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Modelling biodiversity responses to land use in areas of cocoa cultivation

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ABSTRACT

Interest in economically and ecologically sustainable cocoa has grown in recent years. Cocoa-based agroforestry systems are promoted as a potential win-win option for long-term yields, multiple benefits, and the preservation of biodiversity. Yet, even though recent studies have shown such agroforests can support biodiversity, their value relative to natural areas and open-land systems is not fully known. We estimated the biodiversity intactness (BII) of different land uses associated with cocoa-driven land-use change using mixed-effects models. We distinguished between agroforests established under natural shade and those grown from open land, and compared these to intensively grown cropland (including cocoa monoculture), and primary and secondary forest. We found that species richness in cocoa-based agroforestry systems, under both natural and planted shade, was lower than in primary forests but higher than in open-land systems. However, we found that land-use history influenced the biodiversity intactness of agroforests: whilst open-land-derived cocoa-based agroforestry systems and forest-derived cocoa-based agroforestry systems share similar species richness, open-land-derived cocoa-based agroforestry systems have lower community similarity to primary forest than forest-derived cocoa-based agroforestry systems. The results highlight that high levels of BII can be sustained by retaining the natural shade in existing agroforestry systems, but also that incentivising planted shade agroforestry can enhance biodiversity intactness in degraded areas whilst delivering co-benefits. Importantly, the results highlight that cocoa planning seeking to achieve biodiversity benefits should consider the direction of land use and biodiversity transitions.

1. Introduction

Cocoa (*Theobroma cacao*) is native to the Amazon, but is now grown across the tropics, notably in tropical South American countries, West and Central Africa, India, and Southeast Asia. Between 1961 and 2016, the production and area of land harvested for cocoa doubled (Food and Agriculture Organization of the United Nations, 2020). The majority of new cocoa farms are established by smallholder farmers on recently-cleared forests in an attempt to secure fertile soils, stable environments, and disease resistance (Ruf and Schroth, 2004). With an annual growth rate of over 3% in West Africa (Norris et al., 2010), the conversion of tropical forest to cocoa agriculture, alongside other perennial crops, poses a known risk to forest species. It is important to understand the effects such conversions may have on local biodiversity and ecosystem services, and if paths exist to mitigate these effects and preserve these values.

Different studies have found that cocoa plantations, relative to primary vegetation, host fewer forest species (Bobo et al., 2006), restricted-range species (Oke and Chokor, 2009), and species that play key roles in the functioning of ecosystems, such as dung beetles (Davis and Philips, 2005) and termites (Eggleton et al., 2002). However, there is also evidence that cocoa farms can support high proportions of forest species (Holbech, 2009; Waltert et al., 2005) and species that support ecosystem functioning (Tadu et al., 2014), suggesting that the range of biodiversity outcomes across sites where cocoa is produced is large. It is therefore useful to consider the effects of different practices in cocoa production systems.

Agroforestry systems, where one or more shade-tolerant crops are cultivated in combination with trees (Somarriba, 1992), are thought to provide and support more ecosystem services and higher levels of biodiversity relative to open-land alternatives, including perennial monocultures such as cocoa. Various studies have found that growing cocoa in the shade of natural forest trees provides a habitat for greater biodiversity (Mbolo et al., 2016), and benefits farmers and crops via ecosystem services such as pollination and pest and disease control (Tscharntke et al., 2011). For example, some (windborne) viral and

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fungal diseases, such as witches' broom, may be diminished in traditional agroforestry systems compared to monocultures (Andres et al., 2018; Rice and Greenberg, 2000). Carbon storage in cocoa-based agroforestry systems is significantly higher than in monoculture cocoa (Nijmeijer et al., 2019; Schneidewind et al., 2019; Schroth et al., 2016) and agroforestry systems can provide a cooler and more sheltered microclimate (Niether et al., 2020). Additionally, there is evidence that nutrient cycling in agroforestry systems can be comparable to natural systems (Nijmeijer et al., 2019; though see also Blaser et al., 2017). The land-use history and management of cocoa-based agroforestry systems may also affect outcomes for biodiversity and ecosystem services (Bisseleua and Vidal, 2008; Martin et al., 2020). More complex agroforestry systems can support higher levels of some measures of biodiversity (De Beenhouwer et al., 2015), and agroforestry systems under natural shade derived from forests are likely to host higher numbers and densities of certain species – sometimes comparable to that of nearby forests – than open-land derived systems (Sambuichi et al., 2012; Nijmeijer et al., 2019; Martin et al., 2020).

The scale and intensity of cocoa cultivation has risen over past decades to meet growing global demand, including through new more productive hybrids that perform well without the need for shade (Ruf, 2011). The removal of shade from cocoa plantations can increase yields, and therefore farmer income (Clough et al., 2011; Niether et al., 2020), especially in the short term, as shade trees compete with cocoa trees for resources (Blaser et al., 2018; Sanchez, 1995). This drive for intensification has generally led to a reduction in shade levels and shade tree species diversity in cocoa growing areas (Ruf, 2011; Vaast and Somarriba, 2014). Globally, up to 70% of cocoa is grown under light or no-shade conditions, especially in Indonesia and West Africa (Clough et al., 2009), a trend also seen in other perennial cropping systems (Feintrenie et al., 2010). Moreover, there is a perception that the low light, humid environments created by high shade levels facilitate fungal diseases such as black pod rot (Clough et al., 2009). Yet, there is also evidence that reduced shade increases physiological stress to cocoa trees, their susceptibility to certain pests and diseases, and the amounts of fertiliser and insecticides required to maintain high production levels (Clough et al., 2009). In addition, smallholder cocoa farmers are overwhelmingly poor (Waarts et al., 2019) and unable to invest in the required external inputs. As a result, adoption rates of full-sun cocoa have been low, and no-shade systems are now generally considered inappropriate for smallholder farmers.

Intensification, including by removing shade to increase cocoa production, is also seen as a way to avoid the further conversion of forests, as such intensified systems can be achieved in existing plantations, degraded land or other non-forested lands (Ruf, 2011). On the other hand, well-managed shaded cocoa-based agroforestry systems may support more sustainable yields over time (Johns, 1999; Nijmeijer et al., 2019) and similarly reduce the need for further forest conversion. Additionally, the total system yield of cocoa-based agroforestry systems may be higher, as they can provide secondary crops besides cocoa (Blaser et al., 2018; Waldron et al., 2012), support income diversification (Niether et al., 2020), and provide a higher return on labour relative to more intensive, monoculture strategies (Armengot et al., 2016). Such advantages can reduce the need for further conversion, though increased profitability can also drive further forest conversion, which means forest protection policies need to be in place.

Despite some trends towards reduced or no-shade systems, large cocoa companies increasingly promote the integration of shade trees in existing cocoa plantations as part of their environmental and social sustainability strategies, as do governments and NGOs in the cocoa sector (Mondelēz International, 2021; Nestlé, 2020; Republic of Côte d'Ivoire, 2018; Republic of Ghana, 2018). Agroforestry is increasingly seen as a win-win solution to meeting an increasing demand for commodities such as cocoa, coffee, and vanilla, all while protecting local biodiversity and supporting ecosystem services. In light of these initiatives, it is important to understand the impacts on local biodiversity of different practices in cocoa production systems and the implications of promoting transitions such as toward agroforestry.

Individual studies into the biodiversity impacts of cocoa-driven land-use change are often limited to just one area, with one set of baseline conditions, and usually focus on one or a few taxa. The range of outcomes among these studies highlight the need for analyses utilising a broad spectrum of data and investigating the effects of variation within cocoa cultivation methods on a wide range of taxa across many locations. However, quantitative analyses of the effects of cocoa agroforestry on biodiversity have so far been limited by the volume of comparable data and the quality of reporting (Norgrove and Beck, 2016).

In this study, we reinterpret and analyse primary data from a wide range of sites and locations in a quantitative analysis of the effects of land-use change in different types of cocoa agroforestry systems, accounting for agroforest land-use history. We model the effects of land-use change linked to cocoa cultivation on whole-community biodiversity intactness. We collated original biodiversity field data from 36 studies (1295 sites) from the cocoa-producing regions of the world. We estimated species richness and community composition, relative to primary forests, in areas with different land uses to produce estimates of biodiversity intactness in areas with varying land uses related to cocoa agriculture. We used the results of mixed-effects models to make inferences about the potential consequences of a) continuing to replace primary forest with cocoa agroforests, b) maintaining current agroforests under natural shade, and c) using planted-shade cocoa agroforestry to rehabilitate open land.

2. Methods

2.1. Data collection

Biodiversity data was taken from the PREDICTS (Predicting the Responses of Ecological Diversity in Changing Terrestrial Systems) database (Hudson et al., 2017), and supplemented by targeted literature review (Appendix A). The PREDICTS database brings together data from studies where local biodiversity was sampled from a range of land uses, including different crop types, land-use intensities, and differing means of agricultural production.

Specifically, the database consists of a hierarchical structure of data sources, studies (sampling campaigns within data sources), geographic blocks of sites (as identified by data entrants based on maps and sample locations), and study sites. Each study site has an assigned land use following a standardised classification table (Newbold et al., 2016a).

We identified 31 studies from the existing PREDICTS database as suitable for our analysis. We included any study that included one or more sites described as containing cocoa, contrasting with at least one other land use; these studies generally compared either cocoa cultivation types or cocoa cultivation with other crops or land-use types. We supplemented these studies with four new data sources, accounting for five new studies (Da Silva Moço et al., 2009; Haro-Carrion et al., 2009; Kone et al., 2012; Rolim et al., 2017), resulting in 36 studies covering 1295 sites (Table 1). 673 sites were situated in African countries, 330 sites in Indonesia and Papua New Guinea, and 292 in South and Central American countries. Our dataset included 3807 unique taxa (most identified to species level) from across the 36 studies (Table A1).

2.2. Data coding

All sites within the PREDICTS database are assigned a category according to the land use present during sampling, as recorded by the field researchers at the time of sampling. The PREDICTS categories (Hudson et al., 2017) include: primary forest, young secondary vegetation (< 10 years old in tropical areas), intermediate secondary vegetation (between 10 and 30 years old in tropical areas), and mature secondary vegetation ($> = 30$ years old in tropical areas), cropland, pasture, plantation forest, and urban. We subdivided the plantation forest into forest-derived cocoa

Table 1
The distribution of land-use categories in this analysis, with category definitions and their spread at a site- and study-level.

Habitat	Land use	Description	Studies	Sites
Primary forest	Primary forest	Natural tropical forest.	36	392
Secondary vegetation	Young secondary vegetation	Secondary forest > 10 years old.	3	72
	Intermediate secondary vegetation	Secondary forest 10–30 years old.	8	174
	Mature secondary vegetation	Secondary forest > = 30 years old.	3	7
Cocoa agroforest	Forest-derived cocoa agroforest	Cocoa agroforest grown under natural shade	16	87
	Open-land-derived cocoa agroforest	Cocoa agroforest grown from open-land systems, with “planted” shade	18	377
Open-land systems	Cropland, pasture, monoculture cocoa	Monoculture or polyculture open land (no shade).	8	186
Total			**36**	**1295**

agroforest (defined as cocoa under natural shade from thinned forest or remnant forest trees), open-land-derived cocoa agroforest (where shade trees have been planted), non-cocoa plantation, and “open-land systems”, which included cocoa monocultures, croplands and pasture systems. The information necessary to make these classifications for many sites was already available in the ancillary information held in the PREDICTS database; for other sites it was necessary to refer back to the original study (often a published research article) or to reach out to the authors for more information. Overall, our study included 1295 sites from 36 studies and 23 unique data sources (Appendix A), and included a spread of land uses in primary and secondary vegetation, cocoa-based agroforestry systems, and open-land systems (Table 1). These categories were selected to explore recent suggestions that the land-use history of cocoa agroforests may be one of the principal determinants of their biodiversity value and ecosystem service provision (Martin et al., 2020; Tadu et al., 2014).

2.3. *Statistical modelling*

We make a space-for-time substitution to model the effects of cocoa production, using studies that compare nearby areas under differing management regimes. A space-for-time substitution compares otherwise-similar sites which have been subject to a defined set of differing conditions, and assumes that a temporal conversion of a site from one condition to another would cause similar changes in response variables to the differences between the differently-treated contemporary sites.

The hierarchical structure of the PREDICTS database, where each study has its own taxonomic focus, geographic area, sampling technique, and sampling effort, means that a large amount of variation in biodiversity response variables can be assigned to differences unrelated to pressure variables. For example, it allows assessing if biodiversity measurements are more strongly determined by the specific study or by the within-study land use. Mixed-effects models can help to elucidate patterns in the response variables that emerge within this hierarchical structure due to factors, such as land use. This method is established and has been used in analyses of local biodiversity intactness (Newbold et al., 2016a; Sanchez-Ortiz et al., 2019 (pre-print)). When modelling species richness, we used a model with Poisson errors and a log link; when modelling compositional similarity, we applied a logit transformation to the variable, which gave it a suitable distribution to use a model with Gaussian errors. We used the identity of the study as a random effect to control for variation in taxonomic focus, geographic location, sampling methods, and sampling effort. In our species richness modelling, we tested for the inclusion of the geographic block of sites within a study as a random effect to control for the spatial design of sampling within some studies – though this did not lead to improved goodness of fit as measured by AIC (Table A2). We also tested if the inclusion of an ancillary data layer describing human population density in 2015 (CIESIN, 2018) would improve the species richness model; again, this did not lead to improved goodness of fit and so was excluded from the final model (Table A2). In our compositional similarity modelling, we included the geographic distance between the pair of comparison sites as a predictor in the models as it would be expected that nearby sites would share more similar communities – this emerged as significant and was necessary to control for in our projections of the effects of land use.

We performed all analyses in R version 3.6.2, (R Core Team, 2019) using the lme4 package (Bates et al., 2015) to generate all mixed-effects models of biodiversity responses to land-use (see detail in Appendix A). Models were selected using the Akaike Information Criterion (Table A2). In the interests of analytical robustness, we combined the intermediate and mature secondary vegetation categories because the number of sites with each of these land uses was low.

We developed mixed-effects models for community species richness and an asymmetric measure of community composition relative to primary forest sites (the Asymmetric Jaccard Index). To allow for natural variation in spatial turnover between primary forest sites, we rescaled community composition so that it was equal to 1 for primary forest sites, giving a scale of 0 (completely dissimilar) to 1 (completely similar) in our data. Robustness of the model fit was tested using cross-validation using the influence.ME R package (Nieuwenhuis et al., 2012). The richness-based Biodiversity Intactness Index (henceforth BII) is the product of the rescaled coefficients of the models of community species richness and community compositional similarity (Newbold et al., 2016a,b, Eq. (1)). Thus, BII represents the diversity of a system relative to primary forest: 1 means that it is identical to primary forest, and it decreases down to 0, based on having fewer species or species that are not found in primary forest.

$$BII = \frac{SR_{LandUse}}{SR_{Primary}} \bullet \frac{\mathrm{CS}_{\mathrm{Primary-LandUse}}}{\mathrm{CS}_{\mathrm{Primary-Primary}}} \tag{1}$$

Eq. (1) is the formula for the richness-based Biodiversity Intactness Index used in this study. SR represents modelled species richness, CS represents modelled community similarity.

3. Results

Land conversion results in a decline in species richness (Fig. 1a). The land use with the least impact is mature/intermediate secondary forest, whilst the land use with the highest impact is open-land systems. Cocoa-based agroforestry systems maintain a higher species richness than open-land systems, comparable to young secondary forest, but lower richness than in intermediate/mature secondary forest. Species richness impacts do not differ significantly between agroforests derived from forest and from open land (Fig. 1a).

The modelled impacts of different land uses on community composition relative to primary forest also differ (Fig. 1b). Again, the land-use type with the highest negative impact on community composition is open-land systems. However, here the results for open-land and forest derived agroforests differ: the composition of species in forest-derived agroforests is as similar to primary forests as mature/intermediate secondary forests, whereas open-land-derived cocoa-based agroforestry systems' community similarity to primary forest is between open-land systems and young secondary vegetation.

Though all land uses tested had a lower BII than that found in local primary sites, further differences were observed between the disturbed land uses (Fig. 1c). Open-land-derived cocoa-based agroforestry systems and young secondary vegetation have a BII higher than that of open-land systems, but lower than forest-derived cocoa-based agroforestry systems and mature secondary vegetation. The biodiversity intactness of forest-

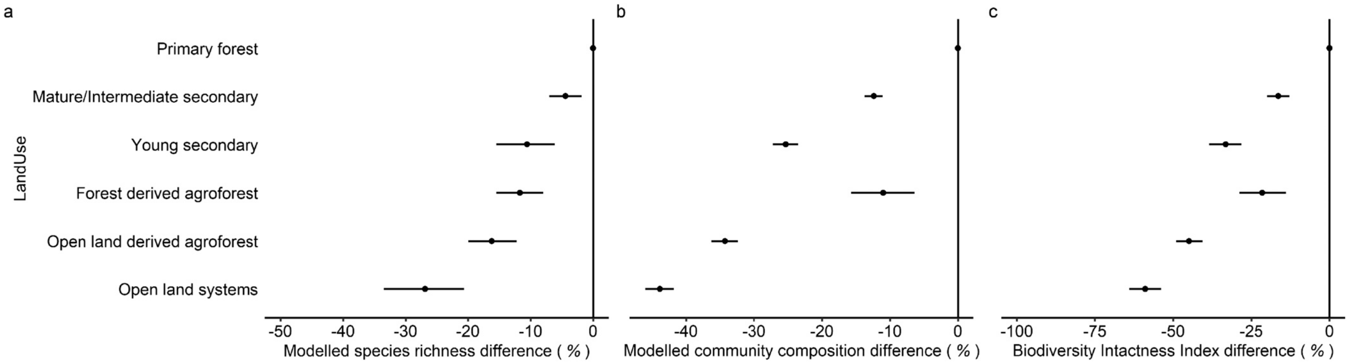

Fig. 1. Modelling results. (a) Modelled species richness difference of each land-use as a percentage-difference from primary forests. (b) Modelled community composition difference (asymmetric Jaccard index) between each of the land-uses and primary forest, expressed as the % of species in each land-use that were also found in primary sites. (c) Overall modelled effects of land-use change on biodiversity intactness.

derived cocoa-based agroforestry systems is comparable to both young and mature/intermediate secondary forests.

4. Discussion

4.1. *Biodiversity in cocoa-based agroforestry systems is lower than in primary forests*

Biodiversity intactness in even the least impactful (forest-derived) cocoa-based agroforestry systems is on average 22% lower BII than in primary forests. The conversion of natural forests to agroforests involves, at a minimum, the removal of understory and thinning of forest canopies (Asare, 2005), and therefore the habitat of some forest species, leading to an overall decrease in the intactness of local biodiversity where this land-use change occurs.

4.2. *Biodiversity intactness in cocoa-based agroforestry systems is higher than in open-land systems*

Our results show that biodiversity intactness is, on average, 14% higher in cocoa-based agroforestry systems than in open-land systems (Fig. 1c). These findings support previous studies that have suggested that the higher complexity of agroforest vegetation, along with the more diverse range of available niches and thermal regulation that forest shade provides, are able to support a wider range of species than open-land farming systems (Niether et al., 2020).

4.3. *Forest-derived cocoa-based agroforestry systems support higher intactness than open-land-derived cocoa-based agroforestry systems*

Biodiversity intactness in forest-derived cocoa-based agroforestry systems is comparable to intactness in secondary forests, and it is higher than in open-land-derived cocoa-based agroforestry systems. This is potentially due to the retention of natural forest trees and the niches they provide (Mbolo et al., 2016). The two components of our BII – species richness and community composition – react differently to these two systems (Fig. 1a and b). The species richness in the two land uses is not significantly different; our estimates suggest that both host 10–15% fewer species than primary forests at a given site. However, the composition of communities drives the main difference in BII between these two types of cocoa agroforest. Forest-derived cocoa-based agroforestry systems host a community with a higher proportion of forest species than open-land-derived cocoa-based agroforestry systems. Agroforestry systems with native shade trees may provide a structural environment more similar to primary forest than systems with planted shade trees. The trees in open-land-derived cocoa-based agroforestry systems likely do not provide this complex structure, leading to a greater divergence from natural communities and a greater number of non-native species too. Forest-derived cocoa-based agroforestry systems may also provide better connectivity, allowing for the movement of forest species between remnant patches of primary forest in a wider matrix than open-land-derived cocoa-based agroforestry systems. This way, forest-derived cocoa-based agroforestry system may improve the beta-diversity of the landscape. However, another reason for the difference in community composition may arise from the matrix itself that surrounds each of these land uses: despite the fact that the distance between agroforests and primary forest is accounted for in our modelling, forest-derived cocoa-based agroforestry systems may be more likely to occur within a mostly-natural matrix, whereas open-land-derived cocoa-based agroforestry systems may be more likely to occur within a mostly-degraded landscape, affecting the kinds of species that appear when each type of site is surveyed.

These results build on previous findings that whilst high-biodiversity cocoa-based agroforestry systems are possible, many, notably those that are derived from open land, have more similar characteristics to open-land systems than they do natural forest (Norgrove and Beck, 2016; Tondoh et al., 2015). There is considerable variability in measurements of biodiversity in cocoa agroforests, as evidenced by conflicting conclusions from across the literature; these can be at least partially explained by the difference between naturally shaded and open-land-derived systems. Our results support the conclusions of Tadu et al. (2014) that the habitat type that cocoa agroforests are established from determines the richness and composition of species that can thrive there. However, it is important to note that the biodiversity condition of agroforests may improve over time if the systems are allowed to mature and undergo some level of succession (Nijmeijer et al., 2019). The mean age of open-land-derived agroforests in our study was ~ 10 years younger than the average age of forest-derived systems, which may have led to some bias in our comparisons. Time-series of biodiversity surveys in before-after control-impact experiments could help understand and control for such effects.

4.4. *Forest- and open-land-derived cocoa-based agroforestry systems represent different transitions for biodiversity intactness*

Open-land-derived cocoa-based agroforestry systems have a lower BII than forest-derived cocoa-based agroforestry systems, but it is important to consider the context and directionality of these two land-use changes. Forest-derived cocoa-based agroforestry systems are necessarily established on land that was previously primary forest at some point in the past. Whilst forest-derived cocoa-based agroforestry systems have a relatively high BII, they still have a BII 22% lower than primary forests. Conversely, an open-land-derived cocoa-based agroforestry system could be established on what was previously open, or even degraded, land – though this is not necessarily the case as a primary forest could also be cleared, and then planted on. A transition from an open-land system such as abandoned cleared forest, cropland, pasture or cocoa monoculture, to a cocoa-based agroforestry system, could lead to an estimated increase in biodiversity intactness of 14%. Finally, further degradation of forest-derived cocoa-based agroforestry systems to open-land systems, as is often seen (e.g. Sonwa et al., 2007), could lead to an estimated 19% further decrease in BII. Thus, conserving the shaded state of forest-derived cocoa-based agroforestry systems would prevent substantial losses in biodiversity intactness. Whilst not as beneficial for biodiversity as large-scale forest restoration, extensive landscape scale tree cover achieved from a mixture of forest restoration, cocoa-based agroforestry implementation and primary forest protection could prove a practical mitigation strategy for the long-term biodiversity impacts of cocoa-linked deforestation.

4.5. *Study limitations and further research needs*

In this study, we were unable to discover enough data on biodiversity in cocoa monocultures to include them as a separate land-use category in our models. A recent review of 52 articles comparing cocoa-based agroforestry systems' performance with that of monoculture systems found that only 10% of these addressed any element of biodiversity (Niether et al., 2020). Some data is available, for example a study in Côte d'Ivoire which found that plant species richness in monoculture cocoa was much lower than forests, at levels similar to our "open-land systems" category (Tondoh et al., 2015), but more studies on the impacts of cocoa monocultures on biodiversity are needed to get a fuller picture of the relative biodiversity costs and benefits of different cultivation methods. Further, this study relies on a space-for-time substitution to make inferences about the consequences of land-use change in areas of cocoa production. Yet, before-after-control-impact comparisons have shown that, in the context of tropical deforestation, studies substituting space for time may underestimate biodiversity impacts (França et al., 2016). Long-term controlled assessments of the biodiversity outcomes of cocoa monoculture and agroforestry, as well as assessments of biodiversity change after planting shade on established cocoa monocultures, would provide a more accurate and precise understanding of the impacts of these land-use transitions.

In terms of impact and policy, incorporating modelled biodiversity impacts into maps of land use in regions of cocoa production could provide a better picture of the overall impacts of land-use change on biodiversity in those regions. Further, incorporation of these models into projections of land-use change under different policy scenarios could help to understand how a mixture of forest protection, maintenance of natural shade in cocoa-based agroforestry systems, and establishment of more open-land-derived cocoa-based agroforestry systems on degraded land could mitigate related biodiversity loss at the national scale. At the moment this is limited by a dearth of spatial data on cocoa growing areas and systems, though ongoing developments in remote sensing and classification techniques will hopefully provide new opportunities. Connecting models of biodiversity impacts to those covering yield and other ecosystem services, including measurements of continuous factors such as percent shade cover, will be necessary to better understand trade-offs and synergies in cocoa-related decision-making. Finally, using these models alongside landscape-scale metrics of connectivity and fragmentation could show how cocoa agroforestry might contribute to different national goals for ecosystems and biodiversity.

4.6. *Implications for decision-making*

Our results have different relevance according to different contexts of historical and ongoing (cocoa-driven) deforestation trends, prevailing cocoa systems and policy objectives in individual cocoa growing countries. In countries such as Ghana and Côte d'Ivoire, with extensive historical and ongoing deforestation due to cocoa and other factors (Brobbey et al., 2020; Vivid Economics, 2020), forest protection, restoration and the increase of tree cover in cocoa landscapes are a major focus of government and private sector sustainability initiatives (e.g. Republic of Côte d'Ivoire, 2018; Republic of Ghana, 2018). For instance, under the Cocoa and Forests initiative in Côte d'Ivoire (Republic of Côte d'Ivoire, 2018), cocoa agroforestry is to be used as a restoration tool in highly degraded forest reserves. For these countries our results show that open-land-derived cocoa-based agroforestry systems (or supported natural regrowth where possible) can support progressive increase in biodiversity intactness in cocoa landscapes and can also lead to an increase in other ecosystem services. On the other hand, there are countries, such as Liberia and Cameroon, with large areas of remaining forest (Buchhorn et al., 2019) that are highly suitable for cocoa (Schroth et al., 2016) and, in light of historical trends, therefore potentially at risk of conversion (Sassen et al. submitted). Agroforestry systems are more prevalent here than in Ghana and Côte d'Ivoire and their maintenance should be supported to avoid a gradual loss in biodiversity values. Where national policies do not have legal provisions that preclude the conversion of forests outside protected areas or other areas of high conservation value, diverse forest-derived cocoa-based agroforestry systems should be supported.

Whether farmers plant or maintain forest trees in their cocoa farms depends on many factors, including perceptions about effects on productivity and diseases, preferences for tree species and also tree and land tenure (Mbolo et al., 2016). Efforts are underway to make tree and land tenure arrangements more conducive to retaining trees on farmland (Republic of Ghana, 2018). High shading can affect cocoa productivity, though most studies find that shade is unlikely to compromise annual productivity at levels up to around 40% (Blaser et al., 2018), or even 60% (Zuidema et al., 2005). Moreover, agroforestry systems can help improve net farmer income through diversification of products from the cocoa farm (Sonwa et al., 2014; Tscharntke et al., 2011); they may also increase resilience (Norgrove and Beck, 2016), and provide a higher total system yield than an intensive full-sun cocoa monoculture when these other products are accounted for (Niether et al., 2020). Tailoring shade species to local peoples' needs and desires, maximising context specific benefits from agroforestry (Gyau et al., 2015), as well as management of shade species succession, can help capitalise on the potential of shade trees to provide multiple products and services over time (Braga et al., 2019). Finally, yields in cocoa agroforests may be more stable over time – this is evidenced anecdotally in the long persistence and productivity of many of Brazil's "cabruca" cocoa plantations in natural shade; some are still active more than 80 years after the take-off of the globalised cocoa industry in Brazil (Johns, 1999). Evidence on the production costs and profitability of agroforestry is mixed (Niether et al., 2020; Ruf, 2011), though it is established that the initial investment in agroforestry can be high when trees need to be planted in open-land systems (Clough et al., 2009; Martin et al., 2020; Ruf, 2011). Farmers therefore need support to make such transitions, including through training, appropriate inputs, market access for diversified products, and finance. In and near high-biodiversity areas, highly shaded and diverse agroforestry systems are especially desirable to maintain landscape integrity. Rewarding farmers for biodiversity and other ecosystem services' conservation through payment for ecosystem services schemes such as carbon finance, or other innovative finance mechanisms, will likely be required in such areas (Waldron et al., 2012).

5. Conclusions

Cocoa-based agroforestry systems are an intermediate-complexity system hosting biodiversity greater than that of open-land systems. In planning for better outcomes for biodiversity in cocoa landscapes, it is important to consider the direction of the biodiversity transition. Though forest-derived cocoa-based agroforestry systems host biodiversity of most similar form and substance to natural forest, they are necessarily degradative, and biodiversity benefits are predicated to an extent on retaining natural species (not exploiting them for a benefit). Planted shade systems represent a clear benefit to biodiversity above comparable open-land systems, and can support biodiversity restoration objectives in agricultural landscapes. In support of ongoing cocoa sustainability efforts, both types of agroforest can play a role in improving and maintaining biodiversity in cocoa landscapes. The re-agroforestation of highly degraded forests and open-land systems with functional, valuable, and useful tree and understory crops may provide further favourable outcomes for farmers, including food security amid volatile cocoa prices. In forested areas where agroforestry systems prevail or where expansion is inevitable, the maintenance and promotion of naturally shaded forest-derived cocoa-based agroforestry systems may provide low-biodiversity-impact options that can still be made economically interesting to farmers. However, the continued destruction and degradation of natural habitats for cocoa agriculture, even alongside restoration planting, may not be enough to prevent further widespread biodiversity loss linked to cocoa. Our results emphasise the importance of protecting remaining natural forest land and promoting the maintenance of existing natural shade systems alongside increased system productivity from cocoa-based agroforestry systems.

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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.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2021.107712.

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