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PERSPECTIVE

From chocolate to palm oil: The future of Indonesia's cocoa plantations

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Abstract Indonesia is the world's third largest cocoa producer, but production is decreasing since 2011. We revisited cocoa farmers for an environmental assessment in Luwu Timur, Sulawesi, 7 months after a socio-economic survey on cocoa certification outcomes and observed many cocoa plantations being converted into oil palm and maize. Including our field data as well as secondary data on commodity prices and yields, we outline reasons for cocoa conversion, potential consequences for biodiversity, and assess the future outlook for the Indonesian cocoa sector. Low cocoa productivity, volatile cocoa prices and higher revenue for oil palm, among others, drive land-use change. If shade trees are cut during cocoa conversion, it may have negative implications for biodiversity. Solutions to low soil fertility, omnipresent pests and diseases, and stable producer prices are needed to increase profitability of cocoa and prevent conversion of cocoa agroforests to oil palm monocultures.

Keywords Certification · Cocoa · Indonesia · Land-use change · Maize · Oil palm

INTRODUCTION

Indonesia is the third largest cocoa producer in the world, producing 13% of global cocoa supply (FAOSTAT 2023). Most of the Indonesian cocoa is produced on Sulawesi (60%) and the sector is dominated by smallholders (99.7%) farming between 0.5 and 2 ha of cocoa (Ruf and Yoddang 2004; USAID 2006; Badan Pusat Statistik 2021). The cocoa tree *(Theobroma cacao)* was introduced to Indonesia in the sixteenth century but production initially remained low: in 1980, cocoa plantations covered only around 19 000 ha producing 10 000 tons of cocoa (Fig. 2a, c) (Smiley and Kroschel 2010; FAOSTAT 2023). Triggered by a spike in the global cocoa price, cocoa production increased exponentially to around 844 000 tons in 2010 and the area planted with cocoa peaked in 2012 with 1.85 million hectares (FAOSTAT 2023). In the last decade, however, cocoa production decreased by 13% and was around 728 000 tons in 2021 (FAOSTAT 2023).

While cocoa production has been decreasing, palm oil production in Indonesia has been steadily increasing and maize production stagnating: Within 10 years, palm oil production doubled from 21.95 million tons in 2010 to 44.75 million tons in 2020, making Indonesia the world's largest palm oil producer and palm oil one of the country's most valuable export commodities (FAOSTAT 2023). Oil palm plantations now cover more than 15 million hectares (8.3 million in 2010) and the sector contributes to about 4.5% of the GDP (Gardner and Rylander 2022; FAOSTAT 2023). The area planted with maize fluctuated around 4.2 million hectares in the last decade (SD 0.7 million ha). Maize is produced for the domestic market, for food and livestock, and only limited quantities are exported (< 1% production quantity) (Kementerian Pertanian 2017).

During an environmental assessment of cocoa plantations in Sulawesi, Indonesia, between July and October 2023, we observed many cocoa plantations being converted into oil palm and maize. Using our field observations and including data from a socio-economic survey, stakeholder

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interviews and farmer focus group discussions on cocoa certification conducted in the same study area in 2022 as well as secondary data on commodity yields, global commodity prices and local producer prices, we outline reasons for farmers to convert cocoa, explore potential consequences for biodiversity arising from the land-use change, and assess the future outlook for the Indonesian cocoa sector.

METHODS

We conducted our study in the district of Luwu Timur in the province Sulawesi Selatan in Indonesia. In Sulawesi Selatan, the area under cocoa in 2021 was 182 000 ha, producing around 93 000 tons (13% of national production; 4% of land area in Sulawesi Selatan) (Badan Pusat Statistik 2021). The climate in the area is tropical humid, temperatures ranging from 23 to 32 degrees and rainfall from 107.1 to 283.8 mm per month (Weather Spark 2023). December to June are months with higher rainfall (> 200 mm) while July to November are drier (< 200 mm) (Weather Spark 2023). Around 33% of the land in Luwu Timur is considered moderately suitable for cocoa cultivation with limitations arising from nutrient availability, 58% is marginally suitable with additional limitations from terrain (slope), erosion and poor drainage, and 9% of the land is unsuitable for cocoa cultivation (Neswati et al. 2019). In the visited villages, cocoa cultivation takes place on moderately as well as marginally suitable land.

Only little remnant forest remains, mainly on steep slopes and in the mountainous areas in the north of Luwu Timur, as much forest was lost and degraded during the cocoa boom in the 1980s and 1990s with cocoa plantations replacing forests as well as cocoa being planted in thinned forests (Rice and Greenberg 2000). The area at lower elevation towards the coast is dominated by smallholder agriculture, primarily oil palm, paddy rice and cocoa, as well as large (state owned) oil palm plantations. Furthermore, there is nickel mining by foreign investors in the area.

Between October and December 2022, 600 cocoa farming households located in 30 villages in the three districts Luwu, Luwu Timur and Luwu Utara, Sulawesi, Indonesia, participated in a socio-economic survey on cocoa certification outcomes (Bemelmans 2022, unpublished data). Among others, the purpose of the survey was to assess if and how certification of cocoa farmers influences cocoa production and household income. For the selection of the 600 farmers, all known villages where cocoa certification was present were mapped. Then, in each district, ten villages were randomly selected; and, in each village, ten certified and ten non-certified farmers were randomly selected and surveyed. The survey data were complemented with 40 key-informant interviews and four focus group discussions with certified producers to get insights into how certification schemes are implemented (Depoorter 2022, unpublished data).

Between July and October 2023, we revisited the ten villages located in the district Luwu Timur and purposely selected 62 cocoa plantations in six villages with a minimum size of 0.2 ha and a slope below 20 degrees to conduct an environmental assessment. The purpose of the environmental assessment was to compare vegetation structure, soil fertility and bird species richness between certified and non-certified cocoa plantations. We selected 31 plantations certified under Rainforest Alliance and 31 non-certified plantations (Fig. S1, Supplementary Information). Rainforest Alliance (RA) certification aims to enhance sustainability in agricultural production requiring cocoa farmers, for example, to refrain from deforestation, keeping a minimum native vegetation cover on plantations and limit agrochemical use (Iddrisu et al. 2020; Rainforest Alliance 2020a, Rainforest Alliance 2020b). In return, certified cocoa farmers (in theory) receive a premium as well as training. However, in practice, we observed that only 64% of certified farmers received a premium (Bemelmans 2022, unpublished data). A non-systematic distribution of price premiums has also been observed in other studies on certification outcomes (Amuzu et al. 2022; Sadeu et al. 2023).

During the environmental assessment, we found that many cocoa plantations were converted or are about to be converted to other production systems, particularly to maize and oil palm (Fig. 1). To explore the trend of cocoa conversion and its implications for biodiversity, we use our observations from both the socio-economic survey and the environmental assessment, as well as the key-informant interviews and the focus group discussions conducted in 2022 and 2023 on cocoa certification in Sulawesi. Furthermore, during the environmental assessment, we had informal conversation with farmers, village representatives and local authorities to understand the problems farmers face in cocoa cultivation and what drives them to convert their cocoa. We include FAO data on area harvested, production quantity, and yield for cocoa, oil palm and maize for Indonesia (FAOSTAT 2023). To include commodity prices and price variability in the analysis, we use primary commodity prices from the International Monetary Fund (IMF) (IMF 2023). Additionally, we use producer prices from the Indonesian Palm Oil Farmers Association (*Asosiasi Petani Kelapa Sawit Indonesi,* APKASINDO) and the Commodity Futures Trading Regulatory Agency, Ministry of Trade of the Republic of Indonesia (*Badan Pengawas Perdagangan Berjangka Komoditi, Kementerian Perdagangan*, BAPPEBIT) (APKASINDO 2024; BAPPEBTI 2024). IMF takes data for cocoa from the

Fig. 1 Cocoa, oil palm and maize cultivation in Luwu Timur, Sulawesi, Indonesia: **a** cocoa plantation intercropped with gliricidia *(Gliricidia sepium)* and pepper *(Piper nigrum),* **b** conversion of cocoa plantation to oil palm with shade trees already cut and cocoa trees being cut once oil palms reach certain height, **c** smallholder oil palm plantation adjacent to cocoa plantation, **d** young oil palms intercropped with maize. Photos were taken by Saskia Dröge

International Cocoa Organisation (ICCO 2023b), for palm oil from the Malaysia Palm Oil Futures (Bursa Malaysia 2023) and for maize from the US Department of Agriculture (USDA 2023). We use the data on average annual yields and the producer prices to calculate gross revenue per hectare for the three commodities. We then use the data given in Nasution et al. (2019) for input costs (e.g. plantation establishment, fertiliser, labour) for cocoa and oil palm to calculate and compare the net revenue per hectare. Data on maize input costs were not available.

RESULTS

During the environmental assessment between July and October 2023, about 7 months after the first socio-economic survey, we observed that some cocoa plantations were already converted to other land uses while other farmers were planning conversion. In Lauwo, for example, four cocoa plantations were converted to other land uses, representing 14% of plantations included in the socio-economic survey in the village. Of the 62 cocoa plantations eventually selected for the environmental assessment, seven plantations (11%) had young oil palms interplanted, with the aim to cut cocoa trees and remaining shade trees once the oil palms overgrow cocoa trees (Fig. 1b). This trend was corroborated by observations we made along the road during the environmental assessment when passing villages and plantations not included in the socio-economic survey. This trend was confirmed by farmers, village representatives and local authorities in informal conversations during the environmental assessment. At national level, FAO data show a decline in cocoa production area and quantity since 2010 (Fig. 2a, c), while for oil palm and maize, the area harvested and the production quantity has been steadily increasing (Fig. S2). During the informal conversation with farmers, we asked for the reasons to convert cocoa to

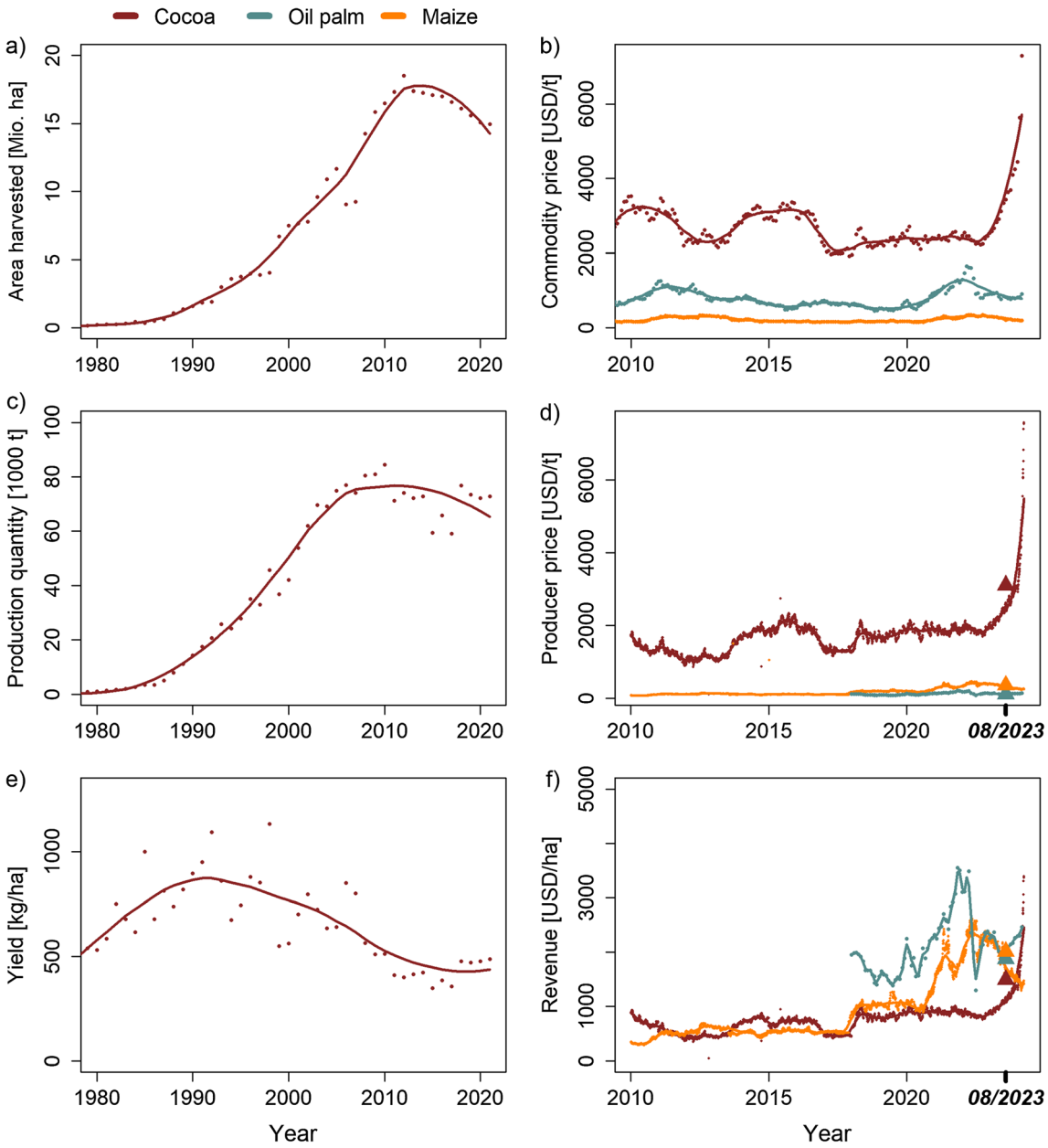

Fig. 2 FAO data on **a** cocoa area, **c** cocoa production quantity and **e** cocoa yields for Indonesia as well as **b** International Monetary Fund (IMF) global primary commodity prices, **d** APKAINDO and BAPPEBTI producer prices for Indonesia, and **f** gross revenue for cocoa, oil palm and maize for farmers in Indonesia (FAOSTAT 2023; IMF 2023; APKASINDO 2024; BAPPEBTI 2024). Data from APKASINDO were only available for 2018–2023. Gross revenue is calculated based on producer prices (APKASINDO; BAPPEBTI) and average yields (FAO) without deducting expenses for inputs (e.g. seeds, fertiliser, labour). Dots represent data points while lines represent smoothing to analyse data trends. Triangles represent producer prices in the study area in Luwu Timur, Sulawesi, Indonesia, during the environmental assessment in August 2023. Commodity prices are for palm oil while producer prices and gross revenue are for oil palm fresh fruit bunches (FFB)

other land uses and farmers referred to the low productivity of cocoa and low income, mostly due to low soil fertility, pests and diseases. The average cocoa yield reported by farmers in the socio-economic survey was 447 kg per hectare in line with the national average of 400–500 kg per hectare (FAOSTAT 2023). The current yields are low compared to, for example, what intensified cocoa plantations in Ghana achieve (1000 kg/ha) and low compared to yields achieved during the first phase of the cocoa boom in the early 1990s with about 800 to 900 kg per hectare (Fig. 2e) (Gockowski et al. 2013; FAOSTAT 2023). All cocoa plantations visited during the environmental survey were affected by diseases, such as black pod *(Phytophthora spp.),* vascular streak dieback *(Oncobasidium theobromae)*, mirid bug *(Helopeltis sp.)*, cocoa pod borer *(Conopomorpha cramerella),* as well as

rats, squirrels and monkeys attacking cocoa pods. All farmers included in the environmental assessment, regardless of certification, stated that they use (chemical) fertilisers and pesticides in their plantations. Yet, during the informal conversations, they reported cheap, subsidised fertiliser to be limited, unsubsidised fertiliser to be costly, and oil palm requiring less work and input (e.g. fertiliser) than cocoa. Compost production and use among farmers in Luwu Timur were low and many farmers stated that they do not know how to produce compost and that it is labour intensive.

Further reasons for conversion mentioned by farmers in the informal conversations include low and volatile cocoa prices. This observation is corroborated by ICCO data on monthly averaged cocoa prices (Fig. 2b). During the socio-economic survey in December 2022, the global cocoa price was about 2456 USD per ton and farmers in Sulawesi received around 762 USD per ton wet beans and 1829 USD per ton dry beans (ICCO 2023b; IMF 2023). At the time of the environmental assessment in August 2023, global cocoa prices were at an all-time high of around 3444 USD per ton (ICCO 2023b; IMF 2023). Cocoa farmers in Luwu Timur confirmed cocoa prices to be high in August 2023, around 1158 USD per ton wet beans (19 Mio. IDR) and 3109 USD per ton dry beans (51 Mio. IDR). Cocoa prices further skyrocketed after the environmental assessment, surpassing 7000 USD per ton in March 2024 (Fig. 2b, d). Reasons for the price spike were lower cocoa production quantities in Indonesia and other cocoa growing countries, such as Ghana and Ivory Coast, due to extreme weather (drought; excessive rainfall) and cocoa pests and diseases (ICCO 2023a). The high price, however, can be an incentive for the remaining cocoa farmers to refrain from converting their cocoa plantations (Zakiah and Frastica 2022): one farmer who had already planted oil palms in his cocoa plantation stated that he regretted planting the oil palms seeing the recent price spike. The price volatility, however, also holds for palm oil and maize, and producer prices in Indonesia follow trends in global commodity prices (Fig. 2d) (Nabhani et al. 2015). The palm oil price, for example, rose sharply after sunflower oil shortages due to the Russian invasion in Ukraine in 2021 and 2022 and plummeted again in 2023 (Fig. 2b).

During the environmental assessment in August 2023, gross revenue for oil palm was still higher for oil palm and maize than for cocoa (Fig. 2d, f, Table S1, supplementary material) (APKASINDO 2024; BAPPEBTI 2024). Farmers oftentimes use paid labour in oil palm increasing its costs compared to cocoa (Nasution et al. 2019). Using input costs for plantation establishment, fertiliser, pesticides and labour given in Nasution et al. (2019), the net revenue calculated based on producer prices in Luwu Timur in August 2023 is higher for oil palm (1496 USD/ha) than for cocoa (1272 USD/ha) (Table S1, supplementary material). The picture, however, changed: updating the calculation with producer prices given by APKASINDO and BAPPEBTI in March 2024, cocoa achieves a higher net revenue than oil palm (3398 USD/ha and 2073 USD/ha, respectively) (Table S2).

In addition to low productivity and volatile prices, government interventions play a role in the decline and conversion to other crops. National agricultural policies are promoting on the one hand staple foods such as maize and rice production to improve self-sufficiency in line with the Indonesian Food Law No. 18/2012, and on the other hand oil palm as priority export commodity and domestic biodiesel provider. In practice, the government tries to achieve self-sufficiency in staple crops by, for example, actively supporting maize production by providing free fertiliser, seeds and training. Table 1 summarises strength and weaknesses of cultivation of each crop.

DISCUSSION

The FAO data show a decline of cocoa and increase of oil palm cultivation in Indonesia (Fig. 2, Fig S2) and our observations in Luwu Timur, Sulawesi, Indonesia, confirm the conversion of cocoa to oil palm and maize. The conversion of cocoa to oil palm is also happening in other cocoa growing areas in Indonesia, such as in the districts Bohorok (personal observation) and Asahan in North Sumatra (Nasution et al. 2019). We identified low cocoa productivity through ageing cocoa trees, pests, diseases and decreasing soil fertility as well as a higher revenue for oil palm and maize as reasons for this land-use change, which were also reported to drive cocoa conversion in previous studies (Nurmedika and Damayanti 2015; Nasution et al. 2019; Supriana et al. 2020; Baja et al. 2021).

This dynamic land-use change is worrying as it can lead to a loss of diversity in the agricultural landscape if shade trees are cut during conversion. While oil palm is usually produced in monocultures (Fig. 1c) and maize produced in both monoculture and intercropped (Fig. 1d) (Grass et al. 2020; Zemp et al. 2023), cocoa is often produced in agroforests intercropped with remnant forest and fruit trees, such as durian *(Durio zibethinus)* and banana *(Musa* spp.*)* (Juhrbandt et al. 2010). These fruit trees provide food and habitat, for example, for frugivorous and nectarivorous birds and increase bird diversity (Clough et al. 2009b). In a study by Yahya et al. (2022) in Malaysia, such agroforests showed higher bird diversity than oil palm monocultures. In oil palm plantations in Sumatra, Indonesia, Prabowo et al. (2016) found 12 bird species in total and, on average, two bird species during each point count. Ramlah et al. (2021, 2024) conducted two studies in oil palm plantations in Sulawesi,

Table 1 Strength and weaknesses of cocoa, oil palm and maize cultivation for the study region in Sulawesi, Indonesia. Bullet points without reference are observations or information given by farmers during the field work in the study region in Luwu Timur, Sulawesi, Indonesia. Cash crop = crop mainly produced to generate income; subsistence crop = crop mainly produced for own consumption (Barbier 1998)

	Cocoa	Oil palm	Maize
Strength	Usually planted in agroforest, benefitting income and biodiversity (Juhrbandt et al. 2010) Perennial crop, soil stabilisation Can be rejuvenated by side grafting Farmed typically with family labour (Supriana et al. 2020)	Less labour and less fertiliser input Perennial crop, soil stabilisation Higher revenue per hectare (Nasution et al. 2019) Domestic and international market, domestic market predicted to further increase due to biofuels (Jong 2023)	Annual crop, more flexibility for land-use change Support from government with fertiliser, seeds and training Subsistence crop Can be intercropped with other crops (e.g. oil palm, cocoa)
Weaknesses	Volatiles prices and lower revenue than for oil palm (Nasution et al. 2019) Most cocoa and cocoa-derived products exported, small domestic market Cash crop (Barbier 1998; Murray Li 2002; Cramb et al. 2009) Low productivity and high prevalence of pests and diseases Takes 3 years to produce cocoa pods Cocoa plants require more maintenance than oil palm (pruning, pesticide application) (Supriana et al. 2020)	Volatile prices Possible to plant in more diverse system/agroforest but practice in Luwu Timur is monoculture Cash crop (Barbier 1998; Koh and Wilcove 2007) Takes 3 years for first harvest and 5 years for full production High impact on local hydrological cycle (Merten et al. 2016) Minimum size of land to produce sufficient amount worth transporting to oil mill more than 1.5 ha (Supriana et al. 2020) Farmed rather with paid labour (Supriana et al. 2020)	Volatile prices Bare soil prone to soil erosion Higher input of pesticides and fertiliser if planted in monoculture

Indonesia. In North Mamuju, the authors found 28 bird species in total while in Central Sulawesi 20 bird species were found (Ramlah et al. 2021, 2024). Conducting point counts during our environmental assessment, we found 71 bird species in total and, on average, six bird species within 25 m radius and 12 bird species within 50 m radius in cocoa plantations in Luwu Timur. Although the study design might differ slightly, it indicates that oil palm plantations are likely to support fewer bird species than cocoa.

Yet, the species richness of cocoa and potential loss during conversion may highly depend on the structure and shade cover of the cocoa. In a meta-analysis, Bennett et al. (2022) found that it is the cocoa agroforests with $> 30\%$ canopy cover and a diverse shade tree layer that maintain a similar number of bird species as primary and secondary forests, though, showing a shift in species communities. In Luwu Timur, shade tree diversity and density in cocoa plantations is low as farmers reduce shade to increase cocoa yields (own observation, see also Steffan-Dewenter et al. 2007). Hence, cocoa plantations might have only one or two shade tree species per plantation (Siebert 2002; Steffan-Dewenter et al. 2007) and impacts of conversion on biodiversity in plantations where no or few shade trees remain might be less substantial. Moreover, Zemp et al. (2023) show that oil palm can be more biodiversity friendly by planting trees in oil palm plantations in Sumatra while related yield losses are limited (see also Teuscher et al. 2015). We, however, did not observe such biodiversity friendly oil palm plantations in Luwu Timur and would like to draw attention to the potential negative implications of cocoa conversion for biodiversity, although shade cover is low. If shade trees are cut during conversion (see Fig. 1b), resulting oil palm monocultures are likely to support less biodiversity (Yahya et al. 2017, 2022) and priority should be maintaining and enhancing tree cover in both, oil palm and cocoa plantations.

OUTLOOK

Several regulatory developments on both international and national level might further drive producers to convert cocoa gardens in the future. At the international level, trade policy developments aimed at making global value chains more sustainable might have implications for the cocoa sector in Indonesia. The European Union Deforestation-free products Regulation (EUDR), which entered into force in June 2023 and will be fully applicable as of December

2024, will prevent companies from importing a range of commodities, including cocoa beans as well as derived products like cocoa powder, cocoa butter and chocolate, to the EU market if they were produced on land deforested after 31 December 2020 and if they were not produced in compliance with national laws. Around 21% of Indonesian cocoa exports are shipped to European countries (Badan Pusat Statistik 2021). The cocoa plantations studied during the environmental assessment were at mean distance of 5.45 km (SD 1.59 km) to primary forest, but some plantations are in areas delineated as forest in the European Commission (EC) Joint Research Centre (JRC) global map of forest cover published for the year 2020 (Bourgoin et al. 2024). The map is based on available global datasets, among others, the WRI Tropical Tree Cover 2020 and UMD Global Land Cover (Bourgoin et al. 2024). Though not legally binding, it points out to the difficulty to distinguish plantations like cocoa from forest and companies may precautionary refrain from sourcing cocoa from such plantations. As chocolate consumption is on the rise in Indonesia, it may give the opportunity to develop domestic cocoa processing as only 10% of the chocolate consumed in Indonesia is domestically produced by artisanal chocolatiers (Nur et al. 2023). The EUDR also includes palm oil, hence, affecting oil palm farmers the same way, including the difficulty with the reliability of forest maps. The EU has, however, a lower market share for Indonesian palm oil (14.35%) than for cocoa (21%) (Rifin et al. 2020; Badan Pusat Statistik 2021). Domestic demand for oil palm is expected to increase as the Indonesian government aims to increase the plant-based share in biofuel from 35 to 50% by 2050 (Jong 2023) and a domestic market obligation was imposed to ensure sufficient domestic palm oil supply. Thus, oil palm farmers might be less effected by the EUDR than cocoa farmers through a stronger domestic market and cocoa farmers might convert to oil palm to meet domestic demands in future.

With this outlook, the future of cocoa production in Indonesia will critically depend on technical and financial support to cocoa farmers to increase profitability of cocoa. To meet the steadily increasing global demand for cocoa (Beg et al. 2017), supporting existing cocoa plantations and farmers might be more sustainable than establishing new plantations elsewhere (e.g. Ivory Coast) (Clough et al. 2009a). On the one hand, it requires producer prices that are high enough for cocoa to be profitable, for example, guaranteeing a minimum price and paying price premiums using certification schemes like Rainforest Alliance. Oil palm and maize both generated a higher gross revenue before cocoa prices started skyrocketing in 2023, with oil palm generating a 20% higher income per hectare than cocoa. Based on producer prices in March 2024, cocoa would generate a 60% higher income than oil palm, but our analysis did not incorporate potential yield losses which might have occurred in 2023. For our calculation, we used average cocoa yields reported by farmers in the socio-economic survey in 2022 (447 kg/ha), but it needs further research if these yields were sustained or if cocoa yields further declined (e.g. effects of drought and excessive rainfall during the El Niño event observed between July 2023 and April 2024). Certification has the potential to buffer this price volatility, but it needs to be ensured that all certified farmers receive benefits such as the price premium.

Cocoa profitability, in the long run, also needs high yields, hence, solutions to low soil fertility, omnipresent pests and diseases, and rejuvenation or replacement of old trees that are beyond productive age (Kozicka et al. 2018). Farmers in Luwu Timur complained about the low availability of subsidised fertiliser, as well as the low quality of cocoa seedlings provided by the government. Training programmes on cocoa production are primarily organised by private, multinational processors and traders such as Mars and Cargill, offering these trainings to their supplying cocoa farmers. Hence, farmers selling to independent traders are excluded from these training programmes. Through public–private partnerships, a stronger involvement of the Indonesian government and a higher uptake of certification more cocoa farmers can be reached, extending the cocoa fertiliser and seedling programmes, creating demonstration plots and cocoa-specific extension services. Wartenberg et al. (2020) showed that common shade trees, such as gliricidia *(Gliricidia sepium),* rambutan *(Nephelium lappaceum)*, langsat *(Lansium domesticum),* and durian *(Durio zibethinus),* increase soil fertility in cocoa agroforests, while providing fodder for livestock, timber and fire wood, and an additional source of income contributing to income security (Clough et al. 2011; Tscharntke et al. 2011; Wartenberg et al. 2020). On average, shade trees and intercrops contribute to 7% of the total revenue farmers generate from a cocoa plantation in Central Sulawesi (Juhrbandt 2010). This is low compared to, for example, coffee farmers in Peru where shade trees contribute to 28% of the farmers' income (Rice 2008). Hence, extension services can provide tree seedlings to farmers for generating income and shade. Toledo-Hernández et al. (2021) found higher shade to increase ants and Diptera in cocoa plantations in Sulawesi, the main cocoa flower visitors in the study. Therefore, higher shade cover and diversity also enhance ecosystem services, such as pollination and predation on cocoa pests (Toledo-Hernández et al. 2021; Ocampo-Ariza et al. 2023). This even becomes more important as another study found pollination to strongly limit cocoa yields and income, but not fertiliser and pesticides (Toledo-Hernández et al. 2020). These observations are in line with the study of Cruz et al. (2019),

showing that organic cocoa plantations maintain the same productivity levels as conventional plantations in Sulawesi although agrochemical input was lower. In addition to shade tree diversification, extension services can include hands-on training on topics like compost production, integrating existing knowledge in trainings. This also reduces the dependency on agrochemicals for which farmers reported availability to be low and costs to be high, and enhancing organic farming benefiting biodiversity and yields (Fahmid 2013; Cruz et al. 2019). Fungenzi et al. (2021) studied outcomes of different fertilisers in cocoa in Sulawesi and highest cocoa yields were achieved by applying compost or a combination of compost and mineral fertiliser. Compost production also offers the opportunity to transform unused biomass (e.g. cocoa pod husks), contributing to circular farming (Hoof et al. 2024).

Lastly, as oil palm potentially remains economically more profitable in future, oil palm plantations can be made more biodiversity friendly either through keeping shade trees when converting cocoa or through subsequently planting trees (Zemp et al. 2023). More research is needed on the effectiveness of current measures supporting cocoa farmers to improve cocoa yields and to sustain existing cocoa plantations in Indonesia. Supporting existing cocoa plantations may also be more sustainable than the establishment of new plantations in other countries such as Ivory Coast to meet global demand for cocoa.

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Data availability statement Data sharing is not applicable to this article as the data analysed are publicly available (FAOSTAT 2023; IMF 2023; APKASINDO 2024; BAPPEBTI 2024).

Declarations

Conflict of interest The authors declare no potential conflict of interest.

REFERENCES

Amuzu, D., B. Neimark, and C. Kull. 2022. Bittersweet cocoa: Certification programmes in Ghana as battlegrounds for power, authority and legitimacy. *Geoforum* 136: 54–67. https://doi.org/10.1016/j.geoforum.2022.08.002.

APKASINDO. 2024. Harga TBS.

Badan Pusat Statistik. 2021. *Statistik Kakao Indonesia 2021*.

Baja, S., L. Harli, R. Padjung. Asrul, and R. Neswati. 2021. The effect of soil chemicals on cocoa productivity in West Sulawesi. *IOP Conference Series: Earth and Environmental Science* 921: 012046. https://doi.org/10.1088/1755-1315/921/1/012046.

BAPPEBTI. 2024. Harga Bursa (Forward-Futures-Spot).

Barbier, E. 1998. Cash crops, food crops, and sustainability: the case of Indonesia. *The Economics of Environment and Development* 2: 96–119. https://doi.org/10.4337/9781035303618.00015.

Beg, M.S., S. Ahmad, K. Jan, and K. Bashir. 2017. Status, supply chain and processing of cocoa - A review. *Trends in Food Science & Technology* 66: 108–116. https://doi.org/10.1016/j.tifs.2017.06.007.

Bemelmans, J. 2022. *Socioeconomic survey of certified and non-certified cocoa farmers in Luwu, Luwu Timur and Luwu Utara.* Unpublished data.

Bennett, R.E., T.S. Sillett, R.A. Rice, and P.P. Marra. 2022. Impact of cocoa agricultural intensification on bird diversity and community composition. *Conservation Biology* 36: 1–10. https://doi.org/10.1111/cobi.13779.

Bourgoin, C., I. Ameztoy, A. Verhegghen, B. Desclée, S. Carboni, J. Bastin, R. Beuchle, A. Brink, et al. 2024. *Mapping Global Forest Cover of the Year 2020 to Support the EU Regulation on Deforestation-free Supply Chains.* https://doi.org/10.2760/262532.

Bursa Malaysia. 2023. Derivatives Prices.

Clough, Y., H. Faust, and T. Tscharntke. 2009a. Cacao boom and bust: Sustainability of agroforests and opportunities for biodiversity conservation. *Conservation Letters* 2: 197–205. https://doi.org/10.1111/j.1755-263x.2009.00072.x.

Clough, Y., D. Dwi Putra, R. Pitopang, and T. Tscharntke. 2009b. Local and landscape factors determine functional bird diversity in Indonesian cacao agroforestry. *Biological Conservation* 142: 1032–1041. https://doi.org/10.1016/j.biocon.2008.12.027.

Clough, Y., J. Barkmann, J. Juhrbandt, M. Kessler, T.C. Wanger, A. Anshary, D. Buchori, D. Cicuzza, et al. 2011. Combining high biodiversity with high yields in tropical agroforests. *Proceedings of the National Academy of Sciences of the United States of America* 108: 8311–8316. https://doi.org/10.1073/pnas.1016799108.

Cramb, R.A., C.J. Pierce Colfer, W. Dressler, P. Laungaramsri, Q.T. Le, E. Mulyoutami, N.L. Peluso, and R.L. Wadley. 2009. Swidden transformations and rural livelihoods in Southeast Asia. *Human Ecology* 37: 323–346. https://doi.org/10.1007/s10745-009-9241-6.

Cruz, A.F., I.N. Suwastika, H. Sasaki, T. Uchiyama, N.A. Pakawaru, W. Wijayanti, Z.B. Muslimin, et al. 2019. Cacao plantations on Sulawesi Island, Indonesia: I—an agro-ecological analysis of conventional and organic farms. *Organic Agriculture* 9: 225–234. https://doi.org/10.1007/s13165-018-0224-z.

Fahmid, I.M. 2013. Cocoa farmers performance at highland area in South Sulawesi, Indonesia. *Asian Journal of Agriculture and Rural Development* 3: 360–370.

FAOSTAT. 2023. Statistics on area harvested, yields, production quantity for cocoa, oil palm and maize by country.

Fungenzi, T., R. Sakrabani, P.J. Burgess, S. Lambert, and P. McMahon. 2021. Medium-term effect of fertilizer, compost, and dolomite on cocoa soil and productivity in Sulawesi, Indonesia. *Experimental Agriculture* 57: 185–202. https://doi.org/10.1017/S0014479721000132.

Gardner, T., and Y. Rylander. 2022. Indonesia makes progress towards zero palm oil deforestation—But gains in forest protection are fragile. *Stockholm Environment Institute*.

Gockowski, J., V. Afari-Sefa, D.B. Sarpong, Y.B. Osei-Asare, and N.F. Agyeman. 2013. Improving the productivity and income of Ghanaian cocoa farmers while maintaining environmental services: What role for certification? *International Journal of Agricultural Sustainability* 11: 331–346. https://doi.org/10.1080/14735903.2013.772714.

Grass, I., C. Kubitza, V.V. Krishna, M.D. Corre, O. Mußhoff, P. Pütz, J. Drescher, K. Rembold, et al. 2020. Trade-offs between multifunctionality and profit in tropical smallholder landscapes. *Nature Communications* 11: 1186. https://doi.org/10.1038/s41467-020-15013-5.

Hoof, B., A. Van, J. Solano, C. Mendez. Riaño, and A.L. Medaglia. 2024. Decision-making for circular economy implementation in agri-food systems: A transdisciplinary case study of cacao in Colombia. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2023.140307.

ICCO. 2023a. *Cocoa Market Report October 2023*.

ICCO. 2023b. Monthly Average Cocoa Price.

Iddrisu, M., R. Aidoo, and C. AbawieraWongnaa. 2020. Participation in UTZ-RA voluntary cocoa certification scheme and its impact on smallholder welfare: Evidence from Ghana. *World Development Perspectives* 20: 100244. https://doi.org/10.1016/j.wdp.2020.100244.

IMF. 2023. Primary Commodity Price System.

Jong, H. N. 2023. Indonesia's biofuel push must go beyond palm oil to reduce risk, experts say.

Juhrbandt, J. 2010. *Economic valuation of land use change - A case study on rainforest conversion and agroforestry intensification in Central Sulawesi*. Georg-August University, Goettingen.

Juhrbandt, J., T. Duwe, J. Barkmann, G. Gerold, and R. Marggraf. 2010. Structure and management of cocoa agroforestry systems in Central Sulawesi across an intensification gradient. In *Tropical Rainforests and Agroforests under Global Change*, ed. T. Tscharntke, C. Leuschner, E. Veldkamp, H. Faust, E. Guhardja, and A. Bidin, 115–140. Springer.

Kementerian Pertanian. 2017. *Corn Industry Development in Indonesia*.

Koh, L.P., and D.S. Wilcove. 2007. Cashing in palm oil for conservation. *Nature* 448: 993–994. https://doi.org/10.1038/448993a.

Kozicka, M., F. Tacconi, D. Horna, and E. Gotor. 2018. *Forecasting Cocoa Yields for 2050*.

Merten, J., A. Röll, T. Guillaume, A. Meijide, S. Tarigan, H. Agusta, C. Dislich, C. Dittrich, et al. 2016. Water scarcity and oil palm expansion: Social views and environmental processes. *Ecology and Society*. https://doi.org/10.5751/ES-08214-210205.

Murray Li, T. 2002. Local histories, global markets: Cocoa and class in Upland Sulawesi. *Development and Change* 33: 415–437. https://doi.org/10.1111/1467-7660.00261.

Nabhani, I., A. Daryanto, M. Yassin, and A. Rifin. 2015. Can Indonesia cocoa farmers get benefit on global value chain inclusion? A literature review. *Asian Social Science* 11: 288–294. https://doi.org/10.5539/ass.v11n18p288.

Nasution, S.K.H., T. Supriana, T.C. Pane, and S.S. Hanum. 2019. Comparing farming income prospects for cocoa and oil palm in Asahan District of North Sumatera. *IOP Conference Series: Earth and Environmental Science*. https://doi.org/10.1088/1755-1315/260/1/012006.

Neswati, R., L. Asrul, A. Molla, N. Widiayani, and S. Nurqadri. 2019. Land suitability for cocoa development in South Sulawesi: An analysis using GIS and parametric approach. *IOP Conference Series: Earth and Environmental Science*. https://doi.org/10.1088/1755-1315/280/1/012014.

Nur, T., A. Hidayatno, A.D. Setiawan, K. Komarudin, and A. Suzianti. 2023. Environmental impact analysis to achieve sustainability for artisan chocolate products supply chain. *Sustainability* 15: 13527. https://doi.org/10.3390/su151813527.

Nurmedika, M. Basir., and L. Damayanti. 2015. Analysis of factors affecting options of farmers changing land of farming in the district of Rio Pakava Donggala Regency. *Agroland* 22: 9–20.

Ocampo-Ariza, C., J. Vansynghel, D. Bertleff, B. Maas, N. Schumacher, C. Ulloque-Samatelo, F.F. Yovera, E. Thomas, et al. 2023. Birds and bats enhance cacao yield despite suppressing arthropod mesopredation. *Ecological Applications* 33: e2886. https://doi.org/10.1002/eap.2886.

Prabowo, W.E., K. Darras, Y. Clough, M. Toledo-Hernandez, R. Arlettaz, Y.A. Mulyani, and T. Tscharntke. 2016. Bird responses to lowland rainforest conversion in Sumatran smallholder landscapes, Indonesia. *PLoS ONE* 11: 24. https://doi.org/10.1371/journal.pone.0154876.

Rainforest Alliance. 2020a. *Deforestation Position Paper*.

Rainforest Alliance. 2020b. *Rainforest Alliance Sustainable Agriculture Standard. Farm Requirements*.

Ramlah, S., Y. Santosa, N. Santoso, and S.B. Rushayati. 2021. The variation of bird diversity in various oil palm land cover in North Mamuju, West Sulawesi, Indonesia. *Biodiversitas* 22: 3068–3074. https://doi.org/10.13057/biodiv/d220761.

Ramlah, S., M. Ihsan, and Y. Yusran. 2024. Avian species diversity in oil palm plantations in Buol District, Central Sulawesi, Indonesia. *International Journal of Design and Nature and Ecodynamics* 19: 267–273. https://doi.org/10.18280/ijdne.190129.

Rice, R.A. 2008. Agricultural intensification within agroforestry: The case of coffee and wood products. *Agriculture, Ecosystems and Environment* 128: 212–218. https://doi.org/10.1016/j.agee.2008.06.007.

Rice, R.A., and R. Greenberg. 2000. Cacao cultivation and the conservation of biological diversity. *Ambio* 29: 167–173. https://doi.org/10.1579/0044-7447-29.3.167.

Rifin, A., Herawati Feryanto, and Harianto. 2020. Assessing the impact of limiting Indonesian palm oil exports to the European Union. *Journal of Economic Structures*. https://doi.org/10.1186/s40008-020-00202-8.

Ruf, F., and Yoddang. 2004. The Sulawesi case. Deforestation, pre-cocoa and cocoa migrations. In *Beyond tropical deforestation: from tropical deforestation to forest cover dynamics and forest development*, ed. B. Didier, 279–300.

Sadeu, M.B.T., S. Mathe, and J.R.M. Nzie. 2023. Les systèmes de certification du cacao améliorent-ils les performances des producteurs? Expérience de la région du Centre au Cameroun. *Tropicultura* 41: 1–19. https://doi.org/10.25518/2295-8010.2268.

Siebert, S.F. 2002. From shade- to sun-grown perennial crops in Sulawesi, Indonesia: Implications for biodiversity conservation and soil fertility. *Biodiversity and Conservation* 11: 1889–1902. https://doi.org/10.1023/A:1020804611740.

Smiley, G.L., and J. Kroschel. 2010. Yield development and nutrient dynamics in cocoa-gliricidia agroforests of Central Sulawesi, Indonesia. *Agroforestry Systems* 78: 97–114. https://doi.org/10.1007/s10457-009-9259-1.

Steffan-Dewenter, I., M. Kessler, J. Barkmann, M.M. Bos, D. Buchori, S. Erasmi, H. Faust, G. Gerold, et al. 2007. Tradeoffs between income, biodiversity, and ecosystem functioning during tropical rainforest conversion and agroforestry intensification. *Proceedings of the National Academy of Sciences of the United States of America* 104: 4973–4978. https://doi.org/10.1073/pnas.0608409104.

Supriana, T., S. K. H. Nasution, T. C. Pane, and S. S. Hanum. 2020. Factors Influencing the Conversion of Cocoa Lands into Oil Palm in Asahan District of North Sumatra: 31–36. https://doi.org/10.5220/0010079000310036.

Teuscher, M., M. Vorlaufer, M. Wollni, U. Brose, Y. Mulyani, and Y. Clough. 2015. Trade-offs between bird diversity and abundance, yields and revenue in smallholder oil palm plantations in Sumatra, Indonesia. *Biological Conservation* 186: 306–318. https://doi.org/10.1016/j.biocon.2015.03.022.

Toledo-Hernández, M., T. Tscharntke, A. Tjoa, A. Anshary, B. Cyio, and T.C. Wanger. 2020. Hand pollination, not pesticides or fertilizers, increases cocoa yields and farmer income. *Agriculture, Ecosystems and Environment.* https://doi.org/10.1016/j.agee.2020.107160.

Toledo-Hernández, M., T. Tscharntke, A. Tjoa, A. Anshary, B. Cyio, and T.C. Wanger. 2021. Landscape and farm-level management for conservation of potential pollinators in Indonesian cocoa agroforests. *Biological Conservation*. https://doi.org/10.1016/j.biocon.2021.109106.

Tscharntke, T., Y. Clough, S.A. Bhagwat, D. Buchori, H. Faust, D. Hertel, D. Hölscher, J. Juhrbandt, et al. 2011. Multifunctional shade-tree management in tropical agroforestry landscapes - A review. *Journal of Applied Ecology* 48: 619–629. https://doi.org/10.1111/j.1365-2664.2010.01939.x.

USAID. 2006. *Indonesia Cocoa Bean Value Chain Case Study*. *microREPORT #65*.

USDA. 2023. National Grain Reports.

Wartenberg, A.C., W.J. Blaser, J.M. Roshetko, M. Van Noordwijk, and J. Six. 2020. Soil fertility and Theobroma cacao growth and productivity under commonly intercropped shade-tree species in Sulawesi, Indonesia. *Plant and Soil* 453: 87–104. https://doi.org/10.1007/s11104-018-03921-x.

Weather Spark. 2023. Climate and Average Weather Year Round in Wotu, Indonesia.

Yahya, M.S., M. Syafiq, A. Ashton-Butt, A. Ghazali, S. Asmah, and B. Azhar. 2017. Switching from monoculture to polyculture farming benefits birds in oil palm production landscapes: Evidence from mist netting data. *Ecology and Evolution* 7: 6314–6325. https://doi.org/10.1002/ece3.3205.

Yahya, M.S., S.N. Atikah, I. Mukri, R. Sanusi, A.R. Norhisham, and B. Azhar. 2022. Agroforestry orchards support greater avian biodiversity than monoculture oil palm and rubber tree plantations. *Forest Ecology and Management* 513: 120177. https://doi.org/10.1016/j.foreco.2022.120177.

Zakiah, Safrida, and N. Frastica. 2022. Performance of cocoa beans production modelling in Indonesia. *IOP Conference Series: Earth and Environmental Science.* https://doi.org/10.1088/1755-1315/951/1/012007.

Zemp, D.C., N. Guerrero-Ramirez, F. Brambach, K. Darras, I. Grass, A. Potapov, A. Röll, I. Arimond, et al. 2023. Tree islands enhance biodiversity and functioning in oil palm landscapes. *Nature* 618: 316–321. https://doi.org/10.1038/s41586-023-06086-5.

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