Improving cocoa harvest can mitigate for crop damage by wildlife in a forest-agriculture matrix

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ABSTRACT

Shade-grown cocoa has been suggested as a more carbon and biodiversity friendly land use around protected forests compared with slash-and-burn farmland, and may be particularly suitable for achieving livelihood, biodiversity and forest protection goals of REDD+ projects. However, loss of cocoa to wildlife perceived to come from forest protected areas can result in lower profits for local people, reduced livelihood benefits from development projects and negative perceptions of conservation leading to reduced conservation impacts. We collected and analysed data on cocoa pod numbers and damage by animals over 2 months of the cocoa growing season, coinciding with peak harvesting season, from 39 plots at 3 forest edge communities around Gola Rainforest National Park, Sierra Leone. We estimate that 20% of pods across the cocoa plantations studied were damaged by wildlife, though there was high spatial variation. Of damaged pods where the animal group responsible could be identified, 87.2% of the damage was by monkeys, 11.1% by rats or squirrels and 1.7% by chimpanzees. Binomial mixed modelling of the proportion of pods damaged by wildlife indicated that this was higher closer to settlements and where pod density was lower. This indicates that the species causing the most damage in this system are disturbance-tolerant generalists which are not dependent on the protected forest, that mitigation measures should be concentrated where damage is highest, particularly close to settlements, and that increasing cocoa yield in these communities could offset damage by wildlife and therefore still be a viable option for, for example, REDD+ projects, even where crop raiding is common.

1. Introduction

Cocoa (*Theobroma cacao*) is one of the main cash crops in the tropical forest zone, with the primary producing countries being Ivory Coast, Ghana, Indonesia, Nigeria, Cameroon and Brazil (FAO, 2016). Global demand and production of cocoa have been increasing steadily over recent years (Gilbert, 2016). It is a perennial crop, with shade growth a requirement for many strains. Although cocoa production itself may represent a deforestation threat where virgin forest is cleared to plant cocoa trees (Ruf et al., 2015; Ordway et al., 2017), the forest-like structure of cocoa plantations and the income potential of the crop has led cocoa production to be proposed as an alternative land use to slash-and-burn farming, potentially leading to lower deforestation, less carbon loss to the atmosphere, less damage to forest biodiversity and

provision of connective habitat for wildlife between forest patches (Asare et al., 2014; Jezeer et al., 2017).

Because the forest-like structure of shade cocoa supports arboreal wildlife, this inevitably includes species capable of using cocoa as a food source. This can result in financial loss to the farmer, which may motivate him or her to adopt alternative, more profitable land uses, depending on local circumstances and market conditions, potentially reducing the effectiveness of cocoa as a development and conservation tool. Where crop raiding of this type is common, it can lead to negative perceptions of forest wildlife and forest conservation and retaliatory killing of wildlife (Meijaard et al., 2011; Nyirenda et al., 2015). Even if the species causing the damage mainly reside in the agricultural matrix rather than inside the high forest, forest wildlife might still be blamed (Kerr, 2013). Several studies also indicate that farmers perceive a

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greater magnitude of damage to crops caused by wildlife than is actually the case (e.g. Riley, 2007; Arlet and Molleman, 2010). It is therefore important to try and make an accurate assessment of the damage caused at a site to determine the magnitude of the problem, the actual rather than perceived taxa involved (so that mitigation can be correctly targeted), and any temporal and spatial patterns in the damage that might help in finding mitigation techniques to minimise damage. Current mitigation techniques for cocoa focus on time and labour-intensive guarding by humans, with no robust studies yet carried out on the effectiveness of such methods for cocoa, though Wiafe and Sam (2014) found chilli-grease fences to be partly effective in deterring elephants from cocoa plantations.

Whilst crop raiding is a major source of human-wildlife conflict in many agricultural systems across the tropics, with a wide range of mammalian taxa shown to be responsible (Bhat et al., 1981; Riley, 2007; Dakwa et al., 2016), the taxa causing greatest damage, the proportion of production lost and the environmental factors that mediate losses are poorly known. A number of factors are likely to affect crop and therefore economic loss to the farmer. These include field or plantation structure; distance to human settlement (both Songhurst and Coulson, 2014); and proximity to natural habitat such as protected forest areas which can act as a source of raider species. Additionally, the type of adjacent habitat may affect the ease of access to the crop and the availability of alternative food sources for wildlife, which may in turn affect raiding frequency (e.g. Hockings and Humle, 2009; Marchal and Hill, 2009; Addo-Boadu, 2010; Riley et al., 2013), with generalists responding more positively to degraded habitat than forest specialists (e.g. Devictor et al., 2008; Gibson et al., 2011). As many of these factors can be manipulated through changes in agricultural and landscape management or improved landuse planning for agricultural expansion, better understanding of such factors helps identify how losses to wildlife might be reduced, in order both to improve livelihoods of highly impoverished communities and to reduce pressure on and conflict with forest wildlife. Of particular interest is the impact of total yield on the level of damage by wildlife since interventions to increase yield are a major aspect of development work. Increased yield could attract crop raiders, exacerbating the problem, or, conversely, might compensate for crop loss by wildlife.

Despite the increasing importance of cocoa to the West African economy, which is responsible for 70% of the world's production (Wessel and Quist-Wessel, 2015), the large land area given over to the crop, and the fact that crop damage is the most prevalent form of human-wildlife conflict facing Africa (Barua et al., 2013), there have been few studies attempting to quantify damage to cocoa by African wildlife (but see Adomako, 2007; Arlet and Molleman, 2007). Given the recent emphasis on cocoa as an environmentally-friendly alternative land use (Asare et al., 2014), there is a pressing need for studies which will help to address concerns over wildlife damage by communities reliant on the income generated by cocoa farming.

Greater understanding of how crop-raiding affects social and conservation outcomes is highly relevant for the application of Reducing Emissions from Deforestation and forest Degradation (REDD+) programs, one pathway by which diverse outcomes might be met and in which cocoa may play a part. Shade cocoa is one strategy used to contribute towards the sale of carbon credits under a REDD+ strategy by avoiding carbon loss to other agriculture in the "leakage belt" immediately surrounding the forest, but must result in an improvement in the livelihoods of the forest edge communities (FECs) and ensure that any impacts on biodiversity are minimised (UN-REDD, 2010; CBD, 2011). Such a livelihood improvement cannot be realised if actual or perceived cocoa losses to crop raiding are too high to make cocoa economically viable, and therefore greater understanding of the factors that influence cocoa raiding within REDD+ projects is needed so that their impact, if any, may be reduced.

Here, we present a survey of wildlife damage of cocoa around Gola Rainforest National Park (GRNP), in eastern Sierra Leone, which is the subject of the first REDD+ project in West Africa and where a cocoa development project is under way, aiming to improve cocoa yield through education and plantation management assistance. One of the major concerns within the FECs is crop raiding, particularly of cocoa, which presents a potential barrier to the success of the REDD+ project through community fears that investment in increasing cocoa yield may not provide the expected returns due to crop loss to wildlife. In 2015, 15 patches of cocoa in three FECs in the leakage belt were visited three times each in October and November when cocoa pods are ripe or nearly ripe and therefore at most risk of damage by wildlife. We counted healthy and damaged pods to obtain an estimate of the minimum loss of cocoa to wildlife, and assessed what habitat, management and landscape factors may influence the extent of damage by the different taxa to aid recommendations on the extent of the problem and mitigation measures that may reduce the impact of crop raiding by wildlife.

2. Materials and methods

2.1. Study site

GRNP, consisting of lowland moist evergreen high forest, lies in the East of Sierra Leone on the border with Liberia, between 7°18′ and 7°51′N and 10°37′ and 11°21′W (Fig. 1a). The Upper Guinea forest of West Africa is a global biodiversity hotspot with high endemism (Myers et al., 2000), and the study site incorporates the largest patch of such forest in Sierra Leone. It is the subject of a REDD+ project, which includes a 4 km leakage belt beyond the boundary of the park, where any deforestation above the REDD+ baseline will be considered leakage. This incorporates land lying in seven chiefdoms managed by 122 FECs. This community landscape consists of patches of community forest, slash-and-burn farmland (active farmland and fallow rotation) mainly for staple crops such as rice and cassava, various plantations such as oil palm, coffee and cocoa and permanent settlements supporting around 25,000 people. This study was carried out in cocoa plantations in two chiefdoms, Malema and Nomo, the first chiefdoms to receive cocoa development assistance as part of a livelihood improvement project for REDD+. In Malema chiefdom work was carried out at one FEC, Madina Malema, and in Nomo chiefdom in two FECs, Madina Nomo and Faama Nomo (Fig. 1b and c).

2.2. Study design

Perimeters of patches of active and abandoned cocoa were mapped using a Garmin GPSMap62s with identities and boundaries of adjacent habitat recorded. Active cocoa patches, where the plantations had been managed within the previous year, were selected in Nomo chiefdom to include as wide a range as possible of patch size and distance to GRNP. The cocoa patch in Madina Malema was selected as the largest patch of cocoa mapped. Patches ranged from 0.02 ha to 37.94 ha and from 0.79 km to 4.22 km from the GRNP boundary. In addition, three patches of cocoa and abandoned cocoa were surveyed at Madina Malema on direction of farmers as examples of plantations where there was a problem with chimpanzee crop raiding, but since these were selected by a different method, and as we knew our initial selection already contained plantations known to be raided by chimpanzees, the results from these were not included in the main dataset in order to avoid bias. In one plantation in Faama Nomo, one extra quadrat was placed where there was recent evidence of chimpanzee cocoa damage but this was also not included in the main dataset.

A 50 m × 50 m grid was superimposed on the land around the three communities with intersections corresponding to the 100 m and 50 m intervals of the X and Y UTM coordinates. In the selected active cocoa patches, 10 m × 10 m quadrats were placed at the intersections of the grid where these fell inside the patch of cocoa. If the patch contained more than seven grid intersections, random numbers were used to
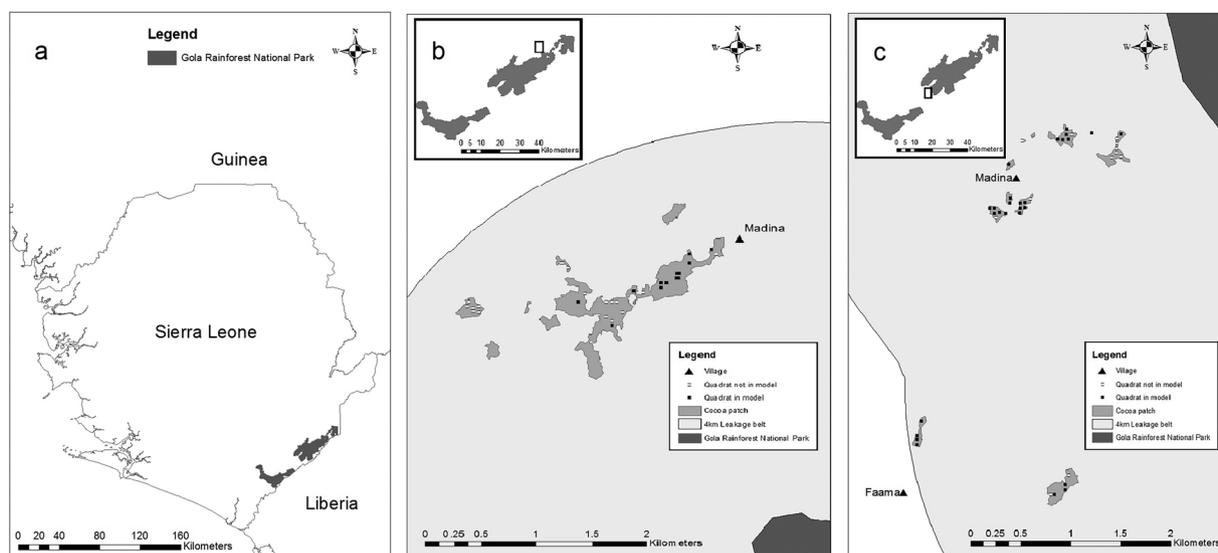
Fig. 1. Location of Gola Rainforest National Park in Sierra Leone (a), cocoa patches around Gola Rainforest National Park (inset) in Madina Malema (b) and Madina and Faama, Nomo (c) with all quadrat locations, including those used in the model.

select between five and seven quadrat locations. At one large patch in Madina Malema, 20 quadrat locations were selected randomly in order to cover the patch adequately (Fig. 1b).

2.3. Field data collection

The field team consisted of one trained scribe, two trained data collectors and one farmer with local knowledge of the cocoa grown in the community. The four corners of each quadrat were marked using stakes. Cocoa trees of 2.5 m in height or above were recorded if more than half of the area of the main stem at ground level was within the quadrat. Cocoa trees were marked with individually numbered aluminium tags.

The number of trees over 14 m tall within 25 m of the centre of quadrat were counted and ground vegetation cover < 3 m high within the quadrat was estimated and recorded as either < 1%, 1–5%, 5–25%, 25–50%, 50–75% or 75–100%.

Quadrats were visited three times between 07/10/2015 and 25/11/2015 with a mean interval of 18 days between visits, ranging from 11 to 24 days. Pods on each marked tree were counted within three length classes (not including the stem: 5–10 cm, 10–15 cm, > 15 cm, estimated with regular calibration checks, pods < 5 cm were too small to be counted accurately from the ground), by colour (brown (rotten), green (immature), yellow (mature), red (mature for some strains), green/yellow (turning mature)) and extent of rot (1–50%, 51–99%, 100%). Damage to pods on trees was noted and described: "small hole" if less than 20% of one side of the pod was missing, "large hole" if more than 20%, half pod if over 50% of the whole pod was missing. We took any damage to a pod by wildlife to mean 100% loss of that pod to the farmer as animals would eat or remove all or most of the contents and rot would subsequently be accelerated by the exposure to the atmosphere. A local farmer estimated the age of the damage and identified the animal taxa from signs on the pod. These signs included tooth marks, which vary in size, shape and frequency between taxa, the size and shape of pod fragments present, with chimpanzees biting pods and cracking pods with their hands, monkeys gnawing holes of various sizes leaving larger gnawed fragments and rodents gnawing pods and seeds leaving small fragments, and the presence of whole seeds dropped on the ground, indicating monkey or gnawed seeds on the ground or inside pods, indicating rodents. The damage was photographed for verification by PD, who is experienced in identifying crop damage to taxa. Damage was identified as caused by monkeys, chimpanzees or squirrels/rodents. The height in the tree of damaged pods was estimated to the nearest half metre. Where there were discrepancies in the identification of taxa damaging pods between the farmers in the field and PD, 12.7% of damage cases, the photo identifications were used. The ground within the quadrat was searched for evidence of animal signs and damaged cocoa pods. Damaged pods were described as above, with the additional damage classifications of "pod fragments" and "whole seed" and photos taken of all damaged pods during the first visit and newly-damaged pods during subsequent visits.

2.4. Data analysis

Age estimations and photos of recently damaged pods were compared between visits for each quadrat to identify pods which had been damaged since the first visit. These were used to calculate the total unique damage for visits 2 and 3. To avoid double-counting, recent pod damage recorded on the ground was only added to recent damage from the tree counts in a particular visit if there were no recently damaged pods on the trees within that quadrat that fragments or seeds could have come from. Pod damage signs on the ground within one week in estimated age of other pod damage signs that could have been from the same pod were counted as one pod only in the totals.

A baseline of the number of pods predicted to have been harvestable for profit over the period of the study, given no damage by wildlife, no loss to disease, invertebrate pests, fruit abortion or theft by humans, all losses which could potentially be mitigated for (Bos et al., 2007; Bailey and Meinhardt, 2016), was calculated. This was total number of healthy pods (< 50% rot, in keeping with local harvesting practices) counted in visit 1, plus pods damaged by wildlife estimated to have been damaged up to and including three weeks previously, as without wildlife damage these pods were harvestable. Age estimations older than three weeks were unreliable, as they could include damaged and diseased pods left unharvested during previous growing seasons. In addition, pods that would have grown to countable length (> 5 cm in length) since visit were added to the estimated baseline by assuming 20 days to grow from 0 to 5 cm and 30 days to grow from 5 to 10 cm, based on expert knowledge of local growing conditions. Assuming equal density of 5–10 cm and 0–5 cm, then 2/3 (to account for the differential growth time between 0–5 cm and 5–10 cm) the total of healthy and recently damaged 5–10 cm pods gives the estimated number of 0–5 cm pods present in visit 1, divided by 20 to get the number of pods that would grow to countable size each day. The total predicted number of pods

growing to a countable size was thus:

a = ((2 × b) / 3) / 20) × c

where:

a = number of pods growing from 0 to 5 to 5–10 cm
b = number of healthy and recently damaged 5–10 cm pods in visit 1
c = number of days between visit 1 and visit 3

The baseline of harvestable pods in the absence of crop-damage was thus:

Potential harvest = d + e + a

where:

d = number of healthy pods over 5 cm in length visit 1
e = number of pods damaged by wildlife within 3 weeks visit 1
a = no. pods predicted to grow from below to above 5 cm between visit 1 and 3

The proportion of pods lost per quadrat was thus:

Prop_damage = (f + g + h) / Potential harvest

Where:

f = recently damaged pods on tree visit 1 + unique recently damaged pods on ground visit 1
g = recently damaged pods on tree visit 2 + unique recently damaged pods on ground visit 2
h = recently damaged pods on tree visit 3 + unique recently damaged pods on ground visit 3

Mixed models with a binomial distribution were fitted using lme4 (Bates et al., 2015) in R 3.4.0 (R Core Team, 2017). Proportion of pods lost to animal raiders in each quadrat was fitted as a response to the following fixed explanatory variables: ln(cocoa patch area); ln(distance to GRNP); ln(distance to nearest settlement); mean number of trees with height > 14 m within 25 m of the centre of the quadrat; proportion of ground vegetation cover (taking the midpoint of each cover category), within the quadrat; proportion of the perimeter of the cocoa patch which bordered on woody habitat (community forest or abandoned plantation); estimated total number of pods. Distance to GRNP and proportion of the cocoa patch's perimeter which bordered woody habitat provide a measure of proximity of habitats which might act as a source of cocoa crop raiding mammals, whilst number of tall trees provide a measure of the plantation's accessibility to arboreal mammals. Ground cover acts a proxy for "good" plantation management, with well-managed plantations having their ground cover removed, potentially reducing accessibility to ground predators. Distance to settlement provides a measure of human disturbance, which might reduce raiding, although, conversely, settlements could act as a source of "pest" species which also consume cocoa pods. A number of interventions to increase cocoa yield around GRNP have been implemented, potentially attracting crop-raiding wildlife, hence the relevance of the total number of pods as a potential covariate. As the total number of pods was calculated including pods on the ground, which might have fallen from trees outside the quadrat or been carried in by raiding animals, quadrats with a potential harvest of < 6 were excluded, as their small sample size would render them vulnerable to bias caused by pods occurring on the ground that had originated outside the quadrat.

As quadrats within cocoa patches are not independent, cocoa patch identity was fitted as a random effect. Initial modelling indicated that the data were slightly over-dispersed for the global model. We therefore fitted an observation-level random effect of cocoa patch in order to increase the accuracy of parameter estimates (Harrison, 2014). To further reduce multicollinearity and ensure that they were on a common scale, all explanatory variables were standardised (Schielzeth, 2010). Models were fitted using the Laplace approximation and the "bobyqa" optimizer to enable model convergence (Bates et al., 2015).

Given that all model selection methods have the potential to result

in inaccurate inference (Burnham and Anderson, 2002; Cade, 2015) and the number of explanatory variables in this case was small, which reduces the penalty of increased variance associated with parameter estimates (Bolker et al., 2009), the global model was used for inference. However, exploratory backwards selection to find the minimum adequate model resulted in the same qualitative inference.

The data were checked for over-dispersion relative to the binomial model and residuals from the global model plotted against fitted values and explanatory variables to check for patterns following (Zuur et al., 2009), with no patterns or outliers detected. Interpretation of p values in mixed models should be conservative due to uncertainties arising from testing on the boundary and the interpretation of degrees of freedom (Bolker et al., 2009): an explanatory variable was therefore considered significant at $p < 0.01$ rather than at $p < 0.05$.

3. Results

3.1. Quadrat data

In total 70 quadrats were surveyed in 15 patches of actively managed cocoa. Of these, nine quadrats and two cocoa patches were removed from the main dataset since they were surveyed post-hoc in areas where chimpanzee damage was known to occur. Once quadrats with a baseline < 6 were removed, this left 39 quadrats in 11 cocoa patches in the modelling dataset.

A summary of baselines, total recorded damage and at all quadrats used in the model is shown in Table 1 and cocoa patch areas and distances in Table 2. For quadrats in the model, the baseline number of harvestable pods predicted over the course of the study ranged from 6 to 105 (mean 29.3, SD ± 26.9) and proportion damage from zero to 0.90 by quadrat, indicating high variation in the proportion of pods damaged. The mean proportion loss, weighted by cocoa patch area, was 0.204 (SD ± 0.159) for the 2 months covered by this study. This represents an estimated 562 pods (SD ± 278) damaged of an estimated baseline of 3075 pods (SD ± 1345) ha^{-1}, or an estimated economic loss to the farmer of US\$25.68 ha^{-1} compared to potential pod value of US\$140.43 based on local 2016 prices of 30 pods = US\$1.37 (Neevel, B. *pers comm*). Based on 55 questionnaires carried out for REDD+ in 2017 a rough estimate of annual income for FEC households with some cocoa farming activity is US\$340 with the average area of cocoa under management 1.2 ha (Horvath, B. *pers comm*). The losses recorded here therefore represent approximately 9% of total annual income lost from cocoa damage by wildlife during this 2 month period with potential further losses during the rest of the growing and harvesting season.

For fewer than 1% of recently damaged pods, the species group causing the damage could not be identified. Of 235 identifiable damage incidents 87.2% were caused by monkeys, 11.1% by rodents (rats and squirrels) and 1.7% by chimpanzees.

3.2. Modelling results

Both distance to settlement and total number of pods were negatively related to proportionate loss, which decreased with increasing distance to settlement and increasing yield (Table 2; Fig. 2). The negative impact of proximity to settlement (Fig. 2a) is particularly marked closer than 0.4 km to a village, with an estimate of a proportionate loss of 0.55 at 0.2 km, 0.38 at 0.4 km and 0.26 at 0.8 km. The more linear trend line in Fig. 2b suggests that increasing yield across the whole range of yields covered in the study will result in lower proportionate loss to wildlife. Indeed, from the trend line at a baseline of 10 pods it is estimated that around 4 pods would be lost, at a baseline of 100 pods it is estimated that around 7 pods would be lost rather than 40 were the proportion loss to remain constant, a potential saving of 33 pods in a 0.1 ha area. Whether increasing yield to mitigate loss is cost effective for farmers clearly depends on the input and labour costs of that increase.

Table 1
Cocoa patches used in model: area, distance to GRNP and distance to settlement. Cocoa quadrats used in model: baseline harvestable pods without wildlife damage (rounded), total confirmed wildlife damage and proportion damage.

Chiefdom	Village	Cocoa patch	Patch area (ha)	Distance GRNP (m)	Distance settlement (m)	Quadrat	Cocoa baseline	Total damage	Proportion damage
Malema	Madina	1	37.94	2821	1603	1	9	2	0.22
						2	105	12	0.11
						3	11	3	0.27
						4	23	2	0.09
						5	10	3	0.29
						6	20	7	0.34
						7	12	2	0.16
						8	27	7	0.26
						9	33	9	0.27
						10	111	13	0.12
						11	21	9	0.42
Nomo	Madina	2	2.58	1389	573	12	81	1	0.01
						13	70	3	0.04
						14	37	5	0.13
						15	49	1	0.02
						16	6	5	0.83
		3	0.02	1058	884	17	77	0	0.00
		4	3.30	824	1139	18	6	3	0.49
		5	1.35	2118	363	19	15	10	0.67
						20	13	7	0.54
						21	29	17	0.58
						22	15	8	0.53
						23	10	3	0.30
		6	1.52	2334	410	24	12	11	0.90
						25	33	15	0.45
						26	64	16	0.25
						27	16	7	0.43
						28	13	11	0.84
		7	0.56	2105	218	29	16	9	0.56
		8	0.50	1942	154	30	6	5	0.83
		9	0.11	1610	463	31	26	7	0.26
	Faama	10	4.98	2737	1511	32	17	0	0.00
						33	16	1	0.06
						34	39	5	0.13
						35	9	4	0.44
		11	1.47	3924	507	36	6	2	0.33
						37	35	5	0.14
						38	15	3	0.20
						39	27	5	0.19

Table 2
Parameter estimates and SEs (in parentheses) from the global model of proportion of cocoa pods lost to crop raiding, derived from a binomial GLMM with logit link. *P* values are derived from z values. Parameter estimates significant at $p > 0.01$ are shown in bold.

Variable	Parameter estimate
Intercept	**−1.029363 (0.198273)**
ln(cocoa patch area)	0.287110 (0.276799)
ln(distance to GRNP)	−0.003354 (0.260132)
ln(distance to settlement)	**−0.721711 (0.229622)**
number of trees of height > 14 m	0.061006 (0.252199)
ground vegetation cover	−0.179455 (0.177618)
proportion of woody habitat edge	−0.140679 (0.239367)
total number of pods	**−0.694849 (0.159930)**

4. Discussion

The proportionate damage of 0.204 is high compared to other estimates of proportion of cocoa damaged in plantations (e.g. Bhat et al., 1981; Arlet and Molleman, 2007; Riley, 2007; Harich et al., 2013), is mostly caused by monkeys and there is a clear trend for decreasing proportionate damage with distance to settlement and increasing yield. Distance to GRNP appeared to have little effect on proportionate damage, suggesting that either raiding species are not primarily forest-dependent, or that the leakage belt itself is sufficiently forested to support significant populations of such species. The high rate of crop raiding at our study site indicates that the communities' concerns that this is a genuine difficulty which might prove a barrier to growing profitable cocoa are justified. However, our results can inform ways to mitigate against loss, such as planting further from settlements, targeting high impact areas and increasing cocoa yield. This could help alleviate community members' concerns about, and improve the impact of schemes such as REDD+ and eco-certification that aim to combine both development and conservation in wildlife-rich areas. The high variability within the data indicates that targeting efforts at those sites and areas where the highest damage is observed, might be an efficient use of resources.

The damage was relatively high, with significant economic consequences for farmers, but the total damage may still be an underestimate since some species, particularly chimpanzees, are known to remove cocoa pods then process and consume them elsewhere. Such removal could be recorded through the ground damage data, but not if damaged pods were removed entirely and consumed outside the plantation. Conversely, however, animals might also inflate ground damage estimates by bringing pods remains from outside the quadrat into it. Whilst further inaccuracies in the damage data might also occur due to the difficulties in matching tree and ground damage, we have attempted to mitigate for this through photo comparisons and conservative rules regarding the likelihood of ground damage being from the same damaged pods as recorded tree damage. Additionally, although our survey season covered the period where the vast majority of cocoa pods were ripe and ready for harvest and therefore most vulnerable to damage by wildlife, the cocoa harvest season in Sierra Leone extends outside this time and therefore some damage will have
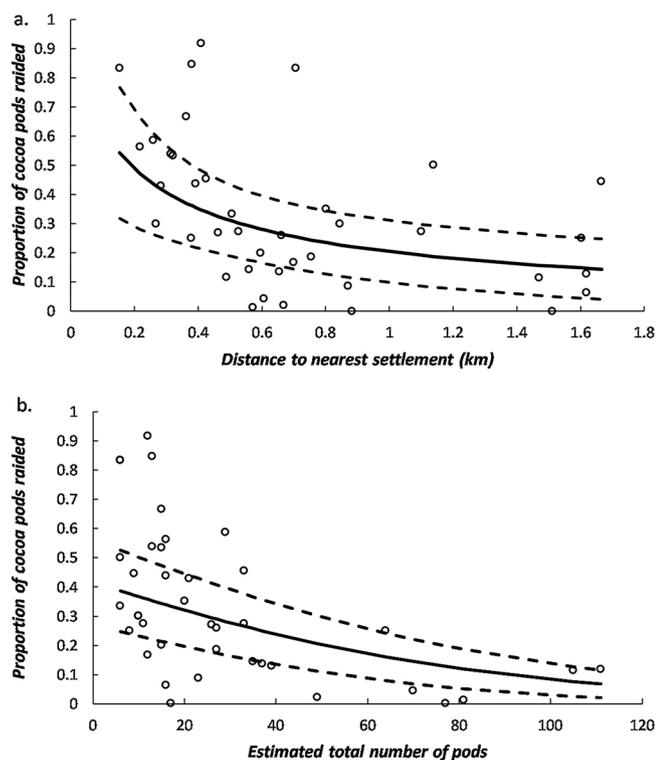
Fig. 2. The relationship between distance to nearest settlement (a) or estimated total number of pods (b) and proportion of cocoa pods raided, derived from the binomial GLMM in Table 2, with 95% confidence limits. Circles represent the actual values for each quadrat (*n* = 39). Other explanatory variables fitted in the model were held to their mean value.

inevitably been missed. Squirrels are thought to also consume unripe pods, so some pre-harvest damage between May and July might have been missed due to difficulties in estimating the age of damaged pods in the hot and humid climate where vegetation rots extremely quickly. There are, therefore, several practical challenges to accurately quantifying cocoa crop raiding damage, and accurate methods to quantify damage are going to be an important concern if cocoa is going to be widely implemented for REDD+ projects. This study represents one of the few attempts to quantify wildlife damage and the factors that might modify it to this increasingly important cash crop, and these data are invaluable in providing an estimate of the extent of the problem around a protected forest, identifying what factors might mitigate it, and guiding future effort to understand how to alleviate the conflict. As the practical limitations of small numbers of plantations from which to collect data and a single field season may limit how far our results can be generalised, we emphasise the urgent need for such work to be repeated elsewhere.

More damage close to settlements suggests that the taxa damaging the pods are attracted to villages, contradictory to the pattern found in some crop-raiding studies (e.g. Songhurst and Coulson, 2014). Identification data indicates that monkeys cause the most damage at this time of year and the prevalence of damage close to villages suggests that these may not be species that are highly dependent on the forest. Species regularly observed close to villages include Campbell's monkey, lesser spot-nosed monkey *Cercopithecus petaurista* and sooty mangabey, all common across the agricultural matrix as well as within the forest interior, with more forest-specialist species such as the Endangered western red colobus *Procolobus badius* and Vulnerable Diana monkey *Cercopithecus diana* being more restricted to the GRNP and other large forest blocks. This suggests that the pristine forest of the GRNP itself does not necessarily provide a source of the most destructive crop-raiding wildlife, reflecting the fact found in previous studies that

relationship to distance from protected areas is highly site-specific, finding more raiding closer to protected areas (Naughton-Treves, 1998; Linkie et al., 2007) or finding no relationship (Gillingham and Lee, 2003; Arlet and Molleman, 2007). The authors (Hulme, M. *pers. obs.*) note that Campbell's monkeys, in particular, tend to forage across the landscape during the day and return to roosting sites close to villages at night, potentially leaving plantations close to villages more liable to raiding. This could be due to the deterrent effect of human presence on animal predators, whilst Islamic beliefs, coupled with the scarcity of firearms in Sierra Leone due to local post-conflict gun laws, means monkeys themselves are not often hunted by people outside the forest. In addition, the presence of plantain, mango and other fruit in and around villages might attract crop raiding taxa. Further research would need to be carried out to investigate the causes of this relationship, the foraging patterns of potential crop raiders, the distribution of fruiting trees and what the impact of potential future cultural and legal changes may have on primate-human interactions. Site-specific differences, which probably reflect variation between sites in the species carrying out the raiding, emphasise the need to understand crop raiding on a site-by-site basis, particularly around protected areas where the conservation consequences of endangered wildlife being wrongly blamed for crop raiding could be profound. We note that the greatest distance to the National Park was 4 km, which may have been too close to detect an effect on larger, wide-ranging species which might still depend on pristine forest, although this variation in distance is large compared to that over which the effect of distance to forest has previously been recorded (e.g. Linkie et al., 2007). The results indicate that, whilst moving existing plantations might not be an option, any new or rehabilitated plantations should avoid the immediate area within 200 m of a settlement if crop-raiding is considered a significant issue, whereas proximity to GRNP may be less important, although additional work would help confirm this

The trend for lower proportionate damage with a higher potential harvest suggests that as pod load and, presumably, profit for the farmer increases, the overall loss relative to income decreases. The absolute number of pods lost does not change with increased pod density rather than more wildlife being attracted to the higher density of food available in well-managed plantations. This also suggests that an effective mitigation technique could simply be to improve yield through improved plantation management even without additional mitigation specifically to reduce crop raiding, although this is likely to vary depending on the site and the taxa involved. The results here suggest that an improvement in yield from 1000 to 10,000 pods ha^{-1} would be associated with a relatively minor increase of only 30 raided pods. This leaves potential income gains of US$241 ha^{-1}, not accounting for other forms of crop loss, such as disease, invertebrate pest damage, fruit abortion or theft, or for increases in costs related to improved management. However, within a framework such as REDD+, many of these costs would be offset by assistance and income from the REDD+ program itself and related efforts to reduce non-crop-raiding losses, such as to disease, could also increase yield to offset losses to crop-raiding. One result of increased resources and income could also be the freeing up of time and labour to perform more frequent harvesting trips to plantations, leaving ripe pods vulnerable to wildlife on the trees for a shorter period of time and further reducing losses to crop raiding.

There are several potential reasons that could explain the finding of lower rates of damage in sites with higher potential yields. These include: an insufficient density of potentially crop-raiding wildlife in the landscape to cause significantly greater damage to higher-yielding plantations; deterrence of wildlife by higher levels of disturbance at well managed sites (though the higher proportionate loss close to settlements would contradict this); and well managed plantations presenting a greater physical barrier to arboreal crop raiding wildlife due to higher levels of vegetation clearing, cocoa tree pruning and shade tree management (although the data presented here gives no evidence of an effect of habitat structure). Continued monitoring would be

required in order to ensure increased cocoa yields do not, with time, attract higher densities of crop-raiding wildlife to the larger potential food source, although our single-season data suggests that this is not currently the case in higher yielding plantations. The study site represents a fine-grained mosaic of small-scale forest, plantations, farmland and settlements within which the arboreal wildlife which might feed on cocoa moves relatively freely and the scope for erecting physical barriers such as fences or nets of sufficient size and strength to exclude arboreal primates and rodents (e.g. Campbell-Smith et al., 2012) would require excessive cost in terms of materials, labour and maintenance. This result could mean that the great effort required to construct such barriers or to perform time-consuming, ineffective and labour-intensive guarding duties (Arlet and Molleman, 2007; Hockings and Humle, 2009) to the degree that might reduce crop raiding damage might better be spent on plantation management that will improve yield and increase profit to a level that will overcome the losses still experienced by wildlife damage. This would also potentially reduce the conflict between development and conservation and reduce hunting or "retaliatory killing", both legal and illegal, of crop raiding and suspected crop raiding species, as well as reducing habitat alteration outside of the plantations to deter wildlife. Hunting is widespread in and around our study site (Jones et al., 2017). There may, however, be a conservation trade-off if well managed plantations are not as attractive as connective habitat for wildlife moving between forest blocks (Asare et al., 2014), which could potentially limit distribution, resource availability and genetic flow, and thus reduce the population. If this is the case then efforts should be made to retain sufficient forest-like habitat in the landscape such as community forest, old unmanaged plantations and old fallow farmland. We also note that, even at sites where damage is low relative to perceptions and to loss of yield for other reasons, such as disease, any damage is likely to be viewed as negative and this represents a challenge that must be faced by managers and conservationists where cocoa is being promoted for livelihood and environmental reasons.

5. Conclusions

Whilst cocoa crop raiding is a complex and, at times, seemingly intractable problem for farmers, plantation managers, and conservationists, detailed studies such as this can provide information that can help to overcome some of the challenges presented by loss of yield and income and the resultant negative perceptions of wildlife and forest, which may otherwise hinder the effective implementation of the carbon, biodiversity and livelihood aims of projects such as REDD+. This study suggests that the species responsible, at least around GRNP, are not forest specialists of the greatest conservation concern, which, if effectively communicated, could also go some way to improving farmer attitudes to the conservation of forests harbouring non-raiding species. We also found that improving cocoa yield, rather than exacerbating the problem by attracting a higher rate of crop raiding, can more than balance out the losses incurred whilst increasing profits for farmers and livelihoods for forest edge communities. These results suggest ways in which the conflict resulting from cocoa crop raiding, even where overall damage is high, can be effectively tackled where the promotion of cocoa is an active policy for development and conservation purposes. Given the role of tropical forests in climate change resilience, the low income of many forest edge communities across the tropical forest zone and the importance of such areas for biodiversity, overcoming the challenge of crop raiding is an issue of global importance.

References

Addo-Boadu, A.M., 2010. Human-Wildlife Conflict Management around Kakum Conservation Area, Ghana.

Adomako, B., 2007. Causes and extent of yield losses in cocoa progenies. Trop. Sci. 47, 22–25.

Arlet, M.E., Molleman, F., 2007. Rodents damage crops more than wildlife in subsistence agriculture on the northern periphery of Dja Reserve, Cameroon. Int. J. Pest Manag. 53, 237–243.

Arlet, M.E., Molleman, F., 2010. Farmers' perceptions of the impact of wildlife on small-scale cacao cultivation at the northern periphery of Dja Faunal Reserve, Cameroon. Afr. Primates 7, 27–34.

Asare, R., Afari-Sefa, V., Osei-Owusu, Y., Pabi, O., 2014. Cocoa agroforestry for increasing forest connectivity in a fragmented landscape in Ghana. Agrofor. Syst. 88, 1143–1156.

Bailey, B.A., Meinhardt, L.W., 2016. Cacao Diseases: A History of Old Enemies and New Encounters. Springer international Publishing, Switzerland.

Barua, M., Bhagwat, S.A., Jadhay, S., 2013. The hidden dimensions of human–wildlife conflict: health impacts, opportunity and transaction costs. Biol. Conserv. 157, 309–316.

Bates, D., Mächler, M., Bolker, B.M., Walker, S.C., 2015. Fitting linear mixed-effects models using lme4. J. Stat. Softw. 67, 1–48.

Bhat, S., Nair, C., Mathew, D., 1981. Mammalian pests of cocoa in South India. Int. J. Pest Manag. 27, 297–302.

Bolker, B.M., Brooks, M.E., Clark, C.J., Geange, S.W., Poulsen, J.R., Stevens, M.H.H., White, J.-S.S., 2009. Generalized linear mixed models: a practical guide for ecology and evolution. Trends Ecol. Evol. 24, 127–135.

Bos, M.M., Steffan-Dewenter, I., Tscharntke, T., 2007. Shade tree management affects fruit abortion, insect pests and pathogens of cacao. Agr. Ecosyst. Environ. 120, 201–205.

Burnham, K.P., Anderson, D.R., 2002. Model Selection and Multimodel Inference. Springer-Verlag, New York.

Cade, B.S., 2015. Model averaging and muddled multimodel inferences. Ecology 96, 2370–2382.

Campbell-Smith, G., Sembiring, R., Linkie, M., 2012. Evaluating the effectiveness of human–orangutan conflict mitigation strategies in Sumatra. J. Appl. Ecol. 49, 367–375.

CBD, 2011. REDD-Plus and Biodiversity. Technical Series. Convention on Biologicl Diversity, Montreal, Canada.

Dakwa, K., Monney, K., Attuquayefio, D., 2016. Raid range selection by elephants around Kakum Conservation Area: implications for the identification of suitable mitigating measures. Int. J. Biodivers. Conserv. 8, 21–31.

Devictor, V., Julliard, R., Jiguet, F., 2008. Distribution of specialist and generalist species along spatial gradients of habitat disturbance and fragmentation. Oikos 117, 507–514.

FAO, 2016. FAOSTAT Online Database. FAO-UN.

Gibson, L., Lee, T.M., Koh, L.P., Brook, B.W., Gardner, T.A., Barlow, J., Peres, C.A., Bradshaw, C.J., Laurance, W.F., Lovejoy, T.E., 2011. Primary forests are irreplaceable for sustaining tropical biodiversity. Nature 478, 378–381.

Gilbert, C.L., 2016. The dynamics of the world cocoa price. The Economics of Chocolate. pp. 307.

Gillingham, S., Lee, P.C., 2003. People and protected areas: a study of local perceptions of wildlife crop-damage conflict in an area bordering the Selous Game Reserve, Tanzania. Oryx 37, 316–325.

Harich, F.K., Treydte, A.C., Sauerborn, J., Owusu, E.H., 2013. People and wildlife: conflicts arising around the Bia Conservation Area in Ghana. J. Nat. Conserv. 21, 342–349.

Harrison, X.A., 2014. Using observation-level random effects to model overdispersion in count data in ecology and evolution. PeerJ 2, e616.

Hockings, K., Humle, T., 2009. Best Practice Guidelines for the Prevention and Mitigation of Conflict between Humans and Great Apes. IUCN.

Jezeer, R.E., Verweij, P.A., Santos, M.J., Boot, R.G., 2017. Shaded coffee and cocoa––double dividend for biodiversity and small-scale farmers. Ecol. Econ. 140, 136–145.

Jones, S., Burgess, M.D., Sinclair, F., Lindsell, J., Vickery, J., 2017. Optimal monitoring strategy to detect rule-breaking: a power and simulation approach parameterised with field data from Gola Rainforest National Park, Sierra Leone. Conserv. Soc. 15, 334.

Kerr, C.H., 2013. Evaluating the Viability of Shade-Grown Tree Crop Plantations as a Conservation Strategy in the Context of Crop-Raiding Adjacent to Gola Rainforest National Park, Sierra Leone. Imperial College, London.

Linkie, M., Dinata, Y., Nofrianto, A., Leader-Williams, N., 2007. Patterns and perceptions of wildlife crop raiding in and around Kerinci Seblat National Park, Sumatra. Anim. Conserv. 10, 127–135.

Marchal, V., Hill, C., 2009. Primate crop-raiding: a study of local perceptions in four villages in North Sumatra, Indonesia. Primate Conserv. 24, 107–116.

Meijaard, E., Buchori, D., Hadiprakarsa, Y., Utami-Atmoko, S.S., Nurcahyo, A., Tjiu, A., Prasetyo, D., Christie, L., Ancrenaz, M., Abadi, F., 2011. Quantifying killing of orangutans and human-orangutan conflict in Kalimantan, Indonesia. PLoS One 6, e27491.

Myers, N., Mittermeier, R.A., Mittermeier, C.G., Da Fonseca, G.A., Kent, J., 2000. Biodiversity hotspots for conservation priorities. Nature 403, 853–858.

Naughton-Treves, L., 1998. Predicting patterns of crop damage by wildlife around Kibale National Park, Uganda. Conserv. Biol. 12, 156–168.

Nyirenda, V.R., Lindsey, P.A., Phiri, E., Stevenson, I., Chomba, C., Namukonde, N., Myburgh, W.J., Reilly, B.K., 2015. Trends in illegal killing of African elephants (Loxodonta africana) in the Luangwa and Zambezi Ecosystems of Zambia. Environ. Nat. Resour. Res. 5, 24.

Ordway, E.M., Asner, G.P., Lambin, E.F., 2017. Deforestation risk due to commodity crop expansion in sub-Saharan Africa. Environ. Res. Lett. 12, 044015.

R Core Team, 2017. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Riley, E.P., 2007. The human–macaque interface: conservation implications of current and future overlap and conflict in Lore Lindu National Park, Sulawesi, Indonesia. Am. Anthropol. 109, 473–484.

Riley, E.P., Tolbert, B., Farida, W.R., 2013. Nutritional content explains the attractiveness of cacao to crop raiding Tonkean macaques. Curr. Zool. 59, 160–169.

Ruf, F., Schroth, G., Doffangui, K., 2015. Climate change, cocoa migrations and deforestation in West Africa: what does the past tell us about the future? Sustain. Sci. 10, 101–111.

Schielzeth, H., 2010. Simple means to improve the interpretability of regression coefficients. Methods Ecol. Evol. 1, 103–113.

Songhurst, A., Coulson, T., 2014. Exploring the effects of spatial autocorrelation when identifying key drivers of wildlife crop-raiding. Ecol. Evol. 4, 582–593.

UN-REDD, 2010. The UN-REDD Programme Strategy 2011-2015.

Wessel, M., Quist-Wessel, P.F., 2015. Cocoa production in West Africa, a review and analysis of recent developments. NJAS-Wagening. J. Life Sci. 74, 1–7.

Wiafe, E.D., Sam, M.K., 2014. Evaluation of a low-tech method, pepper–grease, for combatting elephant crop-raiding activities in Kakum Conservation Area, Ghana. Pachyderm 38–42.

Zuur, A.F., Ieno, E.N., Walker, N.J., Saveliev, A.A., Smith, G.M., 2009. Zero-truncated and zero-inflated models for count data. Mixed Effects Models and Extensions in Ecology With R. Springer, pp. 261–293.