

Digital sustainability tracing in smallholder context: Ex-ante insights from the Peruvian cocoa supply chain

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ABSTRACT

Global demand for sustainable agri-food products creates opportunities for smallholder farmers. But on-farm verification of sustainable practices is costly, making third-party certification inaccessible to many poor farmers. Digital technologies for tracing agri-food products from farm to fork could help: novel traceability systems, based on blockchain technology, can make data about on-farm practices transparently available to downstream stakeholders, enabling them to verify sustainability claims without external audits. There is limited understanding, however, of how such digital tracing systems fit local needs and capacities in smallholder contexts. Through a grounded theory approach, we explore the potential of digital traceability for sustainability monitoring in a case study in the Ucayali region of Peru. Based on interviews with local cocoa sector stakeholders, we identify two major challenges: first, setting up digital traceability systems requires investments that do not seem justified by corresponding increases in income. And second, relying on farmer-supplied data creates the risk of inaccurate information due to insufficient capacity as well as incentives for providing distorted data. Our findings suggest that strong cooperation along the supply chain is needed to ensure adequate return on farmer-side costs and investments. Focusing on sustainability metrics at the community level, in addition to the farm level, may be promising, as these metrics can be reliably collected by external stakeholders and add value beyond existing third-party certification standards. Our case study provides recommendations for local policy makers and supply chain stakeholders to develop inclusive digital sustainability tracing systems with smallholder farmers.

1. Introduction

Agriculture is a major source of livelihood for large parts of the global population, including many rural households in low- and middle-income countries [1]. Across the globe, agriculture faces multiple, interlocked sustainability challenges. For example, agriculture is a major driver of environmental degradation, contributing to habitat loss, soil erosion, or leaching of toxic substances into natural water bodies [2-4]. At the same time, in many parts of the world, low agricultural productivity and low profit margins threaten the economic viability of smallholder farming, contributing to widespread adverse social

outcomes, including poverty, food and nutrition insecurity, child labor, and violent conflicts [5-7]. Loss of agricultural productivity is set to worsen under climate change particularly in Africa, Latin America and the Caribbean [8]. Meeting the Agenda 2030 sustainable development goals will require farming systems to transition to environmentally sustainable, economically viable, and socially inclusive models [9-11].

In recent decades, there has been growing consumer demand as well as pressure from both policy and civil society for stronger sustainability in the production of some globally traded agri-food commodities. For example, the global market for certified organic food and beverages has been continuously growing for the last two decades, from USD 18 billion

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in 2000 to USD 129 billion in 2020 [12]. Likewise, industry initiatives such as the ‘Roundtable on Sustainable Palm Oil’ or the ‘International Cocoa Initiative’ have responded to market demand for more sustainably produced commodities by setting goals and standards themselves. Examples include commitments to halting deforestation, paying minimum wages, and reducing child labor [13,14]. These developments demonstrate considerable private sector interest in sustainable sourcing of agricultural products. In practice, however, verifying sustainable production can be challenging: multiple major commodities, including coffee and cocoa, are frequently sourced from smallholder farmers in weakly governed and under-resourced regions [15,16]. In these settings, evidencing compliance with sustainability standards can be challenging, as products are often aggregated from many small producers and sometimes pass through multiple intermediaries before reaching manufacturers and consumers [17,18]. On-the-ground audits performed by independent third-party certification bodies often serve to verify compliance at farm level. But for smallholder farmers in the Global South, the costs of obtaining and maintaining certification can be prohibitive, thus creating disincentives [19–21].

Over the last decade, the advent of blockchain technology and the growing availability of hand-held digital devices in smallholder regions have created new opportunities for end-to-end tracing of agricultural commodities [22–24]. Blockchain refers to a digital database technology where data points - for example, on supply chain operations and transactions - are replicated across a distributed network of computers. Due to decentralized data storage, data cannot be modified by any single stakeholders, and as data cannot be overwritten, the technology allows tracing recorded transactions along the supply chain. Therefore, there are high expectations that blockchain technology can increase transparency and accountability along food supply chains. Large retailers, such as *Walmart* or *Carrefour*, and major manufacturers, such as *Nestlé*, now routinely use blockchain-based supply chain tracing systems to trace back individual products to the region of origin or producer organization [25]. Predominantly, these systems are in place to monitor food safety (e.g., by tracking all products derived from one potentially contaminated lot of cocoa beans) or authenticate claims of unique origin, for example, for specialty cocoa or coffee [25–28]. Recently though, private sector initiatives have begun to explore the inclusion of sustainability metrics in blockchain-based supply chain tracing. These applications have, in general, been more consumer-facing, for example, by offering customers on-package QR codes to check the origin of a retail product along with the sustainability conditions of its production. Examples include fair-trade coffee that discloses all financial transactions along its supply chain [29], or organic oranges that come with information on harvest date, means of transport, and agronomic management data [30]. In the cocoa sector, multiple global enterprises, including *Barry Callebaut* and *Cargill*, have begun setting up fully traceable supply chains with the aim of substantiating sustainability claims and responding to customer demand for supply chain transparency [31,32]. Since 2020, *Olam International* claims 100 % traceability in their directly sourced cocoa supply chains [33].

These overall developments seem encouraging: digital end-to-end traceability could provide interested consumers insight into the sustainability of cocoa production, while providing small-scale cocoa farmers opportunities for accessing high-value markets [34]. In practice, however, the establishment of traceability systems may face highly context-specific challenges. For example, not all aspects of sustainability are equally well-suited for blockchain-based agri-food tracing, as some metrics are hard to verify without on-site inspections by independent auditing organizations, e.g., absence of child labor. Moreover, the successful introduction of digital technologies in agricultural supply chains requires a careful analysis of locally available technical infrastructure, required investments, and stakeholders’ digital literacy, as well as the specific design of the digital tools and the incentives associated with their use [21,24,35,36]. This means that highly context-specific analyses are needed to understand which technological approaches are viable

and may contribute to improved agri-food sustainability tracing by addressing key information needs of supply chains stakeholders [37].

Many studies on the use of blockchain and other digital technologies for agri-food sustainability monitoring explore technical feasibility (for example, [22,27,38–40]). Little attention has been paid, so far, to the human side of establishing such systems, that is, how they correspond to supply chain stakeholders’ interests, needs, and capacities. For many concrete supply chains, it is unclear what incentives need to be in place for whom, and what investments will be needed to successfully set up digital tracing schemes. Here, we present a locally explicit analysis, to explore concrete, practical opportunities for enhanced sustainability tracing of an important international agri-food supply chain: cocoa in Peru. We explore the perspectives of cocoa producer cooperatives and public policy makers to answer our research question:

How could digital traceability systems support sustainability monitoring in the Peruvian smallholder cocoa supply chain?

Adopting a case study approach, we engage with cocoa producers in the Ucayali region of Peru to explore existing experiences with tracing cocoa as well as expectations toward future participation in sustainability tracing, and identify gaps between existing technologies and local needs and capacities. Based on this analysis, this study aims at informing future efforts of co-designing case-specific sustainability tracing systems that will work for producer organizations in the Ucayali region of Peru.

The following Section 2 provides background information on agri-food sustainability monitoring and opportunities and challenges for supporting it through blockchain-based tracing. Section 3 describes the case study region and outlines our stakeholder interviews. Section 4 highlights key issues brought forward by interviewed cocoa sector stakeholders with regard to future digital traceability initiatives. Section 5 presents persistent gaps between available solutions and local context and discusses key actions for overcoming these gaps. Section 6 concludes with implications of our study for future digital traceability initiatives in smallholder context.

2. Background

Agricultural sustainability is a complex, multi-faceted phenomenon that is approached through various, sometimes competing paradigms. Despite varying priorities, calls for increased farming sustainability typically refer to reducing the harmful short- and long-run side-effects of food production and distribution on the biosphere, human health, and social equity [41–44]. In the cocoa sector, efforts by public, civil society, and private sector stakeholders to promote sustainable farming have predominantly emphasized achieving farmer living incomes, reducing the prevalence of on-farm child labor, and preserving local biodiversity by reducing deforestation or promoting agroforestry systems [45–48]. Because such sustainability-related achievements do not necessarily influence cocoa quality or flavor, they are termed ‘credence attributes’. This means downstream supply chain stakeholders, such as consumers, cannot easily verify respective claims and are bound to rely on the information they are given by upstream stakeholders [49]. Credence attributes are often monitored and guaranteed by third parties, such as governmental agencies (e.g., controlling and enforcing food safety) or non-governmental organizations (e.g., monitoring adherence to organic farming standards). Recently, there is growing interest in using digital end-to-end traceability tools, based on blockchain technology, for enhancing consumer trust in credence attributes in agri-food supply chains, as an alternative to costly third-party certification [50–52].

Many existing digital end-to-end tracing systems serve the purpose of verifying the source origin of agri-food products. In these systems, downstream supply chain stakeholders, such as manufacturer, retailers, or consumers, are enabled to trace products back to the region, producer organization, or even individual farm [26,53,54]. This is useful where the origin is the principal information need, for example, for verifying single-origin food products (such as specialty coffee) or to enforce food

safety requirements [26,28,37,55]. Fully traceable supply chains allow aggregators and retailers to quickly filter out suspicious product batches and hold producers accountable for contaminated products. There is, however, also recent academic interest in exploring the use of agri-food traceability to safeguard sustainability requirements. Regarding cocoa, for example, researchers have explored opportunities for tracing cocoa beans to verify that products comply with environmental sustainability requirements [39], are bought at fair farmgate prices [24], or follow 'zero deforestation' commitments [18].

Employing traceability systems for monitoring agricultural sustainability may pose multiple challenges, however. A key challenge relates to the absence of systematic ground-truthing of traced data. Third-party sustainability certifications, such as organic or Fairtrade, imply regular on-site audits by independent organizations to generate consumer trust [56]. Whether price premia or increased sales on new markets do justify the increased efforts of complying with sustainability standards as well as costs associated with certification is highly case-specific [57,58]. In contrast, end-to-end traceability systems offer a lower-cost option for farmers to access markets that demand evidence on farming sustainability. These systems, however, have only limited means to verify the veracity of data entered upstream. This can work well for some aspects of farming sustainability: only little on-site verification may be required, for example, for tracing the region of origin (e.g., to comply with 'deforestation-free' standards based on geolocated polygons of the production area and historical land use data) or fair payments (all monetary transactions are confirmed by the supply chain actors as they are stored in the blockchain) [24,59,60]. But the lack of stringent on-site audits creates opportunities for fraud: fraudulent claims about the conditions of production can allow producers to obtain a price premium while maintaining unsustainable practices [20,61]. This means that farmers, cooperatives, and agricultural companies may have a rational incentive to make false claims, for example, regarding social (e.g., use of child labor) and environmental (e.g., use of pesticides) sustainability requirements. Secondly, agricultural sustainability is a complex, multi-faceted, often gradual phenomenon, including aspects beyond on-farm practices, such as short distribution networks or decentralized food system governance [41,43]. The highly context-specific nature of measuring sustainability, demanding different parameters for different locations and commodities, can make it challenging to detect incremental changes in sustainability performance across the supply chain, or to compare alternative supply chains [56,62]. This complexity makes agri-food tracing for sustainability more challenging than for authentic designation of origin or food safety accountability [63].

3. Methods

3.1. Case study region

Ucayali is a region of central-eastern Peru, covering about 102,400 km². With roughly 630,000 inhabitants, of which 83 % reside in urban centers, the region's rural areas are sparsely populated [64]. The rural population predominantly relies on small-scale farming with limited inputs. Timber extraction and cash crop production, including cocoa, oil palm nuts, and coffee are important contributors to the local economy [65,66]. Yet in rural areas, poverty and inadequate access to infrastructure and basic services are widespread [65,67]. Overall, 17 % of the population of Ucayali live below the poverty line [68]. Ucayali borders Brazil to the east and forms part of the Amazon basin. Farming activities, in part by immigrants from other regions, as well as illegal logging and mining, have been driving high rates of deforestation in Ucayali [67]. Between 2001 and 2021, roughly 500,000 hectares of forest have been lost [69].

3.2. Cocoa cooperative manager interviews

The extant literature claims that the burden of sustainability

transitions in agri-food systems is often placed predominantly on upstream supply chain stakeholders, i.e., farmers and farmer organizations (e.g., [70]). Therefore, addressing these stakeholders' concerns and achieving their buy-in is key for sustainable innovation processes. To understand the perspective of local cocoa suppliers on the current state of sustainability tracing in the case study region, we conducted semi-structured interviews with selected key informants in October and November 2022. In Peru, four face-to-face interviews were held with representatives of cocoa farmer cooperatives / aggregators. These individuals were purposely sampled based on the research team's established relationships with organically certified cocoa cooperatives in the Ucayali region of Eastern Peru. All four interviewees held leading executive positions in their cooperative (termed 'gerente'/manager or 'presidente'/chairperson in Spanish), having been in that position for an average of three years at the time of research. They were three men and one woman, aged 59 years on average. Two had completed secondary education, one held a university degree in agronomy, and one held a post-graduate degree in rural development.

At the time of research, the four cooperatives included 661 farmers (between 13 and roughly 500 members per organization) with cocoa plot sizes ranging from about 2 ha to 10 ha, on average. In recent years, yields had typically been in the range of 800–1200 kg/ha/year. Raw cocoa beans were generally sold locally to export companies targeting the European and US markets. The majority of the production is EU Organic and Fair Trade certified. Interviews dealt with three major topics:

- Stakeholders' involvement with, or awareness about past and current tracing initiatives
- Challenges and perceived limitations of past tracing initiatives
- Needs, hopes, and expectations towards future tracing initiatives

3.3. Policy maker interview

To understand the perspective of national authorities on the question of sustainability tracing, and situate the private sector's perspective in the policy context, we carried out a semi-structured interview with the senior officer in charge of the cocoa supply chain within the Peruvian Ministry of Agricultural Development and Irrigation (MIDAGRI). Like the interviews with cocoa cooperative representatives, this interview explored existing experiences, perceived challenges, and future needs and expectations towards digital sustainability tracing. In addition, we discussed the current practice of downstream supply chain stakeholders for verifying sustainability claims, and opportunities for policy makers to support greater transparency and traceability in the cocoa sector.

3.4. Data analysis

We employed a grounded theory approach to generate insights from the interviews. Grounded theory is a research technique for inductively deriving an understanding of a research topic by analyzing qualitative data in an open-ended manner [71,72]. Using this approach, insights emerge from iteratively analyzing and systematizing qualitative data, such as interview transcripts [73]. For this, all interviews were transcribed verbatim (in Spanish), and transcripts were subjected to free, fully inductive coding, using MaxQDA 2022 software [74]. Codes are thematic labels assigned to segments of the qualitative data, representing a specific idea or topic present in the interviewee's respective statement. Major themes were identified by grouping codes into coherent categories. By identifying the relative prevalence and wider context of different themes across the difference interviews, we derived meaning, allowing us to answer our research question. Ethical authorization for interviews had been granted by the Institutional Review Board of the Alliance of Bioversity International and CIAT under code 2022-IRB38.

4. Results

4.1. Local cocoa supplier perspectives on digital sustainability tracing

Qualitative content analysis of interviews with four cocoa cooperative leaders in Peru revealed four major themes. These are: (i) cocoa supplier priorities among different aspects of sustainability, (ii) farmers' limited capacity for implementing sustainable on-farm practices, (iii) cooperatives' limited capacity to monitor and ground-truth sustainable practices, and (iv) existing experiences with tracing along the supply chain.

Theme 1: Perspectives on sustainability

Fig. 1 provides an overview of major topics brought up during the interviews, aggregated by dimension of sustainability. All three core dimensions of sustainability were mentioned by interviewees, but economic sustainability aspects were most strongly emphasized. Cooperative managers' perspective on their core mission could be summarized as 'ensuring and increasing business profitability for the benefit of active members'. This included efforts of (i) improving yields, for example through provision of capacity building technical assistance and agricultural inputs, (ii) achieving satisfactory sales prices, for example by building strong relationships with buyers or obtaining group organic/fair trade certifications to enter premium export markets, and (iii) promoting value-addition, for example by supporting the production of chocolate products for local sale or offering to process farmers' non-cocoa products for better marketability.

Environmental sustainability was also brought up by all interviewees, albeit in less detail and mostly as a means to ensure economic sustainability. Sustainable practice was generally defined by the interviewees as fulfilling the requirements of organic labeling. Two cooperatives also mentioned efforts of forest preservation, in response to demand for deforestation-free cocoa from their buyer or certification by *Fair for Life*.

Little explicit emphasis was placed on aspects of social sustainability. Representing a farmer-owned organizations, one cooperative leader expressed commitment to monitoring and promoting local development:

speaking of existing socio-economic survey efforts among cooperative membership, "this will allow us to compare annually, to see how the farmer has improved at the family level and at the community level, and to see the impact of the [cocoa] crop on its environment" (Coop 1). Another interviewee highlighted the cooperative's efforts towards farm and livelihood diversification, also promoting food crops besides cocoa. Interestingly, this also strengthened the link with the cocoa buyer: "as a cooperative we have been trying to discuss with the buyer, they liked the way we work, not only with an isolated product but with the whole environment where the cocoa is produced." (Coop 2) Linked to the avoidance of agrochemicals, two cooperative leaders also highlighted their perceived responsibility towards consumers' health: "so it justifies working organically because you sell at a good price and you protect the health of whoever buys your product (...) wherever it goes, they will consume your product without contamination." (Coop 4)

Throughout the interviews, it became clear that the willingness to monitor and enforce sustainable practice (by organic standards, in particular) is determined by financial incentives (i.e., enhanced economic sustainability). Cooperative leaders stressed the need to increase farmers' incomes above all. For the cooperatives, supporting farmers' implementation of organic farming requires significant investments into staff time, and these investments must be justified by adequate financial returns from higher turnover.

Theme 2: Farmers' capacities for implementing sustainable agriculture

All interviewees highlighted the need for building farmers' capacity to enable them to implement environmentally sustainable, i.e., organic, cocoa farming. They emphasized the high, sometimes prohibitive costs associated with regular trainings and on-site technical support to the cooperative members, as one cooperative leader puts it: "implementing a proper [sustainability] program requires a lot of cash investment into technicians, sometimes the price does not justify [the investment]" (Coop 2).

Beyond technical skills, generating farmer buy-in for environmentally sustainable practice seemed to be a widespread challenge, however. Cooperative leaders criticized the difficulty of ensuring farmers'

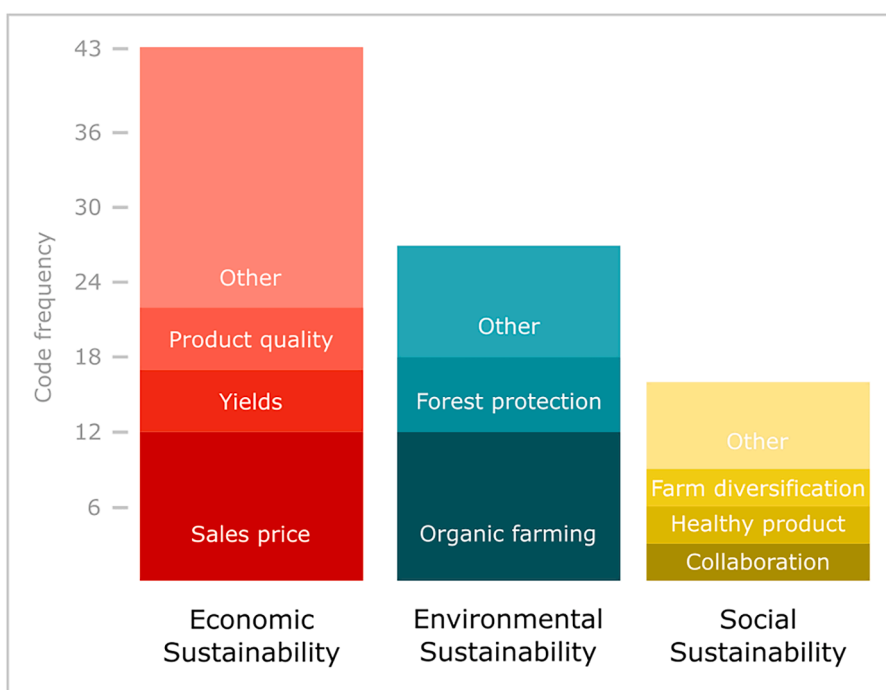


Fig. 1. Sustainability-related topics mentioned by cocoa cooperative managers. The height of bars corresponds to the number of times a topic was mentioned across the four interviews (frequency of the code in interview transcripts). Only the most frequent topics are shown in the figure. Full data on frequency of codes, including the ones subsumed as "other", are provided in the Appendix (Supplementary materials).

compliance with environmental standards due to farmers' overall low level of environmental awareness. Some farmers were suspected of shirking (e.g., implementing sustainable practice on parts of the farm, only) or fraud (e.g., by over-reporting yields and buying conventional cocoa to mix it in with one's own, organic harvest). This increases the need for consistent on-the-ground monitoring by skilled staff, creating additional effort and cost ("up to twice a week because we really need to make sure the beans are organic" Coop 4) and contributes to frustration probably best summed up by this interviewee: "*the members complain, but I tell them it's your fault, the technician needs to supervise you like children to make sure you follow the rules.*" (Coop 2) These challenges make approaches that rely on farmers' reporting for monitoring environmental sustainability seem unlikely to work in the study context.

Theme 3: Cooperatives' capacities for monitoring sustainability

The cocoa cooperatives generally collect three types of data with relevance to sustainability. First, all four organizations carry out member surveys annually, or less frequently, to collect socio-demographic data about farmers' households (e.g., family composition, farm sizes) and living conditions in their communities (e.g., access to medical services, quality of access roads). Second, two cooperatives also collect data on tree populations on farmers' land, including both forest patches and shade trees in productive plots. And third, in all cooperatives, field technicians collect data on agricultural activities at higher frequency (at least monthly), for example, on farming activities, inputs used, or yields. Data are generally enumerated orally from farmers and recorded on paper by cooperative staff during farm visits and personal meetings.

In addition to doubts about the veracity of farmers' reporting (see above), interviewees mentioned the difficulty of incentivizing or motivating farmers to collect and provide data about farming activities at all. In all cooperatives, farmers are requested to track all farming activities in a booklet, and this data is then typically copied by technicians as they visit the farmers. At present, however, farmers do not always maintain their records as required, due to limited motivation and/or lack of formal education (i.e., literacy). There were thus general reservations against relying on farmers for data collection in sustainability tracing, as exemplified by this quote: "*the bottleneck is who supplies the information, if it's the technicians, we need more technicians [...], if it's the members, we know they will not do it*" (Coop 1).

Farm data are, therefore, typically copied by technicians on paper and later digitized in excel sheets. Some experiences with using more sophisticated digital tools for on-farm data collection have been reported, including the use of *iForm* mobile app by technicians. An experiment with farmers collecting on-farm data using smartphones (through the 'MOPAS' platform developed by the United Nations Development Programme, *mopasperu.org*) failed due to farmers' reluctance or inability to use it (Coop 1). In result, there are only limited existing experiences of farmers or cooperative staff using digital tools for collecting on-farm data. The resulting gaps in digital availability of data about farming practice limit the cooperatives' abilities to understand the current state of sustainability in their activities.

Theme 4: Experiences with supply chain tracing

The cooperatives trace cocoa beans internally, from individual farmers to the export batches, as required by organic certification. For every export batch, information is maintained on which members' cocoa beans are included and at what proportions. Thus, product traceability is ensured within the organization, but not across supply chain stakeholders, yet. To date, no specific digital systems for tracing cocoa beans along the supply chain have been used. In principle, the available information on which farmers supplied an export batch can be linked with existing data about these farmers' on-farm practices and other aspects of sustainability, to assess the degree of sustainability of each batch. Regarding this type of analysis, one interviewee mentioned having inquired about a blockchain-based traceability system. After speaking to colleagues at other cooperatives, they concluded that such systems were too complex and currently low market demand did not justify the required efforts: "*I talked to other cooperatives about their experience and*

they consider it very complex and said, don't put yourself in this. They had the pilot, it doesn't convince them, (...) there are few clients who demand blockchain, the volume they will offtake does not justify implementing this" (Coop 1).

4.2. Policy perspective on digital sustainability tracing

Our expert interview with a representative of the Ministry of Agriculture highlighted existing challenges in cocoa sustainability tracing, as well as opportunities and policy priorities for the future. According to the respondent, key government interests include ensuring that Peruvian cocoa complies with food safety regulations, fully avoids the use of child labor, and minimizes greenhouse gas emissions associated with production. To date, there is no country-wide standardized assessment of these metrics, however. One important insight refers to the fact that most export cocoa is already third-party certified, for example, according to organic, Fairtrade, or Rainforest Alliance standards. To increase the value proposition for supply chain stakeholders, therefore, traceability systems should focus on sustainability metrics that are not yet covered by common certification schemes. This might include, for example, metrics referring to social cohesion, participatory governance, land tenure, or overall on-farm biodiversity. Some small-scale initiatives have recently begun setting up tracing systems for Peruvian cocoa, mostly supported by agencies of international cooperation. In practical terms, the first steps for establishing end-to-end traceability consist of georeferencing farms, and enabling autonomous data collection by farmers or farmer organizations, using user-friendly digital services.

5. Discussion

5.1. Overcoming gaps between local cocoa stakeholder needs and existing solutions

Our analysis of the prevalent themes discussed by cocoa sector stakeholders revealed two principal gaps between what cocoa supply chain actors expect and what existing digital tracing solutions offer. The first gap consists of a perceived lack of added value of traceability systems over current third-party certification (see Section 4.1, theme 1 - emphasis on economic sustainability, theme 2 - high cost of training and deploying data enumerators, theme 4 - little demand for end-to-end traceability, and Section 4.2 - prevalence of sustainability certification). The second gap refers to a general lack of user-friendly technical interfaces for real-time upstream data entry (see Section 4.1, themes 2 and 3 - data collection is cumbersome and unreliable, implementation of digital interfaces is hindered by low digital literacy, and Section 4.1, theme 4 - tracing system perceived as overly complex).

This first gap rests on the fact that certification standards, such as EU organic or Fairtrade, cover key aspects of sustainability, including biodiversity protection, soil protection, and adequate labor conditions [19,47,75]. Certification bodies, such as *Ecocert* or *FLOCERT*, are locally present and have established ties with producer organizations. In principle, end-to-end traceability could help increase buyer trust by hampering the intermixing of conventional cocoa with sustainably produced products [76]. However, lack of trust does not seem to limit market demand in our study case, as the domestic and international buyers targeting a premium market generally accept the independent audits performed by certification bodies typically once per year. As a result, there is limited articulated demand from buyers for fully traceable cocoa. This means that supply chain stakeholders have little (financial) incentive to establish traceability systems in addition to third-party sustainability certification. In other contexts, high upfront costs for establishing blockchain-based traceability systems have been highlighted as a disincentive for the adoption of current technical solutions [38,77,78]. More so, these costs are not always equitably shared among supply chain stakeholders, often placing the burden of investment primarily on upstream stakeholders, i.e., farmers and their

organizations [21]. But because farmer organizations often cannot anticipate whether these investments will pay off, they have limited incentives to establish digital supply chain traceability systems [24]. Some third-party certifiers, such as *Rainforest Alliance*, have been gradually implementing traceability schemes themselves, however [79]. This may imply that participation in tracing systems will, sooner or later, become commonplace for sustainability-oriented producer organizations, which underscores the need for addressing the second gap. Also, the fact that multiple major global cocoa buyers have committed to full traceability indicates growing consumer demand and future opportunities also for farmer organizations selling to intermediaries [31-33].

The second major gap relates to a mismatch between complex digital solutions and relatively low digital literacy of local cocoa farmers. Use of smartphones and mobile internet are not widely common among cocoa farmers in Ucayali. In this region, there are 64 mobile internet connections for every 100 inhabitants [80]. This suggests relatively low digital readiness, compared to, for example, 103 mobile internet connections per 100 inhabitants across Peru as a whole [81]. Technical and infrastructural weaknesses in smallholder farming context, as well as little digital experience among farmers, have been reported to limit the viability of digital traceability systems in other places, including West Africa and Indonesia [18,24,82,83]. Therefore, in the study region, current systems of agricultural data digitization - for example, for reporting towards certification bodies - largely rely on one of two strategies. The first is reliance on paper records that were originally created by farmers or cooperative staff and are digitized at a later point. This strategy, however, faces multiple challenges, including farmers' limited literacy. Although adult illiteracy in the Ucayali region is estimated at just 4.3 %, only 3.6 % of the adult population achieve 'satisfactory' results in reading and calculating at primary-school level [80]. These low levels of formal education limit farmers' capacity to provide complete and accurate datasets. On the side of cooperative employees, the increased workload of digitalizing messy paper records is likely to discourage this strategy. The second strategy consists of digitally enumerating data from farmers at the point of delivering produce to the cooperative, using a computer. Enumerating data from farmers weeks or months after the respective events, however, can lead to inaccurate recall [84,85]. In addition, relying on farmer-reported data for sustainability assessment may lead to the underestimation of sustainability concerns due to social desirability bias or even fraud [86].

Altogether, these findings suggest that, to be successful, initiatives for digital sustainability tracing in the Peruvian cocoa supply chain need to address the following criteria. First, cocoa supply chain stakeholders require clear financial incentives for participating in the traceability scheme. This is particularly relevant for farmer organizations, which are expected to bear the major burden of data collection for ground-truthing sustainability claims. Thus, it needs to be ensured that the effort associated with establishing end-to-end traceability is rewarded: this may be achieved by fetching higher sales prices on premium markets. Alternatively, investments in the form of regular, direct payments from government and private sector actors, such as certifiers or industry associations, may be needed to cover the farmers' time spent collecting and entering data, rather than expecting this to be done by farmers or cooperative employees on a voluntary basis. The recent large-scale implementation of traceability schemes by major global cocoa buyers promises to increase transparency on sustainability claims, but it remains unclear how cocoa producers are compensated for any additional efforts [31-33]. Farmers or cooperative employees who record on-farm data through digital tools incur opportunity costs, and producer organizations may need to invest significant time into initial capacity building and recurrent re-training. Ex-ante consumer research can help estimate the growth in turnover associated with providing information on specific aspects of sustainability (see [87]). Then, strong partnership and trust among supply chain stakeholders are crucial for a fair sharing of costs, benefits, and risks (see [70,88]).

Second, to ensure proper ground-truthing of sustainability claims at

manageable costs, tracing initiatives might focus on metrics at community level in addition to farm level, such as levels of political participation, presence of farmer-facing services, or rate of youth in education (social sustainability) [89,90]. It may also be useful to use metrics that change slowly and can thus be reliably enumerated at arbitrary moments, for example, diversification of cocoa farmers' livelihoods (social sustainability), or on-farm crop diversity or tree cover (environmental sustainability). To minimize additional effort for farmers, it will be important to emphasize simple metrics for which data need not be elicited at highly specific points in time, but that can ideally be assessed during regular farm visits by cooperative staff.

Third, effective end-to-end traceability will likely need to avoid (i) paper-based data collection and (ii) relying on farmers for data collection. An emphasis on digitally enabled data collection by cooperative staff during their visits to georeferenced farms seems warranted. For this to work, blockchain-based traceability systems need seamless integration with mobile apps for offline data collection, such as ODK Collect [91] or Kobo Collect (kobotoolbox.org).

5.2. Priorities for developing digital sustainability tracing schemes

Several priorities have emerged for the future development of digital systems for tracing sustainability metrics along the cocoa supply chain. It has become clear that any efforts must emphasize increasing farmers' income and the economic sustainability of cocoa production. This may seem obvious, but in practice, transitions towards increased agri-food sustainability risk disempowering farmers by placing additional burdens exclusively on them and offering little alternatives [21,70]. Because in our study region, most cocoa farmers already comply with one or multiple sustainability standards (see also [47]), on-farm practice may require no or only limited adaptations for being integrated in sustainability tracing initiatives. Nevertheless, to ensure that tracing leads to greater profitability, costs linked with staff training, IT set-up, on-the-ground data collection, and external audits must be kept to a minimum. To keep costs low, cocoa traceability schemes may need to capitalize on existing solutions. Minimizing initial investments may require adopting freely available, open source blockchain frameworks, such as *Hyperledger Fabric* [23,24]. Alternatively, employing ready-made commercial solutions, such as *farmer connect* (farmerconnect.com), *farmforce* (farmforce.com), or *trusty* (en.trusty.id) avoids major investments into software development and ensures implementation of an established and tested system at a pre-agreed license cost.

Another key insight refers to who is put in charge of collecting on-the-ground sustainability data, and if simple verification protocols can be incorporated into the collection process. Because farmers are observed to under-report unsustainable behavior, cooperative managers argued that data collection needs to be carried out by the cooperatives' field staff. This strategy, however, seems unlikely to eradicate the risk of false sustainability claims, as cooperative staff are expected to work for the economic benefit of the cooperative members, rather than police them. In principle, observations made by field staff can be independently confirmed through time-stamped and georeferenced photos [92-94]. Also, farmers' reporting on certain management practices can be verified at later moments using clearly defined bioindicators. For example, sparse herbaceous plant growth between crops can indicate pesticide use, or eutrophication in on-farm waterways can indicate excessive fertilizer use. But such external proofing creates work for external auditors and thus bears costs. Alternative ways for ground-truthing data at low cost can consist in overlaying farm polygons with satellite imagery, which allows assessing key sustainability metrics, including tree cover, with no need for recurrent interventions by field staff ([95], see also *globalforestwatch.org*). Considering local technical capacities, however, a more viable strategy might consist in relying exclusively on sustainability metrics at community level, rather than only farm level, which can be relatively easily verified by other supply chain stakeholders (see previous Section). Collaboration between

multiple stakeholders along the supply chain is needed to identify metrics that can be reliably elicited locally and contribute to national or market-based sustainability reporting needs, while also enabling price premia or triggering public payouts (e.g., through REDD+ carbon credit schemes, [96]) to enable cost recovery for farmers' sustainability transitions.

6. Conclusion

In this study, we evaluated the potential of using digital supply chain sustainability tracing for agricultural products from smallholder farms. We used the cocoa sector in a rural region of Peru as a case study. Our findings indicate that there are important limitations to the implementation of existing digital tracing systems. Firstly, the marginal livelihoods of many cocoa farmers imply that any investments in sustainability monitoring systems must be linked to clear benefits in terms of increased income. Collection of on-farm data requires time commitments by trained farmers, creating opportunity costs. Currently, however, there is limited evidence that fully traced cocoa supply chains will increase incomes, as most cocoa in the study region is already third-party certified and designated for premium markets. Secondly, existing digital traceability tools are often not suited to local challenges, including farmers' illiteracy, and limited digital infrastructure in remote areas. In summary, our findings point to a twofold answer for the research question: how could digital traceability systems support sustainability monitoring in the Peruvian smallholder cocoa supply chain? First, end-to-end traceability schemes must increase farmers' net profits, as local stakeholders are hesitant about any investments (into technology, training, or cooperative staff) with uncertain return. Second, ensuring data accuracy requires close consideration and may be addressed by an adequate choice of sustainability metrics, as well as private or public investments into farmer training and user-friendly digital interfaces for offline data entry.

Our case study findings have practical implications for the cocoa sector in Ucayali region, Peru. With growing demand for transparency about the origin and production conditions of agri-food products, end-to-end traceability is expected to become more widespread. European legislation requires all cocoa suppliers to verify deforestation-free supply chains, making digital tracing more common practice among cocoa suppliers targeting the EU market. Given the observed challenges, our findings suggest that initial efforts to trace sustainability metrics could focus on the community level, rather than only individual farms. This would avoid the need to elicit data from farmers and organizations, which currently seems costly and unreliable. In the long term, however, investments from the cocoa industry, development agencies, or public authorities may help enhance local capabilities for simple data collection at the farm level. This could involve the deployment of digital data entry systems that do not require internet connectivity, such as IVR or USSD, as well as training for farmers and fair compensation for providing accurate on-the-ground data on key sustainability indicators. Future research should focus on the design of technical interfaces to comply with local farmers' levels of digital experience and knowledge about sustainability issues. Participatory research with diverse supply chain stakeholders, including farmers, but also traders and consumers, could help identify feasible incentive mechanisms and payout schemes that ensure increased farmer-side efforts are adequately compensated by higher incomes.

Our case study approach, focusing on only few key informants, bears limitations with regard to the generalizability of findings to other smallholder regions or commodities. The identified principal challenges for implementing state-of-the-art traceability solutions - marginal, risk-averse livelihoods and low digital capacity in rural areas - are likely to affect other smallholder contexts as well. Nevertheless, strong heterogeneity in smallholder farming environments and commercial supply chain management implies that context-specific studies may be required to evaluate the concrete requirements, barriers, and opportunities for

introducing sustainability tracing in concrete value chains. Our study provides an example for such ex-ante explorations.

CRedit authorship contribution statement

Jonathan Steinke: Writing – original draft, Formal analysis, Conceptualization. **Yovita Ivanova:** Writing – review & editing. **Sarah K. Jones:** Writing – review & editing. **Thai Minh:** Writing – review & editing. **Andrea Sánchez:** Writing – review & editing, Investigation. **José Sánchez-Choy:** Writing – review & editing, Investigation. **Jonathan Mockshell:** Writing – review & editing, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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