independent from influence by the commodity producer	Data collection and analysis is carried out by the commodity producer	Data collection and analysis carried out by a third party that is contracted by the commodity producer	Data collection and analysis carried out by an independent third party that is not influenced by the commodity producer being assessed
	Inclusivity	M&M approaches are developed, and outputs are evaluated, via engagement and participation of all relevant stakeholders and potential users	System developed and evaluated without engagement of most relevant stakeholders and users	System developed and evaluated with engagement of a subset of relevant stakeholders and users	System developed and evaluated by all relevant stakeholders and users
Scalability (Systems are economically feasible at large spatial scales and across multiple years)	Cost effectiveness	Benefits of conducting M&M methods and protocols are worth their costs	Costs are prohibitive for all users	Data collection and analysis methods are cost effective for a segment of the supply chain	Access and data are cost effective for all supply chain actors
	Flexibility	The M&M methods and protocols can be applied in other biomes, regions and countries while producing comparable results	Not possible to apply the system to all relevant biomes, regions, and countries	Can be applied in new biomes, regions, and countries without modification	Already applied across diverse biomes, regions, and countries, and producing comparable results
	Sustainability	The M&M system input data will be available and reliable for the foreseeable future	Data will be collected on an as-needed basis	Data is collected regularly, but system longevity is not guaranteed	Data will be collected reliably for the foreseeable future

30% of this expansion resulted in the direct conversion of forests (Morton et al. 2006, Macedo et al. 2012, Gibbs et al. 2015). From 2006 to 2018, soy cultivation expanded by an additional 4 million ha in the Amazon biome, with 1.5% directly resulting in the conversion of primary forests (ABIOVE et al. 2020).

In 2006, major traders of soy signed the SoyM agreement, in which they agreed not to purchase soy from properties in the Amazon biome where soy was planted on land where primary forest was lost after July 2006 (later revised to July 2008). The Soy Working Group (GTS in Portuguese), including the Brazilian Association of Vegetable Oil Industries (ABIOVE), the National Association of Cereal Exporters (ANEC), civil society representatives, and the Bank of Brazil, is responsible for governance and operations of the moratorium. In 2016 GTS agreed to extend the SoyM indefinitely (Soterroni et al. 2019).

The SoyM's monitoring system is often identified as a critical component of the program's success (Nepstad et al. 2014, Heilmayr et al. 2020a). Monitoring is based on PRODES, a Brazilian federal government program that has mapped clearance of primary forest in the Legal Amazon (which includes all of the Brazilian portion of the Amazon biome) since 1988. Starting in 2002, Brazil made PRODES-derived maps publicly available. Brazil's National Institute of Space Research and the Institute of Environment and Renewable Natural Resources together operate the PRODES system. PRODES data is freely accessible from the TerraBrasilis geoportal.

The basis of the area protected by the SoyM is the map of primary forest in the Amazon biome provided by the PRODES system. To produce the maps of deforestation relevant for the SoyM, the monitoring team selects PRODES deforestation polygons that meet the following criteria: deforested after 22 July 2008, minimum aggregate size of 25 ha, located outside settlements, protected areas, and indigenous lands, and located within municipalities with at least 5000 ha of soy in the most recent crop year (Rudorff et al. 2011). In the 2018–2019 growing season, for example, this narrowed the focus of monitoring to the 95 soy-producing municipalities that grow 98% of soy in the Brazilian Amazon (ABIOVE et al. 2020). Then, the monitoring team maps the area of soy crop cultivation in these deforestation polygons, and validates this assessment using aerial surveys (Rudorff et al. 2011). Any property where deforestation was followed by soy cultivation is considered noncompliant with the SoyM.

HCSA for palm oil ZDCs in Indonesia. In 2018, Indonesia produced roughly half of the world's palm oil (FAOSTAT 2020). Rising global demand for palm oil encouraged a fivefold expansion of planted oil palm in Indonesia between 1995 and 2015, which drove at least 2 million ha of forest loss over the same period (Austin et al. 2017b). By 2018, more than 80% of palm oil exports from Indonesia were traded by a company with some form of zero-deforestation policy or commitment (Trase 2020).

The RSPO, initiated in the mid-2000s, developed criteria for certifying oil palm plantations that were not established at the expense of high conservation value (HCV) and primary forest areas after 2005. The HCSA emerged in recognition of the need to be able to practically identify and protect forest strata, including secondary and regenerating forests, that may not be recognized as high conservation value (Rosoman et al. 2017). The HCSA is commodity agnostic and is beginning to be used to support ZDCs in pulpwood, rubber, soy, and cacao supply chains (Cheyns et al. 2020). In late 2018, the HCSA methodology was adopted into the Principles and Criteria of the RSPO, which certified almost 20% of global palm oil production in the year 2020 (RSPO 2020).

The HCSA toolkit (Rosoman et al. 2017) provides guidance for mapping vegetation strata within a planned development area and its surrounding landscape. The toolkit includes a decision tree for assessing patches of different vegetation types and sizes in the delineation of protected forests (HCS forests), which consist of high-, medium-, and low-density forests and young regenerating forests. The approach also integrates concepts of HCV and free, prior, and informed consent.

HCSA assessments are carried out by trained and registered assessment teams that include specialists across a wide range of expertise including biodiversity monitoring, participatory mapping, and remote sensing. Resulting assessments completed prior to November 2017 are peer reviewed by external experts and a summary of the assessment is made publicly available. Assessments initiated after November 2019 must be integrated HCV–HCSA assessments, and are evaluated by a quality panel composed of qualified professionals according to the HCV Resource Network's Assessor Licensing Scheme. Governance of the HCSA methodology is managed by the HCSA Steering Group, which includes representatives from companies, environmental and social civil society organizations, and technical support organizations. A science advisory committee and secretariat support the Steering Group.

Once HCS forest areas have been delineated, the HCSA requires companies to follow their written plans to monitor, protect, and manage these areas. Although the HCSA has yet to define monitoring standards and methodologies, the Global Land Analysis and Discovery (GLAD) alerts (Hansen et al. 2016) and Global Forest Change (GFC) annual change detection (Hansen et al. 2013) are being considered as tools to support monitoring (HCSA 2019).

Attributes of effective ZDC mapping and monitoring systems

We identified 12 attributes of ZDC mapping and monitoring systems that contribute to their credibility, salience, legitimacy, and scalability (table 1). We then assessed the degree to which the SoyM and palm oil HCSA mapping and monitoring systems achieve these attributes (figure 1). Several of these attributes have inherent dependencies and may not

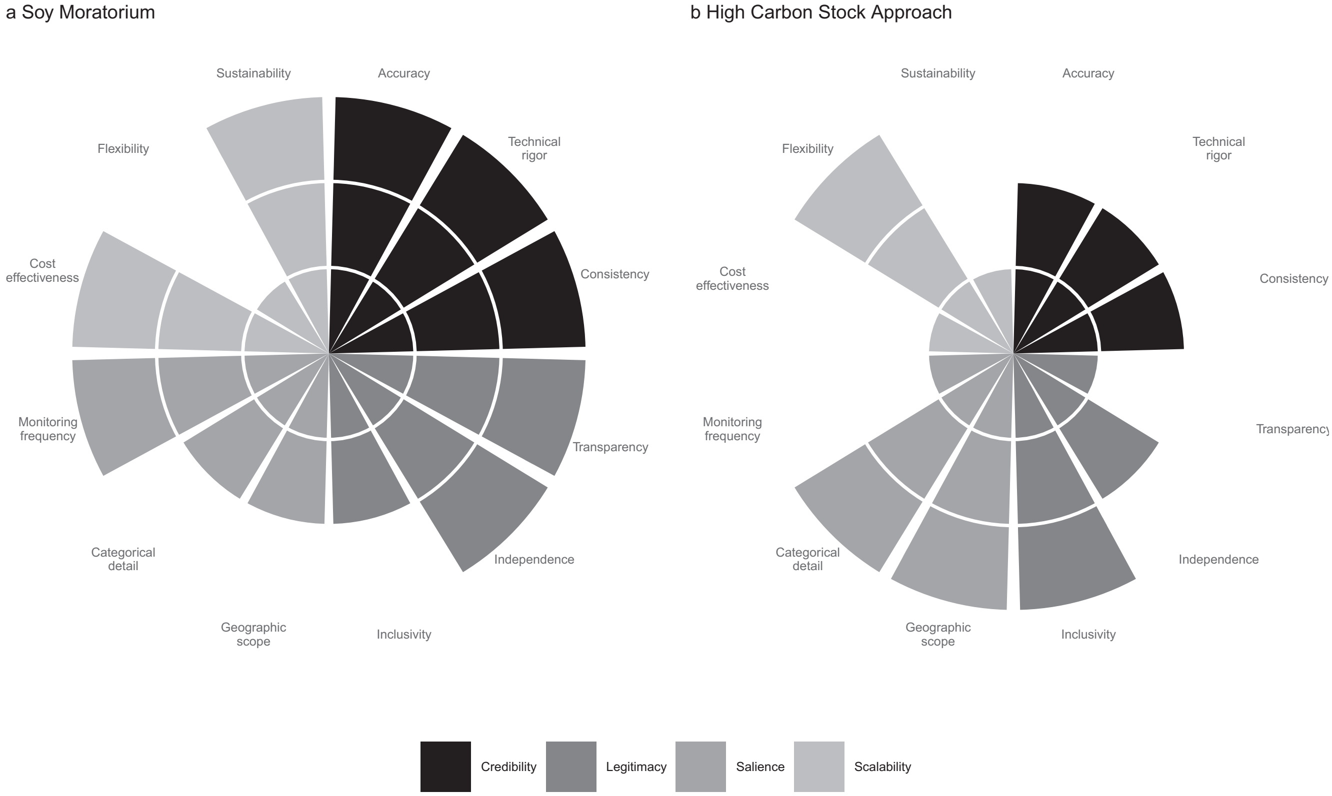

Figure 1. The degree to which mapping and monitoring systems for the SoyM in the Brazilian Amazon (a) and the HCSA approach for palm oil ZDCs in Indonesia (b) achieve attributes contributing to their credibility, saliency, legitimacy, and scalability. Each attribute is scored on a scale of 1–3 according to the rubric provided in table 1.

fall under just one of the four criteria (credibility, salience, legitimacy, and scalability). For example, transparency is a fundamental attribute for building legitimacy but is also an essential part of the scientific process and therefore critical to achieve credibility. We organize each attribute according to these four broad criteria, acknowledging these overlapping influences and relationships.

Attributes contributing primarily to credibility. A credible mapping and monitoring system uses a methodology and produces outputs that are perceived by users to be technically adequate to identify forests and deforestation as defined by the ZDC. The credibility of a mapping and monitoring system is a product of multiple attributes, including the technical rigor and consistency of the technical process used, as well as the final accuracy of the outputs.

Technical rigor. The technical rigor of a ZDC mapping and monitoring system represents the degree to which the system integrates best scientific practices into its protocols. Although these best practices evolve with advances in the scientific methods underpinning land cover and land use change mapping, the scientific literature often provides detailed reviews of the current state of the art (e.g., see Olofsson et al. 2014 for a summary of best practices for accuracy assessment in land cover and land use change mapping or Ghamisi et al. 2019 for a summary of the state of the art in multisensory and multitemporal data fusion). Technical rigor can be achieved when these domain-specific methods are combined with practices that underpin general scientific excellence (e.g., objectivity, transparency).

Technical rigor is typically demonstrated when a system's protocols and resulting outputs are evaluated by qualified experts and found to meet best scientific practices. These experts include trained scientists and practitioners as well as citizen scientists and natural resource users with local ecological knowledge (Mazzochi 2006, Joa et al. 2018).

The technical rigor of the SoyM monitoring approach is underpinned by the PRODES system, which was developed by the Brazilian government to map primary forest loss on an annual basis almost two decades in advance of the SoyM. The methodology and outputs of the PRODES system have been evaluated in the academic peer-reviewed literature (e.g., Hansen et al. 2008, Milodowski et al. 2017, Rajão et al. 2017, Maurano et al. 2019). The system meets general standards of technical rigor but has acknowledged and documented limitations with respect to the ability to track clearings smaller than 6.25 ha (Richards et al. 2017), and forest loss in areas that were not dense primary forest July 2008, including secondary forests (Tyukavina et al. 2017).

The HCSA's mapping methodology was developed via a collaboration between companies, civil society organizations, and academics, and integrates current best practices into its protocols. Each site-specific Integrated HCV–HCSA assessment is evaluated by at least two third-party reviewers. However, the methodological approach has not been as thoroughly reviewed in the peer-reviewed scientific literature as the SoyM system, partly because of its relative recency (though see Deere et al. 2018, Austin et al. 2017a, Leijten et al. 2020). Moreover, for pre-November 2017 assessments, there is not a standardized system in place to require companies to address concerns raised during this review, which potentially undermines the credibility of the final product (i.e., potentially companies could claim completion of the HCSA assessment even if reviewers had raised issues with the final report).

Consistency. Consistent ZDC mapping or monitoring systems use the same—or comparable—methods and assumptions across space and over time, a necessary condition for identifying differences and trends. The PRODES process for mapping and monitoring primary forest loss and soy cultivation under the SoyM is consistent across the Amazon biome and over time. In contrast, the HCSA toolkit released in April 2015 was updated to version 2.0 in May 2017 (Rosoman et al. 2017), and therefore the methodologies and requirements have changed. Furthermore, the flexibility in HCSA toolkit definitions leave room for subjectivity in the development of HCS maps. For example, the toolkit provides wide scope in the eligible approaches to collecting forest structure training and validation data, and in defining non-HCS land cover categories, opening the door for distinct interpretations. Therefore, there is the possibility that—despite efforts to maintain standardization via the toolkit methodology and only allowing individuals who have completed training to lead assessments—different HCSA assessors may make different value judgments with respect to which vegetation types fall into each HCS land cover category, potentially resulting in a lack of consistency across assessments at different locations or over time (Edwards et al. 2012).

Accuracy. Accurate ZDC mapping and monitoring systems correctly identify forest cover characteristics and deforestation occurrence at or exceeding a minimum level of confidence specified by the ZDC initiative in question. Accuracy is assessed by comparing classified forest or forest change maps to a sample of high quality reference data, which is generally based on field observations or other forms of very high spatial resolution Earth observation (e.g., submeter satellite data). Beyond overall accuracy, different users may consider false positives (where deforestation is reported but did not occur) more problematic than false negatives (where deforestation is missed by the monitoring system), or vice versa. For example, a higher rate of false positives could lead to the erroneous exclusion of some commodity producers from a supply chain, whereas more false negatives could undermine the value of the monitoring process in the eyes of environmental advocates. Incorporating procedures to address remaining errors in the map outputs, such as an easily accessible and affordable appeal mechanism for producers, could encourage buy-in from all interested parties.

The SoyM monitoring system tracks deforestation events greater than 25 ha in aggregate and in 2014 reported overall accuracy of 93%, with omission and commission errors of 7% and 1.5%, respectively (Maurano et al. 2019). The monitoring system includes several steps designed to avoid or minimize misinterpretation, including processes for precisely identifying the correct date of deforestation and confirming soy field boundaries using aerial surveys and owner registry data. The system also incorporates a grievance procedure that allows for corrections where another source of evidence disagrees with the original finding, although, thus far, this has not been used by any soy producers.

The HCSA approach to forest mapping requires a minimum spatial resolution of 10 × 10 meter (m) but accepts 30 × 30 m resolution maps based on Landsat data where higher resolution imagery is not available. In practice, most published assessments have used 30 × 30 m resolution maps (HCSA 2020). The HCSA requires overall map accuracy of 80% based on comparison of forest stratification with ground truth data collected in the field (HCSA 2018) As of 2020, publicly available HCSA assessments reported accuracies ranging between 66% and 96% (HCSA 2020).

Attributes contributing primarily to saliency. Mapping and monitoring systems should be salient to users, meaning that their outputs are relevant to these users and address their needs. Therefore, it is critical that the system cover the geographic locations and times critical to monitor and protect forests and allow mapping of land cover and land cover change relevant to the ZDC definitions of forest and deforestation.

Geographic scope. A fundamental requirement of mapping and monitoring systems is that they include the geographic areas where companies with ZDCs using these systems source their deforestation-risk products. The SoyM applies only in the Amazon biome, which is mapped and monitored by the PRODES system. Although PRODES originally covered the Legal Amazon, its spatial coverage has been extended to include the Cerrado and may be further extended into other regions of Brazil. The HCSA methodology was designed to be applied anywhere in the humid tropics and therefore has the potential to cover any geographic area of interest within this biome. However, single HCS assessments are designed to capture specific details of a property or landscape of interest, and therefore have a narrow geographic scope.

Monitoring frequency. ZDC monitoring frequency is the period between repeated assessments and must be sufficiently regular to provide the information needed for user decision-making. More frequent monitoring supports more timely responses to problems and real-time interventions to limit deforestation. Early detection on the order of days or weeks might be a priority for a company that wants to be able to act quickly if unexpected clearing is detected within their property. On the other hand, a system that provides less frequent but more accurate outputs may be preferable when identifying properties or producers that have not complied with ZDC criteria.

The PRODES system provides annual reports of deforestation, which aligns with the annual soy cultivation schedule, and which provides time to vet results. The HCSA has yet to define monitoring standards and methodologies and is considering tools with annual frequency (e.g., GFC) and more frequent reporting (e.g., GLAD).

Land cover categorical detail. Categorical detail refers to the ability of mapping and monitoring systems to distinguish land cover and land cover change relevant to and matching the definition of *deforestation* used by a given individual or collective ZDC.

PRODES maps only primary forest, and loss within primary forest, in the Legal Amazon. Once an area has been deforested, PRODES will no longer map loss within that area, even if secondary forest regrowth has occurred. Although this system is sufficient for assessing compliance with the SoyM (which is limited to preventing primary forest loss), it is not able to track compliance with other ZDCs that use a more liberal definition of *forest*.

The HCSA approach, in contrast, defines several forest classes including high-, medium-, and low-density forests and young regenerating forests, and additionally provides detailed guidance regarding inclusion or exclusion of forest patches depending on size and configuration for initial mapping (Rosoman et al. 2017). An HCSA monitoring system therefore needs to track corresponding forest loss within the same mapped forest categories.

Attributes contributing primarily to legitimacy. Legitimate mapping and monitoring systems are fair and unbiased according to societal or ethical standards. In the case of ZDCs, it is critical that these systems be transparent, that their implementation is independent from the influence of individual companies and producers using the system, and that they are inclusive and therefore designed with the input of all relevant stakeholders.

Transparency. We define transparency as the ability of a ZDC mapping and monitoring system to demonstrate adherence to ZDC methodologies (i.e., procedural transparency) and to ZDC criteria (i.e., outcome transparency; Auld and Gulbrandsen 2010). Making information on ZDC safeguarded areas and forest loss within these areas available and accessible to users is needed to enable vetting of processes and methodologies, which also contributes to the technical rigor attribute described above. In addition, this information can inform decisions and actions among a broad range of users (e.g., in procurement decisions, purchasing choices, regulation enforcement, third party impact assessments). Importantly, these often complex and difficult to interpret data must be distributed in a way that facilitates data access and interpretation (Gardner et al. 2019, Sasa and Acuña 2021).

PRODES spatial data on primary forest cover and loss used in the SoyM is freely and publicly available online and is accessible to users with basic skills in geospatial data analysis. However, data specific to the SoyM, including the map of soy cultivated on previously forested land and a list of noncompliant farms, are only shared with those actors who are part of the SoyM agreement. A nongovernmental organization (NGO) audits the SoyM monitoring process and results to ensure strict adoption of the criteria, and the GTS publishes an annual summary report.

Stand-alone HCSA assessments and associated peer review reports are publicly available online in PDF format (http://highcarbonstock.org/registered-hcsa-and-hcv-hcsa-assessments). However, as of June 2021, HCS land cover and its associated maps were only publicly available as images embedded within PDFs, which makes them inaccessible to most potential users for anything beyond qualitative analysis. The HCSA secretariat plans to make georeferenced plantation boundaries and indicative HCS forest and other conservation areas publicly viewable via a web GIS platform, although other information such as general land cover will only be available to the HCSA secretariat.

Independence. In the present article, independence is the absence of influence of the commodity producers on ZDC mapping and monitoring outputs and findings. Note that we are focusing in the present article on the influence of a commodity producer on mapping and monitoring processes, rather than on the design of a ZDC agreement, including for example the definition of deforestation. Although politics and relations of power are present in all assurance systems (Konefal and Hatanaka 2011), third-party relationships—where the entity conducting mapping or monitoring is separate from the entity controlling the property that is mapped or monitored—are often considered sufficient to ensure independent oversight of system implementation (ISEAL 2018).

In the context of the SoyM in Brazil, deforestation data are generated by the government, and ABIOVE contracts Agrosatélite (a private company) to analyze these data for properties of interest. Individual soy producers therefore cannot influence SoyM mapping and monitoring procedures and outcomes.

In the case of the current HCSA protocol, individual HCS mapping assessments are conducted by an assessment team composed of a licensed and registered lead assessor and at least one registered HCSA practitioner that is contracted by the company managing the property in question and is technically independent of the commodity producer. However, the nature of the assessment process, including the need for company cooperation and the potential subjectivities in HCSA definitions, may leave room in some cases for influence of the commodity producer on the outcome of the assessment. Indeed, members of related initiatives such as the RSPO have called for delinking of the contractual relationship between assessors, auditors, and their client companies to strengthen independence of the monitoring process (EIA 2015).

Inclusivity. Inclusive ZDC mapping and monitoring systems are designed via the participation of all potential users and affected stakeholders, including those who have been traditionally underrepresented. In addition, the implementation and results of these systems are periodically evaluated by a similarly diverse set of actors to ensure that they meet the needs of users. Indeed, one of the necessary conditions for the widespread institutionalization of nonstate market driven governance systems such as ZDCs is the promotion of democratic norms and multistakeholder participation (Bernstein and Cashore 2007).

Brazil's GTS coordinates the execution, monitoring, and evaluation of the SoyM. The GTS includes private sector (including ABIOVE and ANEC), civil society, and the Bank of Brazil.

The HCSA is managed by a steering group which, in consultation with technical working groups and a scientific advisory committee, designs mapping and monitoring guidelines, manages the assessor training program, and evaluates the approach via consultation with technical working groups. Notably, the current HCSA methodology emerged out of a conflict between two methodologies spearheaded by different groups but has since merged these parallel efforts (HCS Convergence Working Group 2016). The HCSA steering group now includes plantation companies, commodity purchasers, smallholder grower organizations, civil society, and technical support companies. In addition, the HCSA requires that producers clarify land tenure and community land use, support participatory mapping, identify locally important landscape features, and generate free, prior, and informed consent, which may increase output legitimacy among communities at commodity development sites.

Attributes contributing primarily to scalability. Systems are scalable if they are economically feasible at regional and national scales and across multiple years. Therefore, they should be cost effective to ensure adoption by many users, flexible so that they can be applied outside the initial use region or case, and sustainable so that they are available to users over time.

Cost effectiveness. Cost effective ZDC mapping and monitoring systems are those for which the benefits of using the system outweigh (or at least equal) the costs. Potential users will consider the cost of the system, and the degree to which use may confer benefits including access to markets, credit, or price premiums, and implications for brand reputation or consumer confidence (Rueda et al. 2017).

The overall cost of the SoyM mapping and monitoring system is relatively low, given reliance on free PRODES data and previous government efforts to map and register property boundaries. In addition, costs of mapping and monitoring fall to soybean traders, who use system outputs to identify, and purchase from, producers that meet the SoyM eligibility criteria. Therefore, soybean farmers do not pay to map primary forest or track forest loss within their property boundaries. Meanwhile, the market access benefits to producers of participating in the SoyM are substantial, because the ABIOVE traders control most soy exported from the Amazon biome (Ermgassen et al. 2020).

The HCSA mapping methodology requires intensive data collection and trained experts and is therefore relatively costly—on the order of US$100,000 per assessment, which, in Indonesia, often covers a single oil palm concession of around 10,000 ha. In Indonesia's palm oil supply chain, larger downstream companies are not able to conduct monitoring on behalf of producers because property boundary data is not widely available. Therefore, costs of HCSA mapping and monitoring fall on producers, and these initial costs are likely to be prohibitive for smallholder farmers and even smaller corporate plantations (Hutabarat et al. 2018). The HCSA is exploring mechanisms to share cost burden among smallholder farmers—for example, via landscape-scale indicative HCSA mapping pilot projects. The cost of regular monitoring will be another important consideration, because the HCSA develops its monitoring guidelines.

Flexibility. Mapping and monitoring systems are flexible if data collection methods and protocols can be applied in other biomes, regions, and countries while producing comparable results.

The SoyM mapping and monitoring system is based on the government's PRODES map of primary forest, which was originally developed for the Legal Amazon and has since been expanded to cover the Cerrado biome. This expansion could therefore support monitoring of a potential ZDC program in the Cerrado, which is expected to experience most soy expansion in the near future (Soterroni et al. 2019). PRODES will not support ZDCs outside Brazil, although similar approaches could be adopted by other governments.

The HCSA mapping protocol, on the other hand, is theoretically applicable to any forested landscape in the world, although as of 2019 the HCSA was only applied in the humid tropics. The HCSA toolkit and guidance are intended to be commodity, geography, and ecoregion agnostic and are intended to be applied across forested regions.

Sustainability. Sustainable ZDC mapping and monitoring systems are based on data that will be available and reliable over the long term. There has been a substantial increase in freely available high temporal and spatial resolution satellite imagery, and accessible open-source software tools capable of classifying such imagery. However, the production of consistent and comparable maps and analyses still requires a sustained commitment of resources.

PRODES plays a prominent role in monitoring and property registration across numerous government-led initiatives in Brazil. These include the Plan for Preventing and Controlling Deforestation in the Amazon and greenhouse gas flux estimation (Richards et al. 2017). The produced maps and analyses are anticipated to be available for the foreseeable future. Therefore, as long as pressure remains on soybean traders to participate in the SoyM, which is likely given that the SoyM has been extended indefinitely, the sustainability of the monitoring system is fairly certain.

On the other hand, HCSA mapping and monitoring systems are custom built on a range of available input data types, including both satellite imagery and extensive field data. Although the availability of input data is reliable over the long term—provided resources are available—the reliance on producing companies to pay for these relatively costly mapping and monitoring efforts may lead to sustainability and consistency challenges. As the HCSA considers monitoring data options such as GFC and GLAD, they will need to consider the extent to which these options will be reliably available over the long term.

Trade-offs between attributes

The SoyM and HCSA's approaches to mapping and monitoring highlight fundamental tensions across the 12 attributes outlined above. To illustrate, we highlight two specific trade-offs that serve as important considerations for the design of ZDCs.

Frequent detection or accurate monitoring. Effective ZDCs require mapping and monitoring systems that fulfill two complementary but differentiated use cases. First, highly accurate and carefully reviewed information is necessary to identify locations for protection, address noncompliance, and assess and communicate ZDC effectiveness. Second, frequent and near real-time data are needed to inform adaptive management and facilitate rapid responses to deforestation threats. Several rapid deforestation detection systems have been developed that are salient to the latter motivation, including the Sistema de Detecção do Desmatamento em Tempo Real na Amazônia (Shimabukuro et al. 2016), Terra-i (Reymondin et al. 2012), GLAD (Hansen et al. 2016), and RADD (Reiche et al. 2021). Historically, these systems were limited to moderate resolution imagery and generally reported substantially lower accuracy than annual change detection products, particularly for small disturbances (Tang et al. 2019). This is one explanation for why monitoring systems designed to support ZDC enforcement currently rely on data products with lower temporal resolution but higher accuracy, such as PRODES. It is possible that centrally coordinated, multistakeholder monitoring systems are best positioned to provide a process for annual definitive monitoring of ZDC violations, whereas individual companies or NGOs may develop their own real-time monitoring systems to support intraannual decision-making. However, improvements in the accuracy of near real-time forest disturbance detection may soon obviate the need for multiple systems (e.g., Reiche et al. 2021).

Local context dependence or large-scale consistency. ZDC mapping and monitoring systems will struggle to balance inherent trade-offs between local relevance, inclusivity, and categorical detail on the one hand, and consistency, frequency, and sustainability on the other (Dunn and Laing 2017, Auld and Gulbrandsen 2010). The HCSA builds credibility and legitimacy by aiming for high accuracy in specific geographies, integrating context-specific land-cover categories, and by including representation of community lands. In emphasizing local legitimacy and salience, the approach has, to some extent, sacrificed consistency—efforts to represent locally unique characteristics will inevitably lead to differences in definitions across landscapes. In addition, HCSA guidelines are less scalable because of the relatively high cost associated with locally refined assessments and, as a result, will be less frequently updated and may exclude some small-scale producers.

In contrast, many downstream purchasers desire globally consistent mapping and monitoring products that enable them to readily track networks of suppliers across multiple geographies or commodities. Similarly, government agencies, environmental NGOs, and academics who want to understand the impacts of ZDC initiatives on forest cover change processes at large spatial scales will require mapping and monitoring products that are available not only across countries or regions of interest, but also in areas where deforestation risk may increase because of leakage or spillover effects from ZDCs (Carlson et al. 2017, Heilmayr et al. 2020a, Heilmayr et al. 2020b). Comprehensive data on deforestation within the sphere of influence of a ZDC initiative, including areas that may be indirectly affected via markets, allows assessment of the extent to which displacement of deforestation undermines the net benefits of the program.

Recognizing limitations emerging from its locally tailored assessment procedure, the HCSA has begun to pilot several innovations to create more scalable solutions. First, it has begun to produce landscape-scale, indicative HCS maps that can serve as a starting point for more locally refined assessments. Second, the HCSA is testing the use of off-the-shelf monitoring systems such as the GFC or GLAD. These monitoring approaches are globally consistent, cost efficient, transparent, fully independent, and relatively sustainable. However, the extent to which a ZDC actor will be able to rely on such global data will depend largely on the accuracy of the data in the target geography, the extent to which it distinguishes salient forest cover classes, and whether it is perceived as legitimate by users.

In addition, the Indonesian government and other third parties (e.g., Barry Callebaut 2021) are developing indicative

HCS maps that may differ from individual HCS assessments. Differences in underlying forest definitions and accuracies between the locally refined HCSA assessments, national- or regional-scale indicative maps, and globally calibrated deforestation products, may introduce newfound confusion and could undermine the credibility of the HCS approach. Careful harmonization will be necessary to facilitate integration of multiple mapping and monitoring approaches.

Conclusions

We identified 12 ZDC mapping and monitoring system attributes that contribute to system credibility, salience, legitimacy, and scalability. We consider common trade-offs between these attributes and recognize that different attributes will be prioritized across diverse ZDC actors and use cases. Indeed, given the diversity of ecological, political, and social contexts in which ZDCs have been made, it is unlikely that a single unified approach to mapping and monitoring will adequately meet the needs of all users. Even a single ZDC may need multiple complementary systems to serve diverse needs (Tabor and Connell 2019). Our attribute framework can be used to evaluate the strengths and weaknesses of existing or potential mapping and monitoring systems, and to identify gaps that could be filled by integrating multiple approaches.

Companies around the world have signaled a commitment to eliminate deforestation from their agricultural production systems and global commodity supply chains. The effectiveness of these commitments will hinge in part on whether and how supply chain actors are able to act on their stated desire to protect forest ecosystems. Their ability to do so will depend, in turn, on whether the information from ZDC mapping and monitoring systems is credible, salient, legitimate, and scalable. Therefore, the design and implementation of ZDC mapping and monitoring systems that achieve these goals is a critical step toward protecting forest ecosystems globally.

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