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Protecting habitats in low-intensity tropical farmland using carbon-based payments for ecosystem services

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Abstract

Tropical land-use change for agricultural expansion is the primary driver of global biodiversity decline. Efforts to stem this decline often focus on protecting pristine habitats or returning farmland to forest, yet such approaches fail to protect vulnerable taxa reliant on habitats within low-intensity farmland. We assess the economic viability of carbon-based payments for ecosystem services (PES) to protect farmland trees and fallowing in Ghana, which provide vital wintering sites for imperiled Afro-palearctic migrant birds and enhance landscape-level carbon storage. We estimate the carbon breakeven prices (BEPs) associated with alternative agricultural management scenarios that protect existing farmland trees. BEPs associated with tree protection on existing farmland were very low, ranging from US\$2.49 to US\$6.45 t^{-1} CO_2. Extending and reintroducing fallow periods also carried competitive BEPs, US\$4.67—US\$15.45 t^{-1} CO_2, when combined with the protection of 50 trees per hectare. Accounting for leakage and economic uncertainty increased BEPs considerably, but scenarios protecting farmland trees and extending fallow periods remained below EU Emissions Trading Scheme prices. Protecting low-intensity farmland habitats and associated biodiversity is cost-effective under carbon-based PES. Implementation should be combined with efforts to close yield gaps, providing greater local food security and resilience.

1. Introduction

Agricultural expansion is the greatest threat to global biodiversity (Laurance 2007). Replacement of natural habitats with crops and grazing for livestock leads to declines in biodiversity (Gibson *et al* 2011), with disastrous consequences for ecosystem functioning and service provision (Cardinale *et al* 2012). With global population and food demand projected to continue rising to at least 2050 (Tilman *et al* 2011), agricultural expansion and intensification will persist, largely to the detriment of global biodiversity (Laurance *et al* 2014).

Conservation efforts often seek to prevent or reverse tropical agricultural expansion by prohibiting the clearance of forests (Peres 2005) or encouraging forest regrowth on abandoned agricultural land (Gilroy *et al* 2014). For instance, sparing primary tropical forest from conversion or allowing secondary forest regrowth on abandoned farmland via agricultural intensification will conserve more biodiversity than protecting wildlife within farmland (land sharing) (Phalan *et al* 2011, Edwards *et al* 2021). However, boosting agricultural yields via intensification reduces 'wildlife-friendly' habitat within agricultural land (Fischer *et al* 2008) or shortens fallow periods (Morton *et al* 2020), which is detrimental to populations reliant on low-intensity agriculture (Pywell *et al* 2014) or agroforestry (Bhagwat *et al* 2008). Land-sparing is often the most effective method of conserving biodiversity (Luskin *et al* 2018). However, in areas with a long history of human disturbance a hybrid 'three-compartment' approach, whereby some low-intensity farmland is retained alongside natural habitat on land that is spared as result of high-intensity agriculture, allows the persistence of species reliant on both natural habitat and low-intensity farmland (Feniuk *et al* 2019).

Low-intensity farmland habitats are particularly important for migratory species (Jones *et al* 1996). For example, low-intensity farmland provides wintering habitat for Himalayan bird species (Elsen *et al* 2017), whilst Afro-Palearctic migrants commonly spend the winter in farmland of sub-Saharan West Africa (Morel and Morel 1992). Long-distance Afro-Palearctic migrants have suffered greater declines than either short-distance migrants or resident species (Sanderson *et al* 2006), and destruction of wintering habitats on low-intensity farmland in sub-Saharan Africa is one of the potential drivers of their population declines (Vickery *et al* 2014). Isolated, mature farmland trees have a disproportionately high positive effect on biodiversity (Fischer *et al* 2010, Douglas *et al* 2014), whilst fallowed land provides suitable habitat for migratory bird species (Deikumah *et al* 2017). However, farmland tree cover is declining (Gonzalez *et al* 2014) and fallow cycles have been shortened or abandoned entirely in an effort to increase productivity (Evenson and Gollin 2003). With food demand likely to continue to increase pressure on farmers to intensify, ensuring the protection of low-intensity farmland habitats is vital to safeguard populations of declining taxa, including migratory birds.

Given limited global conservation funding (Maxwell *et al* 2015), a key question is whether it is economically viable to fund the retention of low-intensity farmland of particular importance to biodiversity under carbon-based payments for ecosystem service schemes. Carbon-based PES schemes used to fund conservation action often focus on preventing forest loss or returning farmland to forest. For example, raising agricultural yields on existing farmland and increasing charcoal-use efficiency in Tanzania can prevent forest conversion at US\$6.50 t^{-1} CO_2 (Fisher *et al* 2011). Similarly, abandonment of cattle pasture in the Colombian Andes and shortening of fallow periods in shifting cultivation farmland in North-east India allow forest regeneration at US\$1.99 t^{-1} CO_2 and US\$0.89 t^{-1} CO_2 breakeven prices (BEPs), respectively (Gilroy *et al* 2014, Morton *et al* 2020). With agriculture now the dominant global land use (Ellis and Ramankutty 2008), finding cost-effective ways to also protect and boost rare farmland taxa is vital to meet biodiversity conservation goals.

Here, we examine the economics of alternative agricultural land management scenarios, calculating the opportunity costs (OCs) and carbon BEPs of protecting existing tropical farmland habitats for the benefit of migratory bird populations. We focus on Ghana, where agriculture is the mainstay in the country's economy, similar to many developing countries (Dethier and Effenberger 2012). High habitat diversity and mosaics of agriculture, grasslands, shrublands, and forests provide important habitats for palearctic migrants—particularly in the Guinea-Congolian/Sudanian transition (Mallord *et al* 2016, Deikumah *et al* 2017). However, population growth and increased food demand is increasing pressure on farmers to expand and intensify (Zhang *et al* 2021), which threatens the persistence of these important habitats and the biodiversity they support.

Using secondary, nationally representative, economic data for Ghana, we simulate the cost of (a) protecting existing trees in agricultural land and (b) extending and reintroducing fallows to farmland. We measure the potential carbon protected in these landscapes, and the future carbon accrued as trees mature over the project period, using tree inventory data from across Ghana. We simulate OCs and carbon BEPs for multiple cropping scenarios at two tree densities—reflecting a diversity of farming practices and attitudes to farmland trees—to assess the potential for carbon-based PES schemes to protect farmland habitats.

2. Methods

2.1. Study area and data collection

Agriculture in Ghana has been an integral part of the country's progression towards middle-income country status (Breisinger *et al* 2009). The country is dominated by smallholders, with over 90% of farms <2 ha (MOFA 2012), and characterized by low yields (Wongnaa *et al* 2019) and minimal fertilizer use (Callo-Concha *et al* 2012). Approximately 80% of land in Ghana is under customary tenure (Pande and Udry 2005). Land-use rights are mostly granted by village chiefs, although, having cleared land for cultivation, land is customarily recognized as the property of the farmer (Chapoto *et al* 2013). Despite steady economic growth (average growth of 6.8% from 2005 to 2017; GLSS7), a large proportion of the population remain below the poverty line, and recent declines in poverty incidence have been minimal—reducing by only 0.8% between 2012/13 and 2016/17 (from 24.2% to 23.4%; GLSS7).

We gathered economic data on crop yields and prices, and agricultural input costs from the Ghana Living Standard Survey (GLSS 7). The GLSS collects information on the livelihoods and well-being of the population, including information on agricultural land use, yields, and costs, from a nationally representative sample of 15 000 households. From the GLSS we extracted yields and input costs for two staple crops: maize and cassava, and several secondary crops: groundnut, soybean, and plantain. Maize is the most important crop in Ghana, with a cropped area of 1 million ha in 2012 (MOFA 2012). Maize is commonly cropped in a fallow cycle, ranging from

1 to 5 years (Hansen *et al* 2012), or intercropped with nitrifying legumes to maximise yields (Kermah *et al* 2017). Cassava is an important source of calories across sub-Saharan Africa (De Souza *et al* 2017) and has an important role in increasing food security as the roots can be harvested all year-round (Rahman and Awerije 2016) and potential exists to massively increase yields (Adiele *et al* 2020).

All subsequent modelling and analyses were carried out in R version 4.0.2 (R Core Team 2020).

2.2. Agricultural management scenarios

We calculated OCs and carbon BEP following similar methods to those previously used in other carbon-based PES schemes (Fisher *et al* 2011, Morton *et al* 2020) to allow for direct comparison. We modeled the OC and BEP associated with four different crop rotations: maize-fallow, maize-legume (groundnut and soybean), cassava-only, and cassava-plantain, under three management scenarios. Scenarios 1 and 2 represent two of the most intense agricultural management regimes currently used in the region, whilst scenario 3 shows a potential route to reduce the intensification of these systems (figure 1). Scenarios were modelled over a 30 year project period, a common length for PES schemes (See Fisher *et al* 2011, Gilroy *et al* 2014).

Scenarios 1–1.2 (figure 1) represent a two-year fallow cycle, the most intensive form of agriculture that still utilises fallow periods, leaving 50% of land under fallow. Scenarios 1–1.2 were modelled for maize as it is uncommon to continuously grow maize on the same farmland without intercropping with legumes. Scenarios 2–2.2 represent continuous cultivation (figure 1). We modelled scenarios 2–2.2 for maize-legume, cassava-only, and cassava-plantain crop rotations. Scenarios 3–3.2 show the conversion of both scenarios 1–1.2 and scenarios 2–2.2 to a three-year fallow cycle (figure 1), leaving 66% of land under fallow. Scenario 3 was modelled for each of the four crop rotations, however, under the cassava-plantain system, plantain was retained in the landscape during fallow years.

2.3. Economic modelling

The net present value (NPV) of scenarios was calculated using economic models (full details of models and variables used is given in supplementary materials). Model parameters were set using GLSS data on crop yields and input costs (including hired labour, equipment, tools, transport, storage, fertilizer, seeds, irrigation, and fuel). To reflect variability in yields and input costs, we sampled parameter values from a normal distribution using the median value bounded by the upper and lower limits of the collected data, weighted by region to account for variable sampling intensity. All economic parameters were adjusted to 2019 US$. We performed 10 000 independent model runs for each scenario, sampling new model parameters each iteration.

We removed cases where farm NPV fell below US$0 (figure S1 (available online at stacks.iop.org/ERL/16/114022/mmedia); 33% of cases) from our calculations of OC and BEP. In these instances, we assume loss-making farmers are involved in informal markets, reflecting a survival strategy (Vorley 2013), using crops to barter for goods and services, and so applying only economic value to the yields of these farmers is inappropriate and gave negative BEP. The OC of alternative scenarios were calculated as the difference between the NPV of the proposed scenario and the NPV of the most intensive alternative for that crop. Retaining trees in the landscape was assumed to have an OC related to an area of no production around that tree, scaled by the tree's size (see supplementary methods). We present OC per 6 ha as this allows us to compare all three farming systems to one another without having to use units <1 ha, but our results are readily scalable to smaller or larger farm sizes.

2.4. Landscape carbon and BEP calculations

We calculated our carbon BEP based on the protection of existing farmland trees from removal. Trees are common features of farmland in Ghana (Hansen *et al* 2012), but population growth, agricultural intensification, and high volatility in landscape transition has reduced tree cover across the Sahel and threatens the persistence of farmland trees (Niang *et al* 2008, Gonzalez *et al* 2014). For example, shea trees—a group with high economic and cultural value, and carbon sequestration potential (Takimoto *et al* 2008)—are rapidly declining in parklands due to population growth and wood fuel demand (Okiror *et al* 2012, Lovett and Phillips 2018).

We populated our landscapes with randomly selected trees from an inventory sampled from three regions of Ghana: Ashanti, Brong Ahafo, and Eastern. The inventory contained information on tree species, height, diameter at breast height (DBH), and wood density for 4973 individuals of 128 species, with trees ranging from 5 to 190 cm DBH (figure S2; see supplementary material for tree sampling methodology). BEPs were calculated assuming the protection of aboveground carbon contained within trees at the start of the project, plus the additional carbon sequestered over the 30 year project. The aboveground carbon held within trees was calculated using the allometric equation developed by Chave *et al* (2014).

For scenarios 1.1, 2.1, and 3.1, we created landscapes in which tree density was set to 20 trees ha^{-1} (figure 1), reflecting the mean tree density of the farmed parklands of the Sahel (Bayala *et al* 2014). For scenarios 1.2, 2.2, and 3.2, tree density was set at 50 trees ha^{-1}, the average tree density of cropped land in northern Ghana (Hansen *et al* 2012; figure 1). Trees

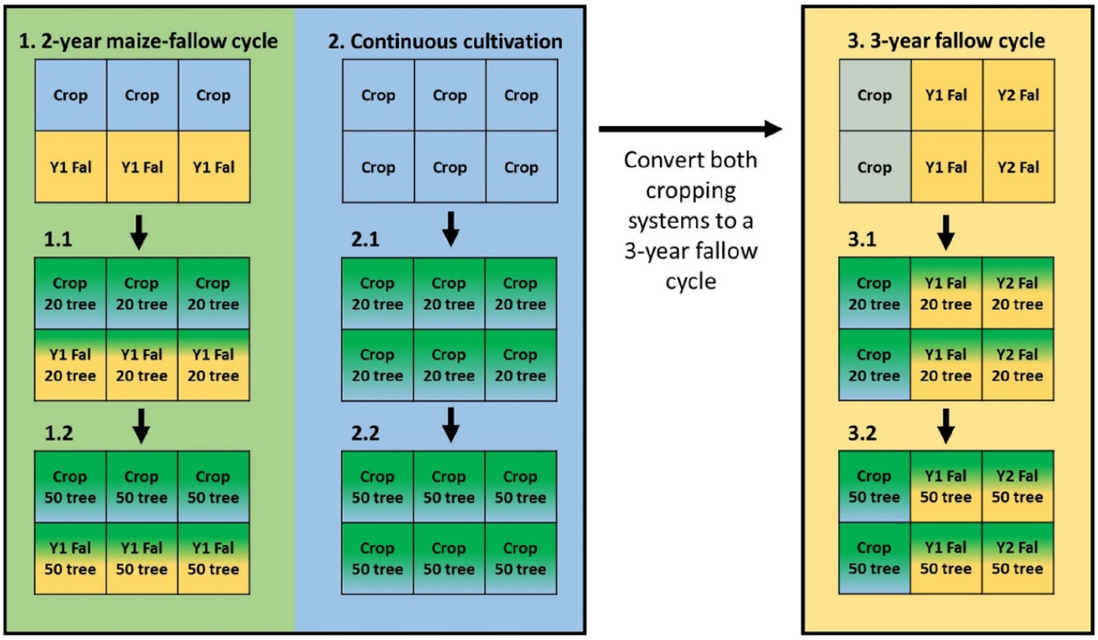

Figure 1. Current and alternative management scenarios for agricultural landscapes in West Africa. (A) Existing two-year maize-fallow cycles, with SC1.1 and SC1.2 showing the protection of 20 and 50 trees ha^{-1}, respectively. (B) Existing continuously cultivated farmland, with SC2.1–2.2 showing the protection of 20 and 50 trees ha^{-1}, respectively. Continuously cropped scenarios were modelled for three different crop types: maize intercropped with legumes, cassava-only, and cassava intercropped with plantain. (C) Conversion of both existing cropping systems to a three-year fallow cycle, with SC3.1 and SC3.2 showing the protection of 20 and 50 trees ha^{-1}, respectively. Colours represent land use: cultivated (blue), fallow (yellow), and tree density (green shading).

were randomly sampled with replacement from our inventory for each of the 10 000 model iterations we performed. Carbon accumulation over our 30 year project period was calculated by maintaining the randomly selected trees within our landscape over the project period and allowing these trees to grow each year, whilst recalculating aboveground carbon. Tree DBH was uniformly increased by 0.55 cm yr^{-1} for all trees—the best available estimate of annual tree growth in the region (Mbow *et al* 2013).

Carbon BEPs were calculated for each of the scenarios using a modified version of the long-term certified emissions reduction scheme (lCER; see supplementary methods). BEPs were calculated to offset both OCs and the predicted costs of project monitoring and management. Monitoring costs were based on existing community-based monitoring schemes (Cranford and Mourato 2011, Murtinho and Hayes 2017; see supplementary methods).

2.5. Leakage and economic uncertainty

Preventing leakage of agricultural activity to regions with lesser restrictions (Latawiec *et al* 2015) is likely to mean BEPs are higher than prices that are only equal to opportunity and management costs. Previous analysis suggests the cost of preventing leakage is likely to be equal to the OCs associated with the project (Fisher *et al* 2011). To account for this, and for potential fluctuations in discount rate, we performed a precautionary reanalysis, doubling OCs and allowing discount rate to vary between 10%-25%. We also perform a reanalysis of our data with reference to a baseline of 10 trees ha^{-1}, reflecting instances whereby farmers may retain a very low density of trees on their farms given the benefits they provide (Sinare and Gordon 2015).

2.6. Regional variations in BEPs

We calculated individual BEPs for ten regions across Ghana (figure S3) using regionalized yield and input cost data extracted from the GLSS and regionalized inflation rates to convert these to 2019 US$ values. We compared breakeven costs between regions, and against the country-wide average, to identify the most cost-effective regions to implement alternative management scenarios.

3. Results

3.1. OCs of alternative management scenarios

Protecting trees in existing two-year maize-fallow (SC1) and continuous cultivation (SC2) farmland had low annual OCs (figure 2), ranging from US$14.17 to US$98.56 for 6 ha of land. Protecting trees in two-year maize-fallow carried the lowest OCs, followed by continuously cultivated maize-legume, then cassava-only, with continuously cultivated cassava-plantain carrying the greatest OC.

Preventing the removal of trees from 6 ha of farmland currently under a two-year maize-fallow cycle had median annual OCs of US$14.17 (SD; ±18.09) to protect 20 trees ha^{-1} (SC1.1) and US$39.41 (±38.44)

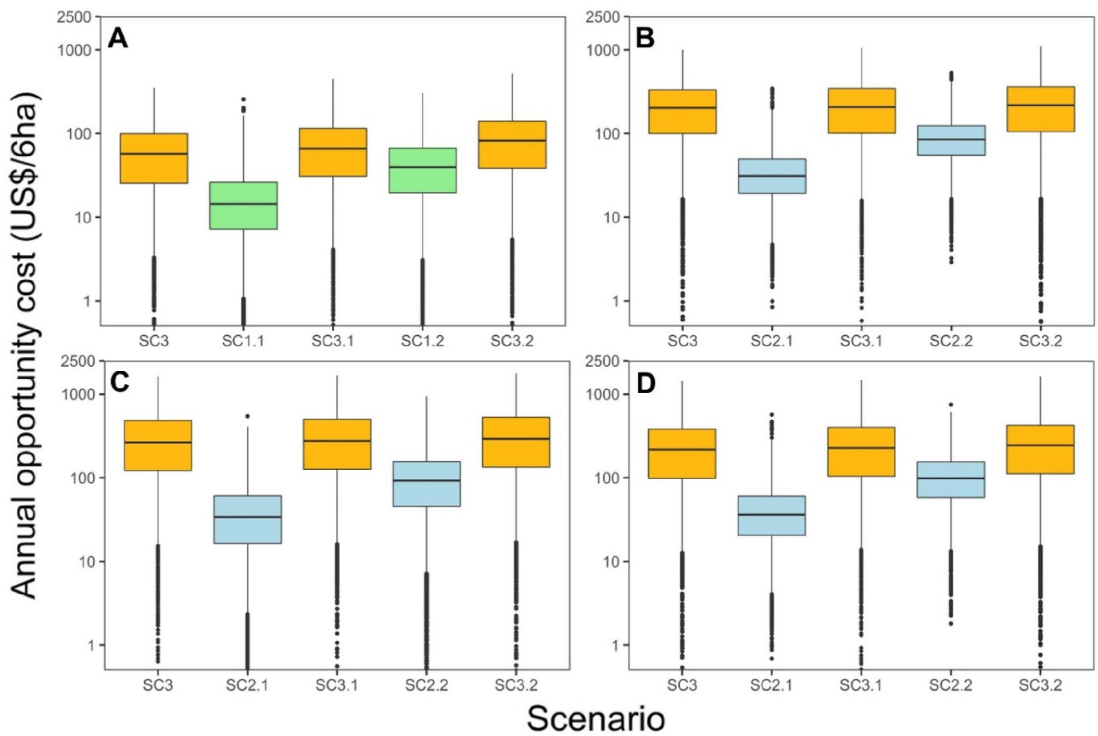

Figure 2. Annual opportunity cost of alternative landscape management over 6 ha of farmland for (A) maize-fallow crop, (B) maize-legume crop, (C) cassava-only crop, and (D) cassava-plantain crop. Box whisker plots show median, interquartile and 1.5× interquartile ranges, and outliers. Plot colours indicate the agricultural system: two-year maize-fallow cycle (green), continuously cultivated (blue), and three-year fallow cycle (yellow). Opportunity costs are fitted to a log scale to aid clarity.

for 50 trees ha^{-1} (SC1.2). Protecting trees in continuous cultivation scenarios (SC2) carried greater OCs for all crop types compared to the maize-fallow system (figure 2). Across 6 ha of continuously cropped cassava, protecting 20 trees ha^{-1} (SC2.1) cost US$33.81 (±42.43) and 50 trees ha^{-1} (SC2.2) was US$92.15 (±90.36). Maize intercropped with legumes had lower OCs than both cassava crop systems at all tree densities (figure 2), with preventing the removal of 20 trees ha^{-1} (SC2.1) costing US$31.06 (±29.18) and 50 trees ha^{-1} (SC2.2) costing US$85.03 (±57.19).

Converting existing two-year maize-fallow and continuous cultivation farmland into a three-year fallow cycle (SC3) had considerably higher OCs than maintaining current regimes (figure 2). However, extending a two-year maize-fallow cycle to a three-year maize-fallow cycle carried much lower OCs than converting continuous cultivation systems to a three-year fallow (figure 2). Extending a two-year maize-fallow cycle to a three-year cycle carried a median cost of US$57.04 (±55.90) for 6 ha of farmland. Exchanging continuous cultivation for a three-year fallow cycle (SC3) was more expensive for all crop types (figure 2), with a median cost of converting maize-legume systems of US$202.24 (±170.78), cassava-only systems of US$264.88 (±263.83), and cassava-plantain systems of US$217.35 (±207.36) for 6 ha of farmland.

Protecting existing trees within the landscape post-conversion to a three-year fallow cycle had marginal effects on OCs for all cropping systems. Over 6 ha of farmland, protecting 20 trees ha^{-1} in a three-year maize-fallow cycle (SC3.1) carried a median cost of US$65.86 (±64.42), whilst protecting 50 trees ha^{-1} (SC3.2) was US$81.70 (±77.14). Following conversion from continuous cultivation to a three-year fallow cycle, OCs remained high for the other three crop types. Cassava carried the highest median costs, with protection of 20 trees ha^{-1} (SC3.1) costing US$275.48 (±273.52), and 50 trees ha^{-1} (SC3.2) costing US$291.69 (±287.60).

3.2. Carbon BEPs of alternative management scenarios

Carbon BEPs for protecting trees on farms whilst maintaining current agricultural practices were substantially lower than the BEPs for converting these systems to a three-year fallow cycle (figure 3). Increasing tree density reduced BEPs in all scenarios and for all crop types (figure 3). Protecting existing trees under a two-year maize-fallow regime (SC1) had the lowest BEP at all tree densities (figure 3(A)), with a median price of US$3.22 (±1.93) t^{-1} CO_2 at 20 trees ha^{-1} (SC1.1) and US$2.49 (±1.80) t^{-1} CO_2 at 50 trees ha^{-1} (SC1.2). The BEP of protecting trees under continuous cultivation was lower in the maize-legume cropping regime than both

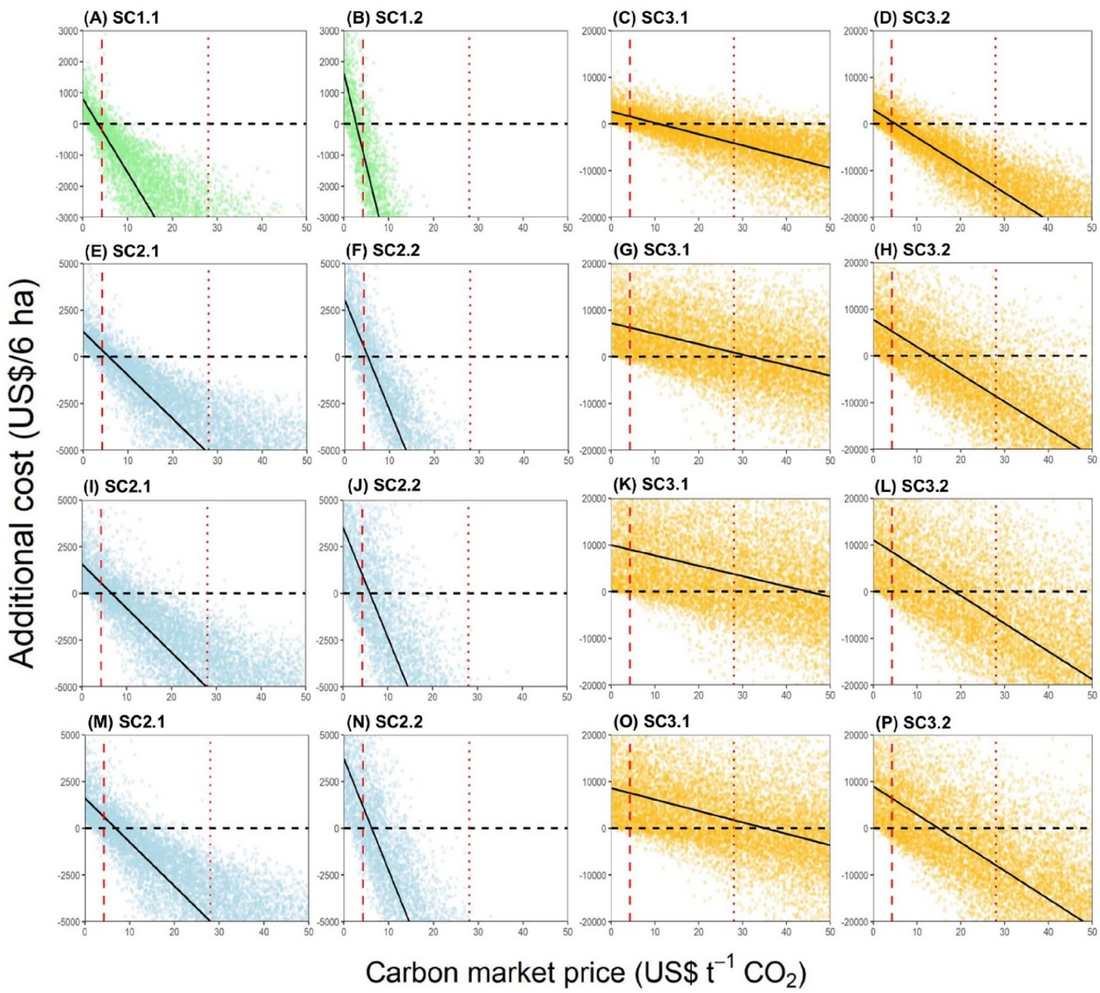

Figure 3. Carbon breakeven prices (BEPs) and additional costs of alternative management scenarios under a range of carbon market prices for maize-fallow (A)–(D), maize-legume (E)–(H), cassava-only (I)–(L), and cassava-plantain (M)–(P). Colours indicate the system: two-year fallow cycle (green), continuous cultivation (blue), and three-year fallow cycle (yellow). Economic models and carbon stocks were independently sampled and fitted each iteration for 10 000 unique model runs. Solid black lines show fitted linear models and dashed black lines show where no additional costs are incurred. Vertical red lines indicate global carbon prices, with the first dotted line = US$4.30 t^{-1}$CO_2$ (Average 2019 voluntary carbon market price), and the second dotted line = US$28 t^{-1}$CO_2$ (Average 2019 EU ETS carbon market price).

the cassava and cassava-plantain regimes for all tree densities (figure 3). The median BEPs for the maize-legume scenarios were US$5.61 (±2.81) t^{-1} CO_2 at 20 trees ha^{-1} (SC2.1) and US$4.96 (±2.58) t^{-1} CO_2 at 50 trees ha^{-1} (SC2.2). Both cassava regimes carried similar, but higher, BEPs, with cassava-only median prices of US$6.01 (±4.37) t^{-1} CO_2 at 20 trees ha^{-1} (SC2.1) and US$5.40 (±4.17) t^{-1} CO_2 at 50 trees ha^{-1} (SC2.2).

Extending existing two-year maize-fallow cycles to three-year fallow cycles (SC3) carried much lower BEPs than converting continuous cultivation scenarios, for all tree densities (figure 3). Median BEPs for extending a two-year fallow cycle to a three-year fallow cycle were US$10.24 (±12.21) t^{-1} CO_2 at 20 trees ha^{-1} (SC3.1) and US$4.67 (±4.43) t^{-1} CO_2 at 50 trees ha^{-1} (SC3.2). Converting cassava-only continuous cultivation into a three-year cassava-fallow cycle carried the greatest BEPs, with median prices of US$39.88 (±54.48) t^{-1} CO_2 at 20 trees ha^{-1} (SC3.1) and US$15.45 (±18.01) t^{-1} CO_2 at 50 trees ha^{-1} (SC3.2).

3.3. Leakage and economic uncertainty

Accounting for leakage and uncertainty in discount rates increased BEPs of protecting trees in existing cultivation scenarios (SC1.1–1.2 & SC2.1–2.2) by an average of 42%. In two-year maize-fallow systems, BEPs for protecting 20 trees ha^{-1} (SC1.1) increased to US$4.47 (±3.29) t^{-1} CO_2 (40% increase) and 50 trees ha^{-1} (SC1.2) increased to US$3.55 (±2.90) t^{-1} CO_2 (43% increase; figure S5). In continuously cultivated cassava farmland BEPs were US$8.43 (±6.90) t^{-1} CO_2 for 20 trees ha^{-1} (SC2.1) and US$7.44 (±6.89) t^{-1} CO_2 for 50 trees ha^{-1} (SC2.2), an increase of 40% and 38%, respectively (figure S5).

BEPs of protecting trees in farmland post-conversion to a three-year fallow cycle (SC3.1–3.2) increased by an average of 46%. The BEP of extending a two-year maize-fallow cycle to a three-year fallow cycle and protecting 20 trees ha^{-1} (SC3.1) was US\$14.56 (±20.61) t^{-1} CO_2 whilst protecting 50 trees ha^{-1} was US\$6.68 (±7.13) t^{-1} CO_2, an increase of 42% and 43%, respectively (figure S5). Converting continuously cultivated maize-legume and cassava-plantain cropping systems into a three-year fallow cycle carried BEPs, of US\$42.29 (±55.42) t^{-1} CO_2 (46% increase) and US\$45.09 (±66.50) t^{-1} CO_2 (41% increase) whilst protecting 20 trees ha^{-1}, and US\$17.13 (±19.80) t^{-1} CO_2 (46% increase) and US\$18.69 (±23.22) t^{-1} CO_2 (46% increase) whilst protecting 50 trees ha^{-1} (SC3.2), respectively (figure S5).

BEPs also increased when accounting for farmers optionally maintaining a very low tree density (10 trees ha^{-1}) on their land. Protecting farmland trees in existing cultivation scenarios increased by an average of 14% (figure S6), with prices ranging from \$2.59 (±1.82) t^{-1} CO_2 to \$7.73 (±4.28) t^{-1} CO_2. Whilst extending fallow cycles from 2 to 3 years increased BEP by an average of 64% (figure S6), with prices ranging from \$5.38 (±5.33) t^{-1} CO_2 to \$83.88 (±137.97) t^{-1} CO_2.

3.4. Regional differences in BEPs

The Northern region of Ghana had the lowest BEPs for alternative management scenarios for both maize-fallow and continuously cropped systems (figure 4). The median BEPs of protecting trees in existing maize-fallow (SC1.2) of the Northern, Upper West, Central, and Brong Ahafo regions of Ghana were all below the country-wide median (figure 4). For continuously cropped cassava systems, BEPs of protecting trees in the Northern, Central, and Brong Ahafo regions of Ghana were all below the country-wide median (figure 4). Extending existing maize-fallow to a three-year cycle (SC3.2) carried BEPs lower than the national median in Northern, Upper West, Central, Eastern, and Brong Ahafo regions (figure 4). Converting continuously cropped cassava to a three-year fallow cycle (SC3.2) was lower than the national median in Northern, Central, and Brong Ahafo regions (figure 4).

4. Discussion

Low-intensity farmland provides important habitats for a variety of taxa, including migrant bird species, but is under increasing pressure of intensification to meet growing food demand. We show that protecting existing farmland trees using carbon-based PES schemes offers a cost-effective method to conserve important tropical farmland habitats. Additionally, OCs incurred by introducing and extending fallow periods, which provide important habitat for vulnerable migratory bird species, can be offset using carbon-based PES when combined with tree protection.

4.1. Economic viability of alternative management scenarios

OCs of protecting trees in current farmland were very low for all cropping rotations and tree densities (US\$14.17—US\$98.56 over 6 ha). Protecting isolated mature trees in farmland is vital given their disproportionate biodiversity value (Fischer *et al* 2010) and positive influence on forest-specialist bird species (Deikumah *et al* 2017). Introducing and extending fallow periods carried much greater OCs (US\$57.04—US\$264.88 over 6 ha) but provides important habitats for migratory bird species (Deikumah *et al* 2017). Encouraging the use of fallow periods and protecting farmland trees offers a win-win by protecting at-risk species and reducing carbon emissions associated with agricultural expansion and intensification.

Using carbon-based PES to protect trees in existing farmland carried low BEPs for all crop types and tree densities (US\$2.48—US\$6.45 t^{-1} CO_2). These BEPs are comparable to those for forest protection through agricultural intensification (Fisher *et al* 2011) and returning abandoned farmland to forest (Gilroy *et al* 2014). Extending two-year fallow to a three-year cycle carried low BEPs when combined with tree protection (US\$4.67—US\$10.24 t^{-1} CO_2). BEPs for converting continuous cultivation scenarios were much higher (US\$11.75—US\$39.88 t^{-1} CO_2) due to the greater area of cultivation foregone. Despite this, BEPs for the protection of 50 trees ha^{-1} in a three-year fallow cycle are competitive compared to the average 2019 EU Emissions Trading System (ETS) carbon market price (US\$28 t^{-1} CO_2). However, voluntary carbon market prices are often much lower (2019 average: US\$4.30), with only the protection of trees in existing two-year maize-fallow systems competitive.

Northern regions of Ghana had the lowest BEPs for both maize- and cassava-based scenarios. Profit efficiency of Northern maize farmers is the lowest in Ghana (Wongnaa *et al* 2019), hence the lower OCs of alternative management scenarios. However, interventions in Northern Ghana should be taken with care as these regions are expected to experience the worst of climate effects on crop yields (Nyuor *et al* 2016). Using payments to increase access to irrigation (Nyuor *et al* 2016) and encouraging farmers to grow more cassava may counteract this, since cassava can be grown in marginal soils under irregular rainfall patterns (Howeler 2017) and produces greater yields (figure S1). Maximizing investment to these areas is the most cost-effective use of scarce conservation resources. However, the reduced growth rate of trees in the drier North may increase the time and area needed to achieve the same carbon sequestration as the wetter South. Future research could expand on our regional analysis and carry out more explicit spatial optimization, including an assessment of the carbon sequestration abilities of

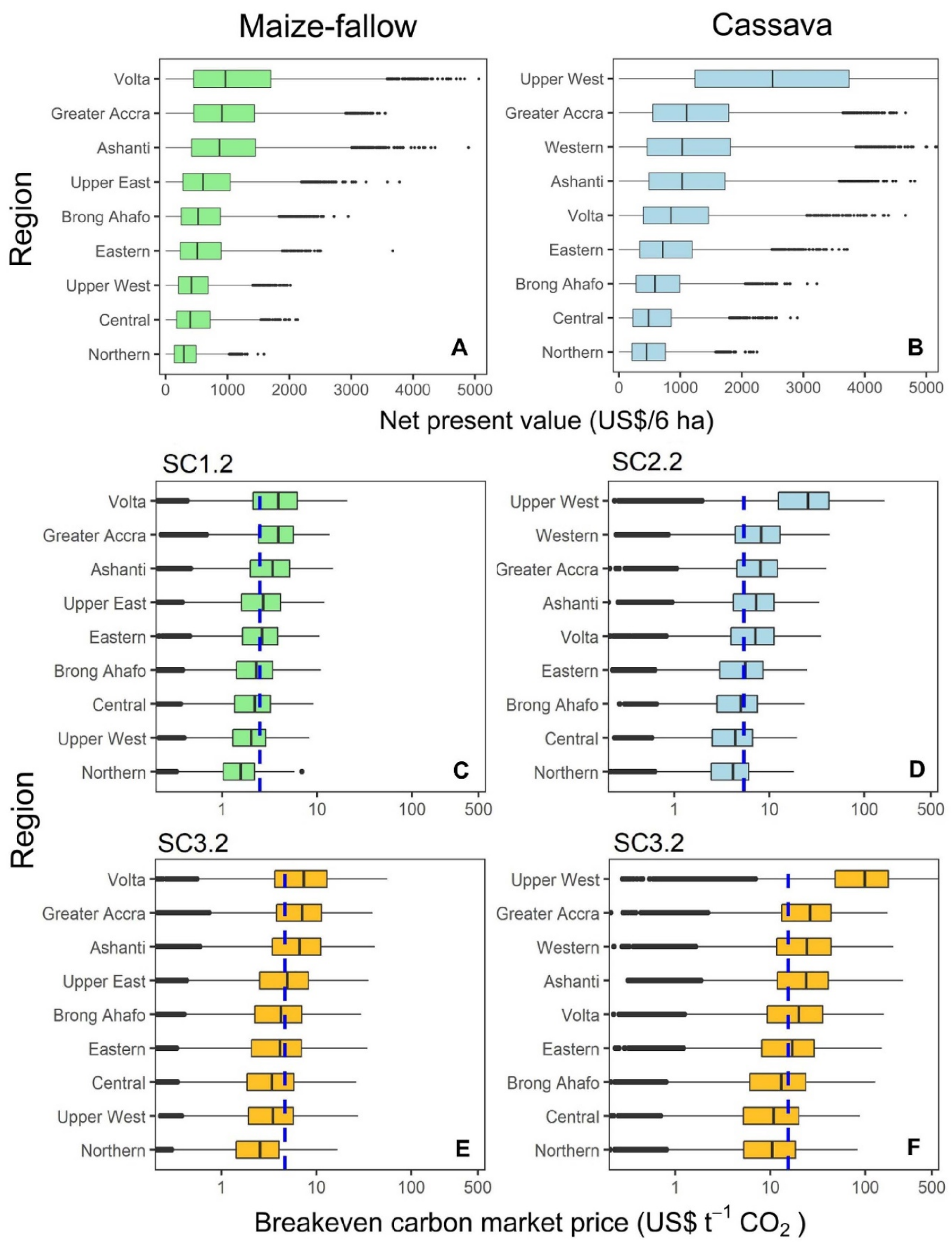

Figure 4. Regional net present value of existing (A) maize-fallow and (B) cassava farmland and carbon BEPs for alternative management scenarios for maize-fallow (C) SC1.2 and (E) SC3.2, and cassava (D) SC2.2 and (F) SC3.2. Box whisker plots show median, interquartile and 1.5 x interquartile ranges, and outliers. Plot colours indicate the agricultural system: two-year maize-fallow cycle (green), continuously cultivated (blue), and three-year fallow cycle (yellow). BEPs are fitted to a log scale to aid clarity. Vertical, dashed blue lines indicate median BEPs from the country-wide analysis: maize-fallow SC1.2 = US\$2.49 $t^{-1}CO_2$ and SC3.2 = US\$4.67 $t^{-1}CO_2$, cassava SC2.2 = US\$5.40 $t^{-1}CO_2$ and SC3.2 = US\$15.45 $t^{-1}CO_2$.

farmland over latitudinal and precipitation gradients and the implications of this for carbon-based PES.

Protecting 50 trees ha^{-1} carried lower BEPs than protecting 20 trees ha^{-1} due to the increased carbon protected (figure S4). Low BEPs for tree protection are likely driven by low OCs associated with maintaining trees in farmland, as the carbon protected in these landscapes is considerably lower than that accrued through forest succession (Morton et al 2020) and primary forest protection (Fisher et al 2011). However, our results further demonstrate the potential of African agroforestry systems to deliver cost-effective carbon sequestration (Takimoto et al 2008), whilst evidence from Mexican tropical dry forests suggests that short fallow cycles may enhance landscape-level carbon stocks (Salinas-Melgoza *et al* 2017). We focused solely on the aboveground carbon stored in farmland trees, neglecting high soil organic carbon stored in even the most intensively managed shifting cultivation farmland (Bruun *et al* 2020). Accounting for the additional carbon stored in soils with the introduction of a three-year fallow cycle would reduce BEPs. Whilst we did not consider carbon enhancements under REDD+, there is potential to increase the rates of tree recovery, growth, and carbon sequestration in shifting cultivation landscapes by optimizing fallow cycle lengths (Salinas-Melgoza *et al* 2017) and restricting livestock browsing to certain areas of these landscapes (Morales-Barquero *et al* 2015).

Combining the protection of low-intensity farmland habitats and the introduction of fallows with increased yields is necessary to ensure that lost production is not displaced to regions with lesser restrictions (i.e. leakage; Latawiec *et al* 2015). Incorporating leakage and economic uncertainty into analyses increased BEPs considerably, but prices for protecting trees within existing farmland and in three-year fallow systems remained competitive compared to EU ETS prices (figure S5). The sensitivity analysis to account for farmers preferentially maintaining very low tree density on their land (10 trees ha^{-1}), making fewer trees eligible for protection under a PES scheme, had a similar effect on BEP as the leakage analysis (figure S6).

Ghanaian maize yields are far below the global average (Wongnaa *et al* 2019), whilst fertilizer use in sub-Saharan Africa is amongst the lowest globally (Callo-Concha *et al* 2012). Government targets for increasing fertilizer use have been consistently missed (currently 35.75 kg ha^{-1} compared with the Abuja Declaration on Fertilizer for an African Green Revolution which set 50 kg ha^{-1} as the primary target (NEPAD 2011, MOFA 2012)), with potential for fertilizers to increase yields of maize and cassava (MacCarthy *et al* 2018, Adiele *et al* 2020). Interventions to reduce leakage would be best focused on increasing fertilizer use (Ragasa and Chapoto 2017), introducing high-yielding varieties of crops (Walker and Alwang 2015), and promoting mechanization (Diao *et al* 2014). Policies that tie the provision of yield increases to the continued protection of farmland habitats as yield potential increases (Phalan *et al* 2018) is important to safeguard vulnerable farmland bird populations. Additionally, with more people experiencing malnutrition in sub-Saharan Africa (Oecd 2018), relative to other regions, and with climate change expected to exacerbate food supply issues (Wheeler and Von Braun 2013) and socio-economic challenges such as educational attendance (Agamile and Lawson 2021), improving food security for local people is paramount to long-term project success.

Land-sparing overwhelmingly remains the most effective method to protect global biodiversity (Luskin *et al* 2018), however, the need to support species reliant on low-yielding farmland points towards a hybrid 'three-compartment' approach, combining high-intensity farmland with low-intensity (conservation) farmland and spared natural habitat blocks (Feniuk *et al* 2019). The effectiveness of sparing is determined by its ability to minimize the externalities associated with intensification and to free land for nature (Balmford *et al* 2018). For example, over-reliance on external inputs (agrochemicals) incurs large carbon emissions—although their widespread use is a long way off in sub-Saharan Africa (Vitousek *et al* 2009). Maintaining trees in farmland provides several ecosystem services, including water regulation, nutrient cycling, and reduced soil erosion (Bayala *et al* 2014), as well as benefits for open-country species (Douglas *et al* 2014). However, trees may compete with crops for resources or provide refuge for pests, with the effect of trees on crop yields in the region remaining unresolved (Bayala *et al* 2012).

Our study points to the potential for carbon funding to support the retention of low-intensity farmland. Furthermore, such actions would intersect with Forest and Landscape Restoration (FLR) projects aiming to protect and enhance carbon stocks within farmland (Sabogal *et al* 2015), whilst reversing landscape degradation that impacts food security.

4.2. Study caveats

Firstly, we used uniform growth rates for all trees, regardless of age and species, due to limited species-specific tree growth data from the region. Tree growth and carbon sequestration is likely to be non-linear and species-specific (Stephenson *et al* 2014). Instead, we applied a uniform DBH growth rate of 0.55 cm yr^{-1}, an average for West African savanna tree growth (Mbow *et al* 2013), recalculating tree carbon annually using the allometric equations of Chave *et al* (2014). This likely generates conservative estimates of carbon accrual since large, old trees fix large amounts of carbon annually (Stephenson *et al* 2014) and DBH growth rates for middle-aged and mature trees is likely greater than 0.55 cm yr^{-1} (Groenendijk *et al* 2017).

Secondly, fallowed land and mature trees could provide alternative income to farmers. Forest and non-forest environmental products can provide up to 38% (Appiah *et al* 2009) and 13%–23% (Pouliot *et al* 2012) of household income, respectively. Incorporating this alternative income source into our OC models could drive BEPs down further, while adding extra security to farmer's livelihoods (Weston *et al* 2015).

Thirdly, data errors or high variance in market prices (table S2) and discount rates could influence our BEP, therefore a sensitivity analysis was undertaken (figures S6–S13) to test for potential effects on our BEP. Additionally, in excluding NPV below US$0 (33% of cases), our BEP is only applicable to profit-making farmers. The large number of loss-making and subsistence farmers in our data is reflective of agriculture in sub-Saharan Africa (AGRA 2017), where a high proportion of farmers are not involved in formal markets. Likewise, unreliable rainfall, extreme climatic events, and invasive species decimate crop yields, incurring heavy losses to farmers (Pratt *et al* 2017) and accentuating negative socio-economic impacts (Agamile and Lawson 2021). As a result, many farmers may be reliant on off-farm activities (Pouliot *et al* 2012) and non-timber forest products to supplement their incomes (Appiah *et al* 2009). Loss-making farmers are usually more engaged in informal markets—trading food for education, transport, etc—making it difficult to quantify economic yields from their land and give accurate OC and BEP. In these instances, increasing access to education and other vital goods and services may be a more appropriate method of compensation for farmers.

Land tenure systems in Ghana are mostly customary and extremely diverse (Lambrecht and Asare 2016), with land rights granted by village chiefs (Chapoto *et al* 2013). Carbon rights in Ghana have yet to be defined, with community-based resource management areas designated as the preferred method of PES implementation (Asare and Kwayke 2013). Hence, project implementation may be reliant upon the support of village leaders and the wider community as opposed to just that of individual farmers, compounding the need for wide stakeholder involvement in project development. Finally, whilst we lack local-level data on farmer's management of farmland trees, we simulate multiple cropping scenarios with two different farmland tree densities using globally accepted secondary data. This forms the basis for further investigation in the region, which may consider the rationale and trends behind farmer's attitudes to farmland trees.

5. Conclusions

Previous analyses of the viability of carbon-based PES schemes have largely focused on returning tropical farmland to forest or protecting remaining forests. Whilst these measures conserve forest biodiversity, they do not protect rare taxa within low-intensity farmland, including many migratory bird species. We demonstrate that use of carbon-based PES to protect farmland habitats offers a cost-effective method of conserving such species. Combining the re-introduction of fallow periods with the protection of farmland trees offers competitive BEPs, comparable to those associated with forest protection and regeneration. Measures taken to protect farmland habitats, however, must be integrated with actions to boost yields, preventing leakage and providing increased food security for local people.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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