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RESEARCH ARTICLE

Assessing trade-off risk between crop production and vertebrate biodiversity in three African countries

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Abstract

1. Governments worldwide are committed to eliminating hunger and conserving biodiversity, reflected in United Nations Sustainable Development Goals 2 (Zero Hunger) and 15 (Life on Land). Expanding agricultural lands to meet growing food demands often threatens biodiversity, creating potential trade-offs between these objectives. To understand the potential trade-off risks, we need to determine the extent to which croplands are located in areas that are also species-rich and which crops pose the greatest biodiversity risk.
2. We identify areas where there is a trade-off risk between vertebrate biodiversity and crop production important for food and livelihoods across Ethiopia, Ghana, and Zambia. We evaluate trade-off risk via three metrics: (i) the footprint, mapping the overlap between crop production and ecological priority areas; (ii) two measures of trade-off risk based on the number of species potentially impacted: one measuring average local species richness affected per unit area used to grow a crop or crop group—domestic or traded (trade-off risk intensity), and a second measuring this average local species richness impacted but summed across the total area used to grow the crop/crop group (trade-off risk potential); and (iii) the hotspots where crops are grown in regions especially rich in vertebrates.
3. Trade-off risk varies more among crop types and regions, and relatively little, on average, between crops grown for international trade versus crops grown

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primarily for domestic consumption. The crops with the greatest total risk potential are wheat in Ethiopia, cocoa in Ghana, and maize in Zambia. In all three countries, coffee poses the greatest trade-off risk intensity to threatened species and bananas exceed the expected trade-off risk intensity.

4. Trade-off risks are context-dependent and optimal management will therefore be both country- and crop-specific. As there is not just one crop posing a consistently high risk of trade-off for biodiversity, and many crops contribute to human diets and livelihoods, identifying areas with high trade-off risks is important for prioritising future research, including fieldwork, which could then identify farming practices that have the lowest impact on biodiversity. Importing nations will need to share the responsibility for mitigating biodiversity costs of their agricultural imports.

KEYWORDS

Africa, agriculture, biodiversity, food security, land-use change, sustainable development goals, trade-offs

1 | INTRODUCTION

Trade-offs between UN Sustainable Development Goals 2 ('zero hunger') and 15 ('life on land') are intensifying as global populations and affluence grow, increasing the demand for agricultural land (Kehoe et al., 2017; Magrach & Sanz, 2020; Phalan et al., 2013; Williams et al., 2020; Zabel et al., 2019). In agricultural systems, biodiversity supports ecosystem processes that underpin agricultural productivity (e.g., pest control, pollination, and soil fertility) but can also be a source of conflict when, for example, wildlife encroaches on farmland, causing damage to crops (e.g., see Yang et al. (2020)). Goals focusing on sustainable food, economies, and conservation often appear to be in direct conflict (Hanspach et al., 2017), with agricultural activity a leading global driver of biodiversity loss, for instance (IPBES, 2019; Jaureguiberry et al., 2022; Maxwell et al., 2016; United Nations General Assembly, 2015).

Potential trade-offs are especially acute in sub-Saharan Africa, where a drive for self-sufficiency in key crops, coupled with rapid population growth and export-driven agriculture, is putting additional pressure on land use (FAO WFP and IFAD, 2012, Conceição et al., 2016, Van Ittersum et al., 2016, Hall et al., 2017, Williams et al., 2020). Agricultural expansion is further accelerated by declining soil fertility, drought and other climate change impacts, policies and incentives, income, and land tenure (Jellason et al., 2021). Yet, the extent to which these dynamics interact with biodiversity conservation efforts remains underexplored, especially in the context of specific crop types and land-use strategies.

Identifying areas where croplands spatially overlap with species-rich areas is a crucial step in managing potential trade-offs between food and livelihood security and biodiversity conservation (Mehrabi et al., 2018; Molotoks et al., 2017; Molotoks et al., 2023). Previous studies, including those analysing the feasibility of the idea of setting aside of half of the Earth's land for conservation (Ellis & Mehrabi, 2019; Mehrabi et al., 2018), have provided important insights into such trade-offs, but they often combine different crops into a single 'cropland' land-use category or focus on a handful of well-studied traded crops (e.g., cocoa, coffee, and oil palm (Asase et al., 2010, Fitzherbert et al., 2008, Koh & Wilcove, 2008, Phalan et al., 2013, Teuscher et al., 2015)), limiting understanding of how different crops relate to biodiversity outcomes. This is problematic because there are different drivers of land-use change associated with different crops, particularly internationally traded commodity crops versus locally consumed food crops. The former might be more influenced by international commodity prices, but the latter more directly by domestic policies, growing costs, and consumer preferences. We need to understand the risks associated with different crop groups for policy and management decisions. For instance, we know which policy levers are available for traded crops (e.g., certification schemes), but if impacts on biodiversity are greater for crops consumed domestically, the mechanisms for managing such trade-offs are less straightforward (e.g., asking for: dietary change to increase the number of people fed per unit area of cropland (Cassidy et al., 2013), conservation areas, or changes to agricultural practices (Tilman & Williams, 2020) which might not be practical in lower income countries at present). Gaps also remain in our understanding of how potential trade-offs vary by crop type, particularly in regions like sub-Saharan Africa, where small-scale farming dominates, but detailed spatial data are scarce.

Mapping specific crops at high spatial resolution in Africa, and in many places globally, remains challenging. This is in part caused by difficulties in interpreting and classifying satellite imagery when farm sizes are small, and when farming methods include intercropping, crop rotation, mixed crops, or agroforestry, which often resemble natural forest cover (See et al., 2015, Bégué et al., 2018, Dang et al., 2019). These limitations hinder our ability to assess the risk of trade-offs between agriculture and biodiversity accurately. Nonetheless, global-scale maps using modelled and survey data of cropland, alongside expert estimates of the distributions of species, provide a foundation for developing indicators of trade-off risk, such as those we define in Figure 1, which can guide more targeted research at local levels. We know where there are historically suitable areas for vertebrate species from range maps. If these are in crop production areas, we know that this biodiversity is likely at risk (Chaudhary & Kastner, 2016; Delzeit et al., 2017; Kehoe et al., 2017; Phalan et al., 2011). We can also hypothesise that crop type causes different biodiversity impacts because

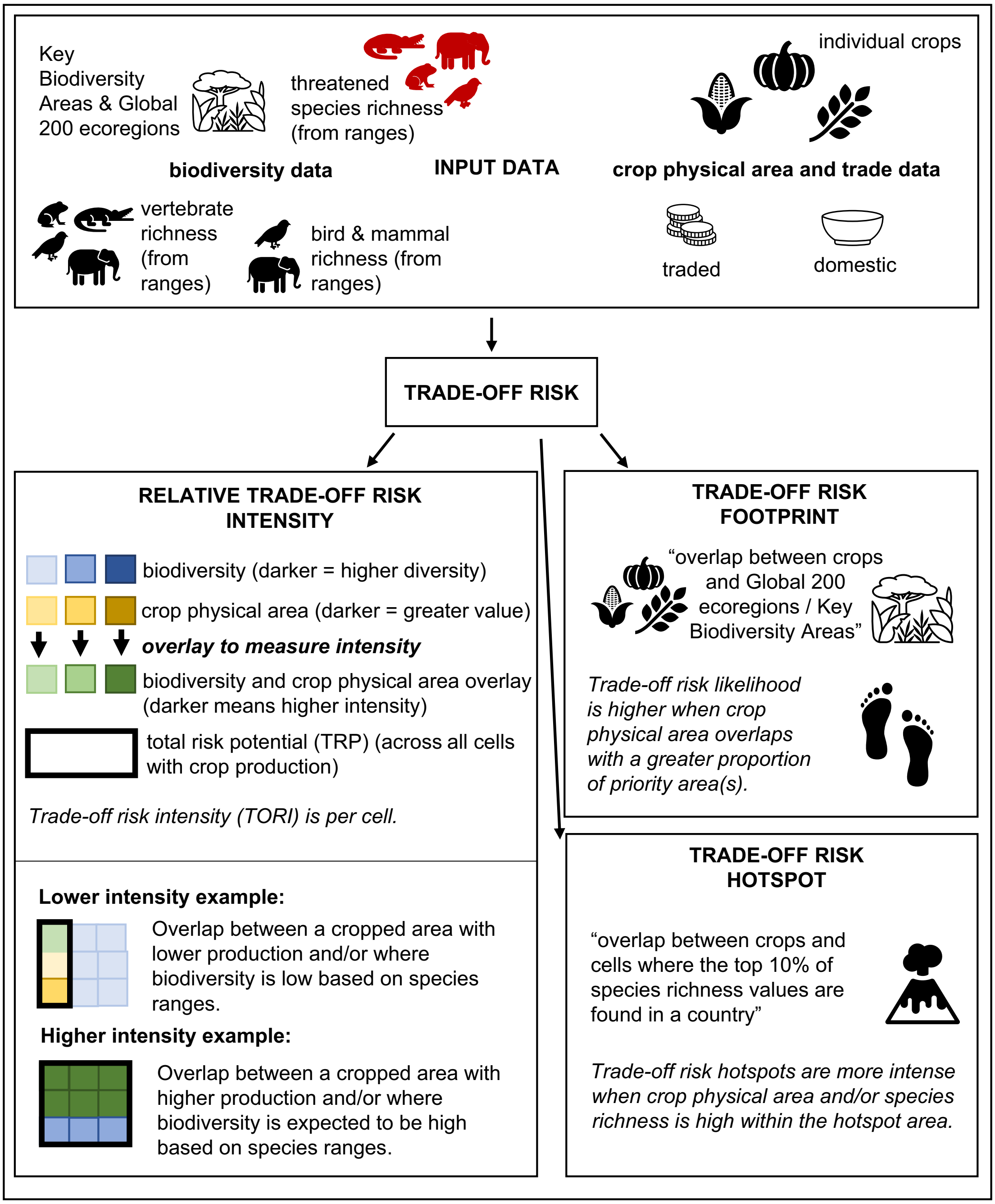


FIGURE 1 Diagram summarising the main differences between trade-off risk footprint, trade-off risk intensity, and trade-off risk hotspot. These measures offer complementary perspectives on the potential trade-off risks posed by a given crop or crop group (domestic vs. traded). Footprints assess the overlap between cropland and biodiversity priority areas (in our case key biodiversity areas, or KBAs, and Global 200 ecoregions). Trade-off risk intensity represents the overlap between cropland and the most naturally species-rich areas per unit area, whereby high crop production and/or high biodiversity in a cell could result in a higher intensity. This is measured per cell where a given crop/crop group is grown as 'trade-off risk intensity' (TORI), or across all cells where the crop/crop group is grown as 'total risk potential' (TRP). We also produce 'hotspot' maps, which delineate the crop physical areas overlapping with the 10% most biodiverse areas within each country. We use the term 'intensity' here and throughout this work to identify crop physical areas with particularly high trade-off risks, rather than intensity of agricultural land use and associated inputs.

growing requirements (e.g., climate, terrain, water availability, etc.), and thus the spatial distribution where they are grown, vary among crops. Much previous research could not consider this because it generally treated all crops together as 'cropland' (though see Chapman et al. (2025), for an analysis focusing on biodiversity pressures of fruits and vegetables). However, datasets now available enable us to map the location of specific crops, to consider the role that the location of different crops plays in influencing risks to vertebrate species.

In this study, we aim to: (i) develop new measures of the potential trade-off risk between crop production and vertebrate biodiversity that can be used to compare across different crops and countries; (ii) quantify the relative trade-off risks posed by different crops produced in three African countries with contrasting environmental, ecological and social contexts, but similar small-scale farming, rapid recent agricultural development, and policies for self-sufficiency (Ethiopia, Ghana, and Zambia; Figure S1.1); and (iii) investigate whether trade-off risk differs between crops which are largely domestically consumed and those which are internationally traded.

2 | MATERIALS AND METHODS

Our research did not involve human participants and uses publicly available data so ethical approval was not required.

2.1 | Defining relative trade-off risk

Our work aimed to highlight the areas (grid cells) where trade-off risk is greatest. First, however, we needed to define trade-off risk (Figure 1) and the components for which risk of trade-off was being measured (crop production and biodiversity).

We classified crops into 'crop groups' according to their role as predominantly 'domestic' or 'traded'. We defined 'domestic' crops as those primarily grown for consumption in the country in which they are grown. Domestic crops can be consumed at home or sold locally, and so differ from 'subsistence crops', which are used exclusively by the grower and their family members. We defined 'traded' crops as those sold in relatively large quantities internationally (sometimes termed 'export crops'), rather than being grown for the most part to be consumed domestically. We avoid the term 'cash crops' (used widely by ecologists) because, in social and economic fields of study, 'cash crops' are simply crops which are sold. Specifically, we classified domestic crops as ones for which >90% of total production by weight remains in country, and traded crops as ones for which more than 10% of total production by weight is exported ('traded') (see 2.2.3). To measure biodiversity, we considered only taxonomic diversity (rather than, for example, functional, phylogenetic, or genetic diversity) based on known species ranges. We included amphibians, birds, mammals, and reptiles, as these are the taxonomic groups for which species distribution estimates are most consistently available for our focal countries. We also used different metrics of taxonomic diversity (threatened species and birds and mammals) as described in 2.2.4.

Next, we defined measures of relative 'trade-off risk' (Figure 1). In a classic trade-off, one desirable outcome is reduced when another, different desirable outcome is increased (Oxford English Dictionary, 2023). A trade-off between objectives can occur at any scale. In this study, we focus on trade-off risk specifically (White et al., 2025) as there are not yet suitable data for our focal countries for quantifying trade-off impact, although it is known that this can vary according to agricultural management practices, inputs, and field sizes, among other factors. Overlap between the physical area of a crop and an area rich in biodiversity does not guarantee a negative impact on biodiversity but does highlight areas where a trade-off is more likely. Previous studies have shown that cropland areas tend to have lower species richness than natural habitats (Fan et al., 2024; Jung et al., 2017; Newbold et al., 2015; Norris et al., 2010; Phillips et al., 2017). Versions of our trade-off risk measures, described below, have also been used in work assessing trade-off risk for biodiversity (Chapman et al., 2025; Molotoks et al., 2023).

We measure the likelihood of a trade-off using the 'footprint' (Figure 1). The likelihood of trade-off increases with the proportion of a crop or crop group's physical area which overlaps with an area of high biodiversity. The 'footprint' measures this overlap, representing the spatial extent over which a trade-off risk may occur (Figure 1). A bigger footprint suggests a greater likelihood of trade-off between biodiversity and a crop.

We measure the relative intensity of trade-off risk as the average risk to biodiversity per unit area used to grow a given crop/crop group (Figure 1) and term this metric 'trade-off risk intensity'. For trade-off risk intensity (TORI), a crop or crop group with a risk greater than that of another crop or crop group poses a greater risk to biodiversity on average across the area it is grown. It can also be presented relative to the median expected TORI for the country (as in Figure 2) so that values greater than one highlight crops or crop groups which pose a greater risk of trade-off than we might expect, and crops or crop groups with values below one pose a lower risk of trade-off than expected, based on the median crop area among all crops in a country and median species richness for that whole country. We also measure the 'total risk potential' as the total number of species which could be locally impacted, summed across the entire area (all grid cells) over which a crop or crop group is grown.

Finally, we identify 'hotspots' of trade-off risk to complement our metrics of footprint, trade-off risk, and total risk potential (TRP). 'Hotspots' tend to map areas with overlapping services (Lin et al., 2018; Schroter & Remme, 2016). We define a hotspot as an area where a crop or crop group's physical area overlaps spatially with particularly high species richness (specifically, cells with the highest 10% of species richness in the country; Schroter & Remme, 2016, Lin et al., 2018). Within this hotspot, the intensity of overlap varies according to the physical area of crops being grown within it and/or the number of species found within it (with more of either, or both, creating a 'hotter' hotspot, with a more intense trade-off risk in an already high-risk area).

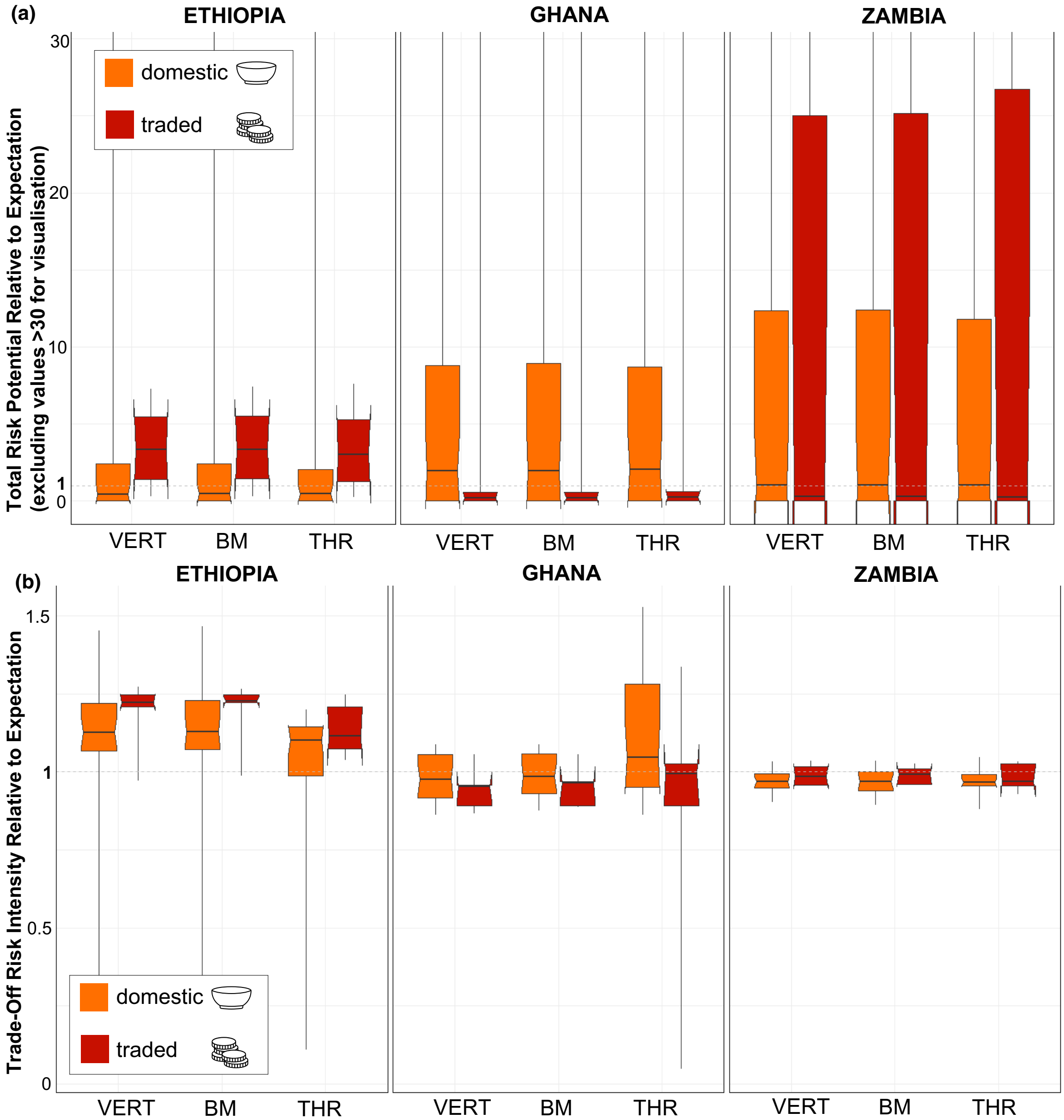


FIGURE 2 Total risk potential (TRP) (a) and trade-off risk intensity (TORI) (b) associated with domestic and traded crops in Ethiopia, Ghana, and Zambia, relative to the expectation if a crop with median area across all crops in a country were grown in areas of typical species richness for that country (highlighted with a dashed grey line, at (1)). Values above 1 suggest that the risks are above the expectation for the country and values below 1 show risks are below the expectation for the country. The total risk potential (a) measures the product of the total cropped area (in hectares) and the average local vertebrate species richness in these areas for each crop in each country. Trade-off risk intensity (b) represents the average local richness of vertebrate species, per unit area, across areas in which each crop (or crop group) is grown. The values are summarised for domestic (orange) and traded (red) crop groupings, with the boxplots representing the range of values for individual crops. Each set of boxplots is presented for different subsets of species: 'VERT'—all vertebrate species, 'BM'—just bird and mammal species, and 'THR'—threatened vertebrate species. The median across all individual crops is shown by the horizontal lines within each box, with confidence captured by notches. The whiskers show the minimum and maximum values (cropped in panel a to a maximum value of 30). Median values for trade-off risk intensity and total risk potential are presented in Table 1. Welch's two-sample *t*-tests are reported in Table S8.1 and further summary statistics are available in Table S8.2.

2.2 | Data processing

2.2.1 | Study area

We focus this study on three contrasting countries spanning different ecoregions of Africa and representing three of the main regions of sub-Saharan Africa: Ethiopia (East Africa, with ecoregions including highlands, flooded grasslands, and savannas), Ghana (West Africa, with forests and mangroves in addition to savannas), and Zambia (Southern Africa, with miombo woodlands, montane woodlands, and flooded savannas, for example) (Olson & Dinerstein, 2002). These were the focal countries for the 'Sentinel' project, which sought

TABLE 1 Median total risk potential and trade-off risk intensity per crop group, species group, and country.

	Total risk potential (TRP)			Trade-off risk intensity (TORI)		
	VERT	BM	THR	VERT	BM	THR
Ethiopia						
Median, all crops	70,399	61,101	3052	3.66	3.19	0.16
Median, domestic	56,669	49,973	2600	3.60	3.15	0.16
Median, traded	**424,703**	**372,191**	**17,126**	**3.91**	**3.42**	0.16
Ghana						
Median, all crops	63,544	49,351	1918	4.91	3.83	0.15
Median, domestic	**200,625**	**155,681**	**5916**	**4.94**	**3.83**	**0.15**
Median, traded	20,104	15,469	717	4.82	3.77	0.14
Zambia						
Median, all crops	12,878	10,661	285	5.79	4.77	0.13
Median, domestic	**13,414**	**11,056**	**296**	5.75	4.72	0.13
Median, traded	3795	3032	68	**5.85**	**4.83**	0.13

Note: The greater of the median values, comparing domestic crops with traded crops for each country and species group, is shown in bold text. These medians were calculated using raw estimates for total risk potential and trade-off risk intensity, rather than values relative to median expectations (e.g., as shown in Figure 2). As with other figures, domestic crops are represented with a bowl icon and traded crops with an icon depicting a stack of coins.

to address the trade-offs between feeding populations, reducing inequalities, and conserving ecosystems in sub-Saharan Africa (Sentinel, 2021) (Figure S1.1 and Figures S1.5–S1.7). All three countries have a growing population, although Ethiopia's is substantially larger than that of Ghana, which in turn is larger than Zambia. Ethiopia also has the highest gross domestic product and percentage share of the gross domestic product in agriculture, and Zambia the smallest (The African Development Bank, 2024). These countries have different agricultural norms and development pathways, with Zambia having the smallest share of its total land area dedicated to agriculture in 2022 (~32%, compared with ~34% in Ethiopia and ~55% in Ghana (The African Development Bank, 2024)). All three countries have national policies oriented towards food self-sufficiency for food security and are also agricultural exporters. These countries therefore enable us to assess the trade-off risks associated with domestic and traded crop groups in different regions of Africa and with distinct environmental and ecological conditions.

2.2.2 | Country-level crop maps

We extracted country-level data from the freely available 'MapSPAM' (Spatial Production Allocation Model (International Food Policy Research Institute, 2024, You, Wood-Sichra, et al., 2014)) database, which contains maps of the physical growing area for 46 crops (including groups of crops, such as 'vegetables' and 'citrus') in 2020 (International Food Policy Research Institute, 2024), the most recent year for which crop-specific data are available for the three focal countries. MapSPAM combines geospatial data on crop production statistics (43.5% of coverage of SPAM crops sourced from crop production statistics for sub-Saharan Africa, similar to Europe (You, Wood-Sichra, et al., 2014)), classified satellite land-cover imagery, crop-specific suitability information (e.g., irrigation, climate, landscape, and soil), population density, cropping intensity, and prices, to feed into an optimisation model using area and production constraints to allocate crops into individual pixels (International Food Policy Research Institute, 2024; Koo et al., 2016; You, Wood, et al., 2014; You, Wood-Sichra, et al., 2014). These data estimate crop distributions at a 10 × 10 km grid cell resolution but rely to some extent on national level statistics (Koo et al., 2016). Data in MapSPAM for Ethiopia, Ghana, and Zambia include subnational level data (75–95% at subnational level 1, such as state-level, for Ghana, Zambia, and most of Ethiopia and 25–50%, 50–95%, and 50–75% respectively at subnational level 2, such as county/district level (You, Wood-Sichra, et al., 2014)). The data in MapSPAM have been validated by local experts via the Consultative Group for International Agricultural Research Centers (You, Wood, et al., 2014). We used physical area data to capture the actual area where a crop is grown, rather than including multiple harvests per hectare, as captured in harvested area data. We also do not measure yield. Our metrics are more relevant for understanding the potential impacts of agricultural expansion—a dominant agricultural development mode in many African countries. Whilst most crops analysed are foods, we also capture some non-food crops (i.e., cotton and tobacco) and some that are ingredients used in foods (e.g., cocoa, palm oil, rapeseed, etc.), which we keep in our analysis as they contribute to livelihoods.

We resampled the MapSPAM crop maps to the same c.10 × 10 km resolution as the species-richness maps (see 2.2.4), using bilinear interpolation, appropriate for our continuous data, which estimates values using the weighted average of the four nearest cells to the new cell, implemented in the raster package (version 3.6–23) in R (Hijmans, 2023; R Core Team, 2023). These data are the most suitable for our study aims, enabling us to map the broad distributions of individual crops.

2.2.3 | Crop classification

To classify crops according to their use as predominantly 'domestic' or 'traded' (Table S2.1), we used data produced using the method described in (Dalin et al., 2017; Kastner et al., 2011), averaged for the years 2015–2017 to best align with the 2020 MapSPAM data. We did not use more recent data as there were reporting delays in more recent years and 2020 was affected by global trade changes because of the COVID-19 pandemic. The international food trade volumes are estimated using FAOSTAT detailed bilateral trade matrices and corrected to identify the first exporter, which is important to ensure that the possible environmental impacts are correctly associated with the origin of food production. For example, the correction enables the association of sugar produced in Ghana and transiting through the Netherlands before reaching its destination with the impacts of Ghanaian sugar production, and not with the impacts of Netherlands sugar production. The correction follows the trade correction methods from Kastner et al. (2011) and conversion of processed commodities into primary crop equivalents based on FAO categorisations as done by Dalin et al. (2017). First, we compiled the trade data on production and export for Ethiopia, Ghana, and Zambia, and all trade partners. Next, we classified the MapSPAM crops according to whether they predominantly (>90% of total production by weight) remain in country ('domestic'), or if more than 10% of total production by weight is exported ('traded'), as the same crop can have a portion of its production used domestically and a proportion of its total production traded. We used the 10% threshold to define traded crops owing to the overall low level of exports from the focal countries and tested the sensitivity of our results to this choice of threshold (see Results).

2.2.4 | Mapping biodiversity: Species-richness estimates

We used global estimates of vertebrate species richness at approximately 10-km spatial resolution from Etard et al. (2020), which were based on comprehensive estimates of the extent of occurrence of all terrestrial vertebrate species (reptiles, amphibians, birds, and mammals) (Birdlife International & Natureserve, 2012; IUCN, 2013), adjusted to remove areas beyond species known elevational limits. We clipped these data to each of the three focal countries and reprojected from cylindrical equal-area projection to WGS84 (Figures S3.1–S3.3). There are known limitations to using range maps to estimate biodiversity (Herkt et al., 2017). For instance, we are not able to include all areas where a species has been historically present but had become extinct before the species extent of occurrence was mapped. We must also assume that a species is present across the whole area within its estimated extent of occurrence, which may not be the case for many species because of limiting factors such as lack of suitable habitat or interactions with other species. Nevertheless, these data are suitable for representing the broad distribution of vertebrate species richness across each of our focal countries, enabling us to compare the relative trade-offs associated with different regions and crops for the first time.

Birds and mammals often have better characterised range maps than amphibians and reptiles, which depend on different habitats to birds and mammals (e.g., agricultural and forested land) and tend to be under-represented in conservation prioritisation (Tyrrell et al., 2020). Across vertebrates, threatened species are more likely to experience losses due to pressures like crop production and associated habitat loss (Maxwell et al., 2016). We therefore assessed biodiversity in three ways: first, including mammals, birds, amphibians, and reptiles (referred to as 'vertebrates'); second, considering only mammals and birds; and third, for threatened species (classified as Vulnerable, Endangered or Critically Endangered in the IUCN Red List (IUCN, 2013)).

2.2.5 | Mapping biodiversity: Global 200 ecoregions and key biodiversity areas (KBAs)

To complement the species-richness data, we further focused on two sets of areas considered to be priorities for biodiversity conservation: first, the 'Global 200' ecoregions, which are a subset of the ecoregions of the world, selected for their irreplaceability or the distinctiveness of the species and/or habitats they contain (Olson & Dinerstein, 2002); and second, key biodiversity areas (KBAs), which have been identified as sites necessary for global species persistence according to at least one of 11 criteria, under five higher level categories capturing species' threat, species' geographic restrictedness, ecological integrity, biological processes, and irreplaceability (IUCN, 2016). We selected these types of priority areas because they indicate where conservation should be a priority but are not necessarily always managed as protected areas, which can vary in management and protection.

2.3 | Comparing individual crops and crop groups (domestic and traded)

To compare the spatial extents and distributions of domestic and traded crops, we summed estimates of the physical area of each crop within these groups, using the R raster package (version 3.6–23) (Hijmans, 2023; R Core Team, 2023) (Figure S4.1). The spatial distribution of individual crops can be mapped as shown in the code linked in the caption of Supporting Information Figure S6.1.

To compute footprints, for each country we computed the physical area of a given crop that overlapped with: (i) Global 200 ecoregions, and (ii) Key Biodiversity Areas (KBAs). We compared the areas inside these different conservation priority areas for: (i) domestic and traded crop groups, and (ii) specific crops, using the 'raster' (version 3.6–23), 'dplyr' (version 1.1.4) and 'ggplot2' R packages (Hijmans, 2023; R Core Team, 2023; Wickham, 2016; Wickham et al., 2023).

We measured the relative TORI by calculating the expected average number of local species impacted per unit of physical area of a given crop, or crop group, which we term 'trade-off risk intensity' (TORI):

$$\text{TORI} = \frac{\sum \left(\text{species richness} \times \frac{\text{crop physical area}}{\text{cell area}} \right)}{\sum (\text{crop physical area})}$$

We also computed a measure of 'total risk potential' (TRP), using the numerator of TORI only—that is, the total number of species locally impacted, summed across the entire area over which the crop is grown (all grid cells). We compared the TORI and TRP of domestic versus traded crops using Welch's two-sample *t*-tests in R (R Core Team, 2023).

To aid interpretation of the TRP and TORI, we present all results relative to what would be expected if a crop with median growing area, among all crops grown in a country, overlapped with areas of typical (median) species richness across the whole country. To do this, we first calculated this expectation as follows:

$$\text{Expectation} = \frac{\text{median species richness} \times \frac{\text{median crop physical area}}{\text{median cell area}}}{\text{median crop physical area}}$$

Median species richness is the median species richness across the whole country. Median crop physical area is the median across all crops grown in the country. Median cell area is the median area of grid cells across the country.

Next, we divided each of the TORI and TRP values, respectively, by this median expectation. This means that values above 1 highlight crops which have an above-expected trade-off risk and values below 1 have a below-expected trade-off risk. We present these relative values in Figure 2 and provide them for individual crops in Table S9.1.

To complement our measures of trade-off risk footprint and intensity, we also identified trade-off risk 'hotspots' (Schroter & Remme, 2016). For instance, we identified hotspots as those areas where crops are physically grown coincident with the 10% most species-rich area of each country. We also identified these hotspots based on the richness of (i) just birds and mammals (Figure S5.1) and (ii) only threatened species (Figure S7.1), as well as all crops in each country (Supporting Information S6).

3 | RESULTS

3.1 | Total risk potential and trade-off risk intensity

There is no significant difference between the TRP or trade-off risk intensities of domestic and traded crops in any of the three focal countries (Figure 2; Table S8.1). This is also the case in sensitivity tests, where 5% and 15% thresholds were used to classify domestic and traded crops (Tables S2.2–S2.3). The per-unit area risk (TORI) is above the expectation for both domestic and traded crops in Ethiopia, while this is only the case for traded crops according to TRP (Figure 2). It is only for the TRP and per-unit area measure of TORI for threatened species in Ghana that we see domestic crops exceeding the expectation for the country (Figure 2). The outcome varies by metric for Zambia, with domestic crops closer to the expectation for the country, on average, and traded crops below the expectation for TRP, but both traded and domestic crops being below Zambia's expectation in terms of per-unit area TORI (Figure 2; Table 1). Domestic and traded crops had the same relationship with the expectation when 5% and 15% thresholds were used to classify the crop groups as a sensitivity test (Figures S2.1–S2.2). The individual crops with the highest associated risks are from both domestic and traded crop groups across all three countries (e.g., variability in Figure 2; Table 2). For instance, the highest TRP crops are: wheat (domestic, Ethiopia), cocoa (traded, Ghana), and maize (traded, Zambia) and the greatest trade-off risk intensities are associated with: yams (domestic, Ethiopia), coconuts (domestic, Ethiopia), coffee (traded, Ethiopia, Ghana, and domestic, Zambia), plantain (domestic, Ghana), and tea (traded, Zambia) (Table 2). Across all measures and species groups, there is more variability in the relative risk among individual crops of interest than between domestic and traded crops or species subsets.

Whilst TRP is consistent across species subsets, individual crop trade-off risk intensities vary further when measured for just bird and mammal species and for threatened species. For example, Ethiopia-grown coconuts and yams, Ghana-grown plantain and coffee, and Zambia-grown tea and coffee have the highest associated trade-off risk intensities when all vertebrates and just mammals and birds are considered (Table 2). The risks posed to threatened species differ when measured using TORI as a metric, where the greatest risks are associated with coffee grown in all three countries (Table 2). Bananas are the only crop for which the expectation of TORI is exceeded for all three countries (Table S9.1). The expected TRP is exceeded by beans, groundnuts, maize, sorghum, soybeans, and sweet potatoes in all three countries (Table S9.1).

3.2 | Total risk potential versus trade-off risk intensity per unit area

When we look at trade-off risk per unit area of land used (trade-off risk intensity in Table 2), some crops, like yam, plantain, tea, and coffee, show different results compared with their total overall risk across the area used to grow them (total risk potential in Table 2). When we measure the trade-off risk potential, crops with the largest physical area on which they are grown (Table S9.1) unsurprisingly appear to pose the highest risk. For example, cocoa in Ghana, maize in Zambia, and sorghum in Ethiopia cover large areas and have high TRP (Ethiopia sorghum: TRP: 5,015,001, relative to a mean across crops of 800,967; Ghana cocoa: TRP: 6,673,683, relative to a mean across crops of 733,923; Zambia maize: TRP: 5,997,975, relative to a mean across crops of 270,524). However,

TABLE 2 Crops with the minimum and maximum total risk potential and trade-off risk intensity for each species group and country.

	Group	Country	Minimum	Maximum
Total risk potential (TRP)	VERT	Ghana	Sesame, traded, 20.73	Cocoa, traded, 6,673,683
		Ethiopia	Plantain, domestic, 2.33	Wheat, domestic, 5,451,823
		Zambia	Small millet, domestic, 26.15	Maize, traded, 5,997,975
	BM	Ghana	Sesame, traded, 16.28	Cocoa, traded, 5,187,640
		Ethiopia	Plantain, domestic, 1.87	Wheat, domestic, 4,764,510
		Zambia	Small millet, domestic, 21.57	Maize, traded, 4,923,117
	THR	Ghana	Sesame, traded, 0.05	Cocoa, traded, 196,727
		Ethiopia	Plantain, domestic, 0.04	Wheat, domestic, 264,209
		Zambia	Small millet, domestic, 0.54	Maize, traded, 133,297
Trade-off risk intensity (TORI)	VERT	Ghana	Pearl millet, domestic, 4.36	Plantain, domestic, 5.50
		Ethiopia	Yam, domestic, 4.64	Coconut, domestic, 0.84
		Zambia	Rice, domestic, 5.36	Tea, traded, 6.16
	BM	Ghana	Sorghum, domestic, 3.40	Coffee, traded, 4.52
		Ethiopia	Coconut, domestic, 0.66	Yam, domestic, 4.09
		Zambia	Rice, domestic, 4.36	Coffee, domestic, 6.14
	THR	Ghana	Sesame, traded, 0.01	Coffee, traded, 4.52
		Ethiopia	Cassava, domestic, 0.02	Coffee, traded, 3.99
		Zambia	Sugarcane, domestic, 0.12	Coffee, domestic, 6.14

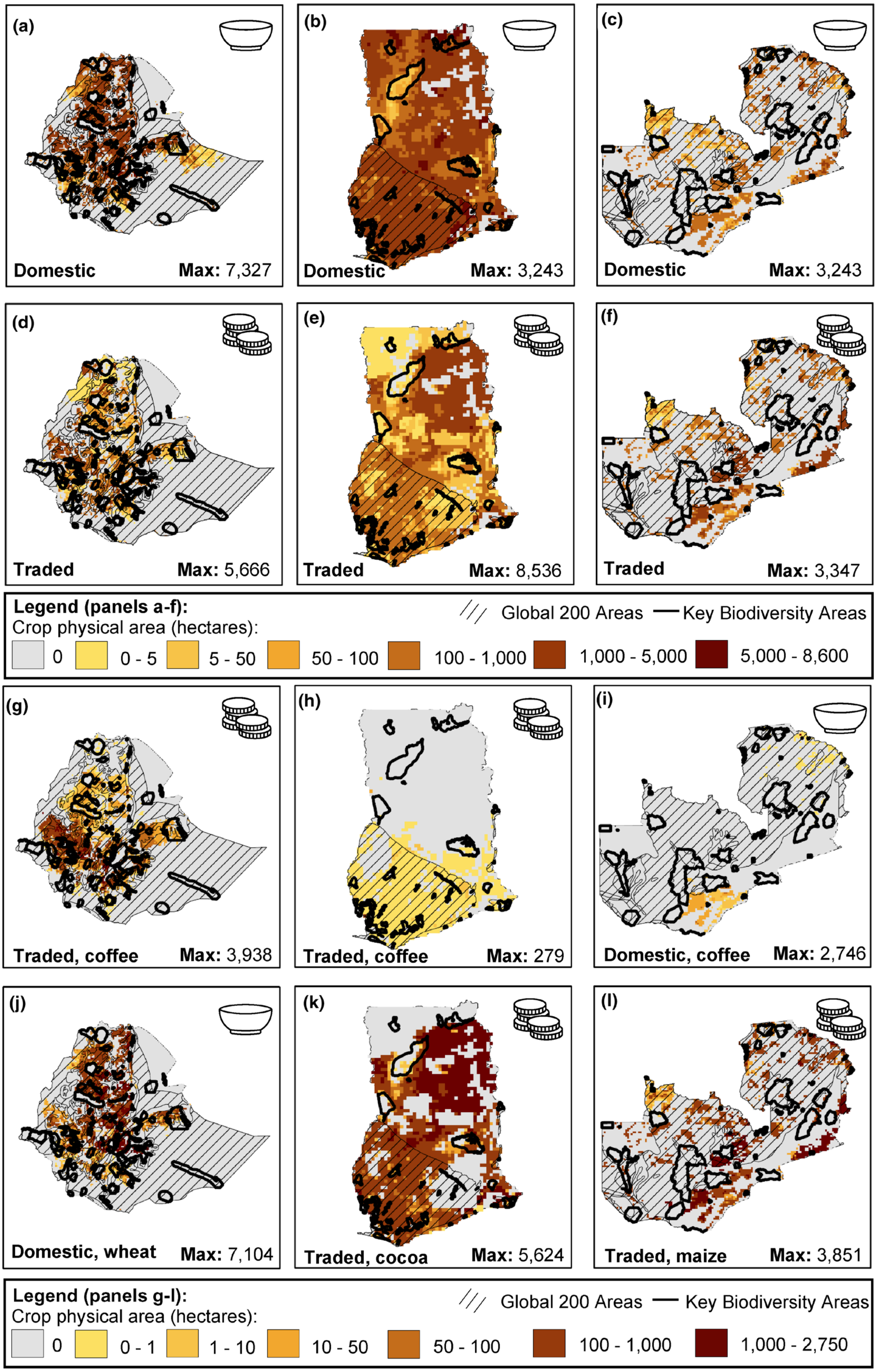
Note: Values are listed in the order: Crop, crop group, and value and are presented for raw values, rather than values relative to the median expectation for the country (e.g., as in Figure 2). As with other figures, domestic crops are represented with a bowl icon and traded crops with an icon depicting a stack of coins.

if we measure the trade-off risk based on how many vertebrate species are affected on average per unit growing area (trade-off risk intensity—TORI), the crops with the highest TORI are plantain in Ghana (TORI: 5.50) and tea in Zambia (TORI: 6.16), whereas the crops with the largest area have lower TORI per unit area (Ethiopia sorghum: TORI 3.37, relative to a mean across crops of 3.55; Ghana cocoa: TORI 4.82, relative to a mean across crops of 4.89; Zambia maize: TORI 5.69, relative to a mean across crops of 5.77) (Table S9.1).

3.3 | Footprints and hotspots of trade-off risk

The footprint-based outcome shows considerable overlap between cropland and conservation-based priority areas in all three countries (Figure 3; Table S8.3). Global 200 areas cover much of Ethiopia and Zambia (Table S8.3), making such overlap unsurprising. Nevertheless, there are important differences between the countries. In Ethiopia, wheat overlaps with more Global 200 ecoregion and KBA space than coffee (Figure 3; Table S8.3). In fact, more than three quarters of Ethiopia's total wheat physical area is within Global 200 ecoregions and a quarter within KBAs (Figure 3; Table S8.3). Coffee also has strong overlaps, with nearly 60% of the physical area of coffee in Ethiopia overlapping with Global 200 ecoregions and more than 10% with KBAs (Figure 3; Table S8.3). Ethiopia has the largest amount of the country under Global 200 and KBA priority areas, relative to Ghana and Zambia, however (Table S8.3). In Ghana, the domestic crop footprint has a larger spatial extent than the traded one, which is more concentrated towards the northeast of the country (Figure 3). Species richness is lower in this part of the country (Figure 4, Figure S3.2). Coffee overlaps with the Global 200 ecoregion and KBAs in the southwest corner of Ghana, with 86% of its physical area in Global 200 ecoregion space but only 1.6% overlapping with KBAs (Figure 3; Table S8.3). Cocoa has a greater spatial footprint and a larger overlap with KBAs (2.4%) but a smaller area overlapping with Global 200 ecoregion space (17%) (Figure 3; Table S8.3). In Zambia, coffee harvests are relatively concentrated in southern and northeastern regions (Figure 3). Maize is more widespread and has greater physical areas (Figure 3). However, both crops have around half of their physical area overlapping with Global 200 ecoregion space (Figure 3; Table S8.3). They differ substantially in their overlap with KBAs, as coffee has around 5% overlap whereas maize has nearer zero (Figure 3; Table S8.3).

We also find that trade-off hotspots vary with country, crop group, and species threat status (Figure 4, Figures S5.1 and S7.1). Whilst bird and mammal hotspots are in similar locations with similar intensity to those based on all vertebrates, hotspots are located in different places if focusing on threatened species in place of species



richness (Figure 4—all vertebrates, Figure S5.1—birds and mammals, and Figure S7.1—threatened species). Yet, all species subsets consistently highlight differences in trade-off hotspots between domestic and traded crop groups, with domestic crops having a greater growing area within the most species-rich areas (although the distinction between crop groups is less clear and more location-specific in Zambia [e.g., greater area overlap for domestic crops in the northeast and for traded crops in a central eastern area] [Figure 4, Figures S5.1 and S7.1]).

FIGURE 3 Trade-off risk footprints: Spatial footprints of physical area (hectares) of domestic and traded crop groups, and selected individual crops of interest, inside Global 200 ecoregions (hashed lines) and/or key biodiversity areas (KBAs, shown as solid black polygons). Darker colours represent a larger physical area in a given cell, with white representing zero physical area. The maximum physical area (ha) value in the country is labelled in text in each panel. The proportions of physical areas of given crops and crop groups within Global 200 ecoregions and/or key biodiversity areas (KBAs) are listed in Table S8.3. Crops of interest were selected because coffee has the greatest associated trade-off risk for threatened species in all three countries and wheat, cocoa, and maize had the greatest associated total risk potential in Ethiopia, Ghana, and Zambia, respectively, across all species subsets (vertebrates, birds and mammals only, and threatened species) (Figure 2 and Table 2). As with other figures, domestic crops are represented with a bowl icon and traded crops with an icon depicting a stack of coins.

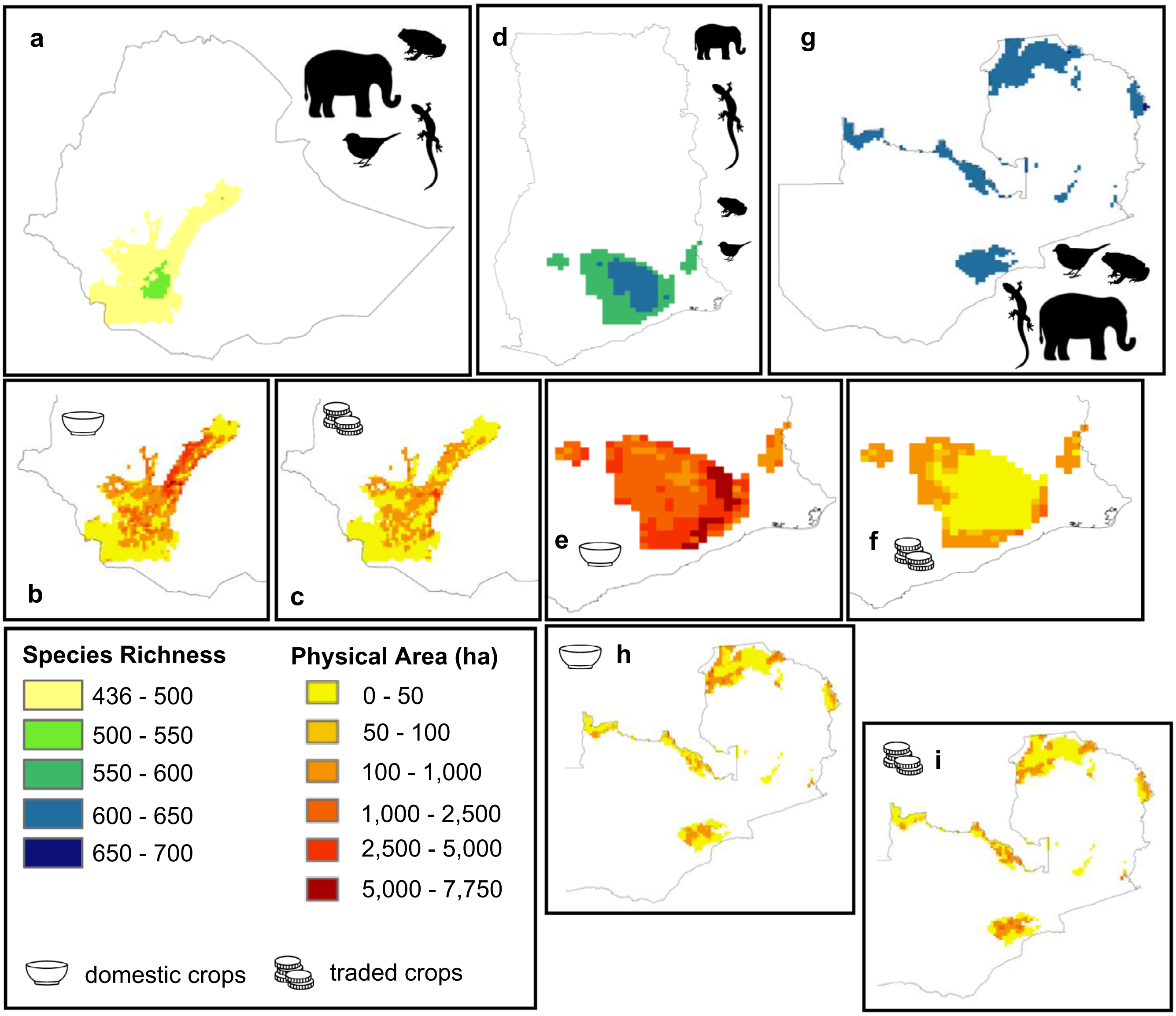


FIGURE 4 Trade-off risk hotspots in Ethiopia (b, c), Ghana (e, f), and Zambia (h, i). Hotspots depict the spatial extent of the most speciose areas (the top 10% of cells in terms of species-richness value, shown in Figures S1.2–S1.4) for each country (panels a, d, and g, respectively), and the physical area per grid cell (ha, hectares) within these hotspots for a given crop group (panels b, c, e, f, h, and i). Hotspots for domestic crops are marked using a bowl icon and traded crops with an image of a stack of coins. Hotspots associated with individual crops are available as map files on GitHub (described and linked in Supporting Information S6).

4 | DISCUSSION

4.1 | Trade-off risks and implications

In this study, we show that cropland coincides with particularly biodiverse areas in three countries in Africa which span a variety of ecoregions. We show that both domestic and traded crops have potential trade-offs with biodiversity, though the extents and locations of their trade-offs differ. Hotspots of trade-off risk were stronger for domestic crops than traded ones in Ghana and Ethiopia, but TORI and TRP metrics reveal that within-country and crop-specific variability is more important than whether a crop is predominantly used for domestic consumption or international trade. This also emphasises how our multiple measures of trade-off risk offer complementary perspectives on both footprint and intensity and how both measures are needed to understand risk. Specific crop production systems are also important when considering trade-offs and impacts for people and nature in the context of agricultural land-use change. Rather than suggesting there should be more or less production of certain crops, or a change to cropping location, our findings highlight a need for agricultural practices which put less pressure on vertebrate species in areas with high risk of trade-off.

The finding that both domestic and traded crops pose similar trade-off risks to biodiversity suggests that a future focus on domestic crops, in line with current national priorities for self-sufficient food systems in Ethiopia, Ghana, and Zambia (Franks et al., 2020; Franks & Gebrehiwot, 2020; Hou-Jones et al., 2020), would need to consider potential risks to biodiversity, as would increasing traded crop production. To date, attempts to reduce biodiversity loss from land use across the globe have tended to focus on internationally traded crops, for example through certification schemes (Mas & Dietsch, 2004; Perfecto et al., 2005; Phalan et al., 2013; Tscharntke et al., 2015). Whilst such schemes make an important contribution and can also be used in domestic crop production (e.g., organic certification), our results suggest that strategies also need to be developed that focus specifically on domestically consumed crops, whilst remaining sensitive to the potential direct and indirect consequences of management decisions on livelihoods, well-being, and equality of local people. Nevertheless, as the trade-off risks posed by export crops are similar to those from domestic crops, our findings also emphasise the importance of international trade partners sharing responsibility for designing and supporting agricultural management practices associated with lower risks to biodiversity. This, itself, will likely be crop- and import-country-specific, as cereals traded with neighbouring countries may have different opportunities and challenges to crops which are traded trans-continentally, for example. We identify coffee and bananas as having high potential trade-off risk for all countries, suggesting an urgent need for mitigation for these crops. This urgency increases when we consider that feedback loops may be present, wherein loss of biodiversity will also negatively impact future crop production. For instance, pollinator-dependent crops like coffee and cocoa (Millard et al., 2023) are both high trade-off risk crops in our analysis.

Crops can overlap with high biodiversity areas for many reasons, one of which is that some crops may do well in climatic conditions that also promote high levels of biodiversity. Previous research grouping all crops together does not allow a nuanced understanding of the different risks posed by different crops. Here, by considering individual crops and crop groups, we can see that trade-off risk is crop- and location-specific. This means that policies seeking to increase international trade and to improve domestic self-sufficiency will each have substantial effects on biodiversity. This matters further still because traded crops matter for livelihoods as much as domestic ones, with traded crops providing essential income, contributing to food security, and domestic crops contributing to food self-sufficiency. The policy levers for traded and domestic crops are, however, distinct. Whilst we are able to measure trade-off risks associated with specific crops and crop groups, further country-level research and local- and regional-scale fieldwork will be required to quantify impacts and to identify the best mechanisms for trade-off mitigation, which do not further inequality, hunger, or damage local livelihoods.

4.2 | Considerations for the future management of land use and agriculture in Ethiopia, Ghana, and Zambia

Our identification of areas of trade-off risk in Ethiopia, Ghana, and Zambia, provides an important first step in understanding where different sustainable development goals may come into conflict in a food systems context. Based on our findings, considerations for the future management of land use and agriculture in Ethiopia, Ghana, and Zambia will need to be crop-specific or allow for crop-dependent variation in implications. As many farmers in these countries are growing crops—both domestic and traded—to support their own livelihoods, rather than farming at large scales for external entities, considerations must always account for the needs of local people, land tenure, and other factors, to ensure conservation of biodiversity alongside improvements to livelihoods and equality. We note that biodiversity conservation will, in cases without human–wildlife conflict (e.g., animals consuming or trampling crops), also benefit livelihoods in the long term, as agricultural production is supported directly (e.g., via pollination and pest control) and indirectly (e.g., via soil improvement) by biodiversity. Food supply therefore depends on reducing and preventing biodiversity losses.

There are a number of ways that potential trade-offs between agriculture and biodiversity could theoretically be mitigated via future decisions on where crops are grown, but, in reality, these decisions are complex. Whilst our assessment of trade-off is static, land-use change is dynamic, responding to market forces, policies, and growing conditions, for example. A common first proposal is that crops that suit growing conditions found in conservation priority areas could be grown in more suitable alternative areas. However, this is not a viable or appropriate solution in many cases given land rights and the implications of such a decision for local people dependent on a given crop for their livelihoods. Second, crops associated with high trade-off risk could be swapped with lower risk alternatives (e.g., those that can be grown in the shade of native vegetation using agroforestry practices (Waldron et al., 2017)) of similar nutritional and/or economic value. This option is also unlikely to be practical in most cases, given the importance of suitable growing conditions and implications for land ownership and associated livelihoods. Switching crops is perhaps more likely for traded crops than domestic, as domestic crops might be selected by consumers and growers in line with cultural norms and accumulated knowledge. Importing food would lower in-country trade-off risk, though this has many socio-economic implications (e.g., for food security, employment, and human well-being) and will be associated with biodiversity impacts in the producing country (Chaudhary & Kastner, 2016; Marques et al., 2017).

Potential trade-offs could more practically be mitigated through changes in land management and agricultural practices. An overlap between crop production and areas of high potential biodiversity represents a range of possible situations depending on the management of the cropland (Figure 5), offering options for reducing or preventing a trade-off from occurring. For example, we do not identify specific crops, types, or areas consistently associated with the highest trade-off risks but, if crops can be grown in a way that maintains biodiversity and associated ecosystem functions in farmed areas (Seppelt et al., 2020; Waldron et al., 2017) this should create long-term 'win-wins' for people and nature, as yields should, in time, increase, even if changes to farming in the short-term might generate lower yields as an ecosystem rebuilds. 'Win-wins' might be quite rare, however, especially if short-term financial interests need to take priority (e.g., rapid intensification of production (Burian et al., 2024)). Accordingly, any short-term costs associated with farming in a way that is more beneficial to biodiversity could potentially be assisted by contributions from countries that are importing food from those countries experiencing biodiversity loss because of production for export.

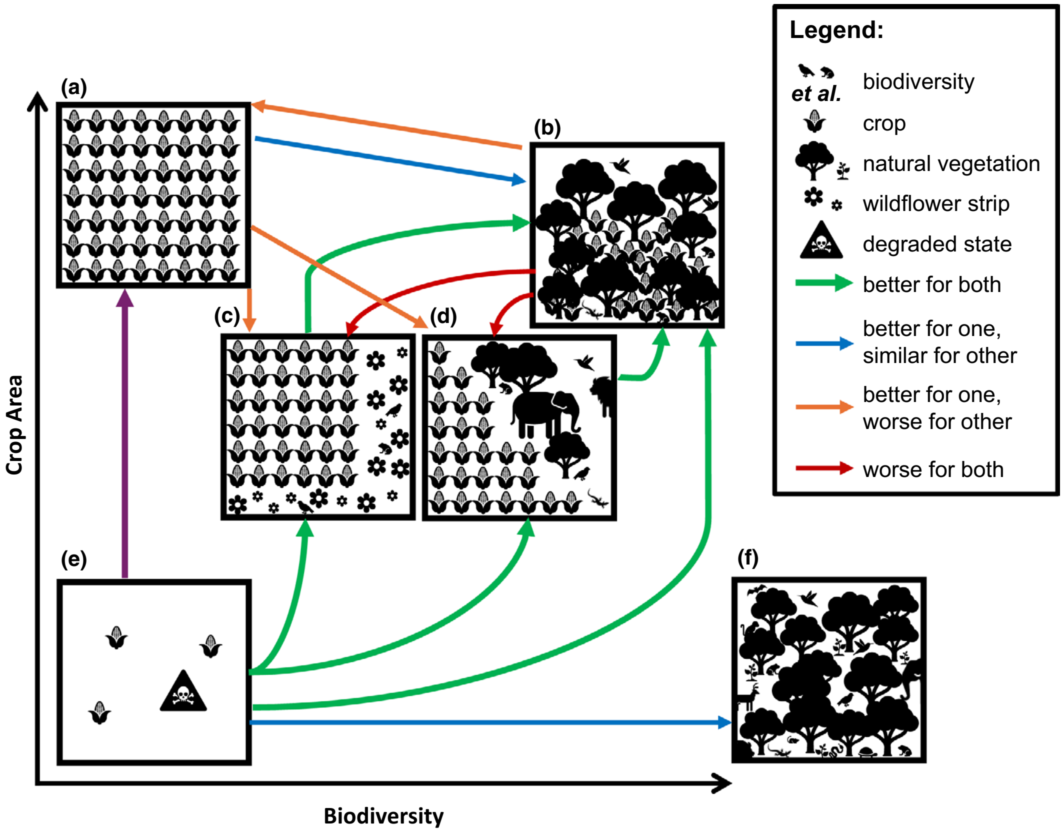


FIGURE 5 A contextual illustration of example land management situations where crop production coincides with naturally biodiverse areas, and outcomes of potential management changes. All examples are hypothetical and are used to highlight the complexity of the context of our study and the need for future fieldwork, to establish which situation is present on the ground and, thus, which might be a suitable next step for reducing trade-offs between people and nature (where needed). Situations (a–e) represent areas where crops and biodiversity coincide, whereas (f) describes a completely natural ecosystem, either never farmed or where agriculture has been abandoned. The landscape in (e) represents a low yield (degraded), low biodiversity scenario (a 'lose-lose' situation for biodiversity and agriculture). Block (c) shows a landscape where some space is preserved for biodiversity (e.g., as in the case of 'wildflower strips', where native, self-seeding flowering plants are left to grow alongside fields of crops) and (d) shows a mixed-use landscape with areas of intensive cropland interspersed with natural habitats. In (b), crops are planted among natural vegetation (e.g., an agroforestry system using native vegetation for shade). The landscape in (a) is entirely given to crop production, where yields are high, but biodiversity is low. 'Win-win' decisions for biodiversity and crop yields are highlighted with thick, green arrows. Orange arrows indicate trade-offs, while red arrows represent lose-lose transitions.

Poverty is one of the leading drivers of agricultural expansion. The impacts on biodiversity associated with trying to increase yields, however, might lower future crop yields, creating a paradox. Trade-off mitigation is often discussed in the literature without considering the potential impacts on specific countries or local people. We expect our identification of relatively higher and lower risk areas and crops to be useful for prioritising the future field-based research needed to guide land-use management and conservation decisions in Ethiopia, Ghana, and Zambia. We expect our approach could also be used in other countries for which high-resolution data on specific crops and production methods are unavailable, to gain important insights as to the areas and crops where potential trade-offs are highest. Nevertheless, interpreting our results in a spatial land management context requires caution. Specific decisions regarding particularly high-risk crops need to be managed carefully and appropriately for the country context, with a spatially just approach, to prevent high risks of trade-off between biodiversity and human livelihoods.

4.3 | Limitations and future research

Our work is subject to several necessary limitations. First, the actual on-the-ground impact of agricultural land use on biodiversity varies with land-use intensity and agricultural practices (Clough et al., 2011; Dudley & Alexander, 2017; Mclaughlin & Mineau, 1995; Newbold et al., 2015; Semenchuk et al., 2022; Tscharntke et al., 2012), as well as among crop types (Fan et al., 2024; Phillips et al., 2017), which we cannot capture with data available at present. For instance, data on farm sizes would facilitate a greater understanding of the relative scales of impact associated with domestic and traded crops (Ceaușu et al., 2025). In general, agriculture has a negative effect on species richness (Jaureguiberry et al., 2022; Newbold et al., 2015; Newbold et al., 2017; Phillips et al., 2017). Still, we need more comprehensive biodiversity sampling and up-to-date maps of individual crops (see also See et al., 2015), to assess biodiversity impact, which would enable us to understand whether a trade-off is taking place, rather than merely the risk of a potential trade-off.

Second, we focus on present-day crop production rather than hypothetically what might be grown in an area. It is therefore important to acknowledge that if a country were to stop growing crops in one particular area, there are a number of possible outcomes, including a switch to producing a different crop, increasing demand for a similar crop, or movement of the production to another country, which would have different implications for biodiversity and agricultural incomes (e.g., see Taheripour et al., 2019). Furthermore, given the limitations associated with cropland distribution estimates and species-richness estimates based on vertebrate species ranges (2.2.4), our findings should not be used alone to prioritise specific locations for conservation attention or agricultural expansion. Rather, they allow us to assess overall and relative trade-off risks from different crops. Whilst beyond this study's scope, a scenario-based approach could be used in future, especially when much-needed dynamic data on crop distributions under different market values and policies are available.

Third, our footprint measure will be affected by biodiversity priority region choice. We did not choose protected areas as priority areas, as the presence of a protected area does not always mean strong protection is in place. We identify that Global 200 ecoregions—considered priority regions—cover large proportions of the focal countries and, inevitably, therefore overlap with large areas of crop production. Key Biodiversity Areas are more targeted and trade-off risk footprints overlapping with these might provide more useful insights for conservation and land-use planning. Our results highlight that it remains important, despite limitations, to complement footprint-based trade-off risk measures with per unit area measures of TORI to capture crop- and country-specific differences in trade-off risk independent of conservation prioritisation approaches.

Fourth, the varying trade-off risks among crops, and the crops posing the greatest trade-off risk varying among countries, is likely, at least in part, explained by overlap between the natural habitat preferences of many vertebrate species and the best growing conditions for crops, although there are few explicit tests of this in the scientific literature (though a global overlap between areas suitable for oil palm and areas rich in biodiversity has been demonstrated; Fitzherbert et al., 2008). The most in-demand, valuable, and productive cropland is likely to be found in higher rainfall areas, with soil, light, and climatic conditions beneficial for maximum growth—areas which are also beneficial for wild plant species, and thus, indirectly, also vertebrates. Here, we advance previous research into the relationship between cropland and biodiversity (e.g., Marques et al., 2019; Newbold et al., 2017; Phillips et al., 2017), by using multiple metrics and a broad range of specific domestic and traded crops to demonstrate that there are measurable, crop-specific differences in the trade-off risk posed by agriculture to biodiversity in Ethiopia, Ghana, and Zambia—countries home to a variety of environmental conditions and ecoregions. Given the likely relationship between environmental conditions and the footprint and intensity of trade-offs between food crops and biodiversity, the implications of our findings under future climate change will warrant further investigation when future projections of the distributions of specific crops are available to compare with future projections for vertebrate species (e.g., Ethiopia and Zambia are highlighted as areas likely to experience significant wetting and drying in Global 200 priority regions due to climate change in work by Aukema et al., 2017).

Fifth, patterns in vertebrate biodiversity, which we focus on in this study, do not necessarily reflect patterns in broader biodiversity. Thus, when country-wide data are available on invertebrates and soil fauna, these should be a focus for future research, as well as incorporating metrics of functional and phylogenetic diversity across all measurable groups. We present our analysis as a first stage, computable in relatively data-poor regions whilst such data are awaited.

A priority for future work could be to use datasets such as BioTIME (Dornelas et al., 2018) and PREDICTS (Hudson et al., 2014) to consider a change in trade-off risk for both crops and species through time and under different land-use scenarios. We could not do this because, presently, such datasets have more limited coverage in tropical than temperate regions of the world and few data points from our focal countries. Similarly, we focus this study on agricultural expansion, as this has been a dominant mode of agricultural development in many countries across Africa due to low yields and is a process we can study using data available at this time. However, intensification is also a likely mode of yield increase already being pursued, and likely to be pursued further in future. Considering additional variables of influence on the impact of crops on biodiversity—such as farm size and farming system, crop longevity and rotation, yields (Ceaușu et al., 2025), and inputs such as pesticides and herbicides—is currently not possible with the data available for the focal countries. When such data become available, we recommend this as a key focus for future research to capture how intensity of agriculture influences trade-off risk, along with more comprehensive biodiversity metrics able to capture the impact of such change, but note that, while trade-off risks will be more urgent with intensification, the location of the cropland, and thus the species being put at risk, will not change substantially.

5 | CONCLUSIONS

In conclusion, our finding that trade-off risk is crop- and country-specific underlines the importance of land-use and land-management strategies working to minimise biodiversity impacts where overlap between crops and biodiversity does occur, while considering the costs to local livelihoods. Our new multi-metric method for trade-off risk assessment and our results suggest that metrics of both footprint and intensity are needed to avoid highlighting only crops with bigger growing areas, or countries with larger conservation areas, for instance. Whilst previous conservation-oriented research has tended to focus on cropland in general, or on important globally traded crops, we focus here on individual crops of importance within each country, allowing us to consider the relative trade-off risk also posed by crops that are predominantly consumed in-country versus crops that are traded. By highlighting areas with relatively higher and lower potential for trade-offs, we identify priorities for future research, which will need local- and regional-scale field studies of the impacts of different farming methods for specific crops on biodiversity, as well as decision-making.

Increases in human populations (both within the countries we studied as well as globally), changes in diets, and associated increases in food demand create an urgent need to characterise the potential for trade-offs between agriculture and biodiversity, and to identify solutions to ensure people's livelihoods, successful crop growth, and the conservation of biodiversity. Our work makes an important step towards this goal, showing that both domestic and traded crops pose potential risks to biodiversity and that trade-off risk management to meet multiple sustainability goals will require a crop- and country-specific approach.

AUTHORS' CONTRIBUTIONS

Abbie Chapman and Tim Newbold conceptualised the manuscript, with input from all authors. Abbie Chapman and Tim Newbold sourced data, developed code, conducted analyses, and wrote the first draft. Selase Adanu and Adam Devenish made substantial contributions to early versions of the manuscript and Liz Robinson and Geoff Griffiths gave substantial support during revisions. Carole Dalin provided data on domestic consumption and international trade, and support with associated methods, for the manuscript. All authors edited the manuscript and approved the submitted version.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to declare.

DATA AVAILABILITY STATEMENT

The data used in this manuscript were openly available for download, as described and cited in the methods. The R code used to generate the results presented in this study is available from: https://github.com/abbiesachapman/SENTINELdomtraded.

STATEMENT ON INCLUSION

This study was based on analysis of secondary data, rather than primary data, so there was no local data collection. However, the authorship team comprises researchers from a range of countries and disciplines, and authors from each of the focal countries of the study have contributed to this work.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Figure S1.1. Map highlighting the locations of each of the focal countries in our study. This map, and all others presented in this manuscript and Supporting Information, was produced using ArcMap software (ESRI); here, the source data are from Global Administrative Areas (2012).

Figure S1.2. Zones of Ethiopia in and surrounding the area richest in species (areas with the top 10% of Ethiopia's species-richness values, denoted with a thick, black line) from the GADM database of Global Administrative Areas (Global Administrative Areas, 2012).

Figure S1.3. Districts of Ghana in and surrounding the area richest in species (areas with the top 10% of Ghana's species-richness values, denoted with a thick, black line) from the GADM database of Global Administrative Areas (Global Administrative Areas, 2012).

Figure S1.4. Districts of Zambia in and surrounding the area richest in species (areas with the top 10% of Zambia's species-richness values, denoted with a thick, black line) from the GADM database of Global Administrative Areas (Global Administrative Areas, 2012).

Figure S1.5. Ecoregions of Ethiopia (as defined in Olson et al., 2001).

Figure S1.6. Ecoregions of Ghana (as defined in Olson et al., 2001).

Figure S1.7. Ecoregions of Zambia (as defined in Olson et al., 2001).

Figure S2.1. Trade-off risk intensity (TORI) associated with domestic and traded crops in Ethiopia, Ghana, and Zambia, where domestic and traded crops were classified using an alternative, 5% threshold (i.e., >95% of total production by weight remaining in country being classified as 'domestic' and >5% of total production by weight being exported is classified as 'traded'). Values are shown relative to the expectation if a crop with median area across all crops in a country were grown in areas of typical species richness for that country. Values above 1 suggest that the risks are above the expectation for the country and values below 1 show risks are below the expectation for the country. Trade-off risk intensity represents the average local richness of vertebrate species, per unit area, across areas in which each crop (or crop group) is grown. The values are summarised for domestic (orange) and traded (red) crop groupings, with the boxplots representing the range of values for individual crops. The median across all individual crops is shown by the horizontal lines within each box, with confidence captured by notches. The whiskers show the minimum and maximum values. The values are summarised for domestic (orange) and traded (red) crop groupings but the data used to create each boxplot is for individual crops. These boxplots are presented for all vertebrate species and are thus comparable to the 'VERT' boxes in panel b of Figure 2. Welch's two-sample *t*-test revealed no significant difference ($p > 0.05$) in trade-off risk intensity between domestic and traded crops in any of the species' subsets under this alternative 5% threshold (Table S2.2).

Figure S2.2. Trade-off risk intensity (TORI) associated with domestic and traded crops in Ethiopia, Ghana, and Zambia, where domestic and traded crops were classified using an alternative, 15% threshold (i.e., >85% of total production by weight remaining in country being classified as 'domestic' and >15% of total production by weight being exported is classified as 'traded'). Values are shown relative to the expectation if a crop with median area across all crops in a country were grown in areas of typical species richness for that country. Values above 1 suggest that the risks are above the expectation for the country and values below 1 show risks are below the expectation for the country. Trade-off risk intensity represents the average local richness of vertebrate species, per unit area, across areas in which each crop (or crop group) is grown. The values are summarised for domestic (orange) and traded (red) crop groupings, with the boxplots representing the range of values for individual crops. The median across all individual crops is shown by the horizontal lines within each box, with confidence captured by notches. The whiskers show the minimum and maximum values. The values are summarised for domestic (orange) and traded (red) crop groupings but the data used to create each boxplot is for individual crops. These boxplots are presented for all vertebrate species and are thus comparable to the 'VERT' boxes in panel b of Figure 2. Welch's two-sample *t*-test revealed no significant difference ($p > 0.05$) in trade-off risk intensity between domestic and traded crops in any of the species' subsets under this alternative 15% threshold (Table S2.3).

Figure S3.1. Species richness of vertebrates (a), birds and mammals only (b), and reptiles and amphibians only (c), in Ethiopia. Classification for symbology determined using natural breaks ('jenks').

Figure S3.2. Species richness of vertebrates (a), birds and mammals only (b), and reptiles and amphibians only (c), in Ghana. Classification for symbology determined using natural breaks ('jenks').

Figure S3.3. Species richness of vertebrates (a), birds and mammals only (b), and reptiles and amphibians only (c), in Zambia. Classification for symbology determined using natural breaks ('jenks').

Figure S4.1. Spatial extents of all crops (a, d, g), domestic crops (bowl icon; b, e, h) and traded crops (coins icon; c, f, i) for Ethiopia (a–c), Ghana, (d–f), and Zambia (g–i). All maps depict physical area in hectares. The lowest values for domestic and traded crops are near zero across all countries and the maximum values are given in the annotations provided on each panel. The physical area maps for individual crops in each of the three focal countries can be created by clipping the data available from MapSPAM (IFPRI, 2024) to the country of interest. As MapSPAM data are open access, but were not created by the authors, we do not provide .tif files of these clips but share code on GitHub (https://github.com/abbiesachapman/SENTINELdomtraded) demonstrating how to perform the cropping/clipping process.

Figure S5.1. A version of Figure 4 produced using vertebrate richness data, computed including only bird and mammal species, highlighting trade-off hotspots with respect to areas of the greatest numbers of bird and mammal species (the top 10% of cells in terms of bird and mammal species-richness value, shown in Figures S1.2–S1.4), for Ethiopia (b, c), Ghana (e, f), and Zambia (h, i). Within each hotspot, the physical area (ha, hectares) for a given crop group is shown. Hotspots for domestic crops are marked using a bowl icon and traded crops with an image of a stack of coins.

Figure S7.1. A version of Figure 4 produced using threatened species-richness data, identifying trade-off hotspots with respect to area of greatest threatened species richness (the top 10% of cells in terms of threatened species-richness value, shown in Figures S1.2–S1.4), for Ethiopia (b, c), Ghana (e, f) and Zambia (h, i). Within each hotspot, the physical area (ha, hectares) for a given crop group is shown. Hotspots for domestic crops are marked using a bowl icon and traded crops with an image of a stack of coins.

Table S2.1. Classification of crops analysed, wherein a crop was classified as 'traded' if more than 10% of the total production by weight was traded and a crop was classified as 'domestic' if more than 90% of the total production by weight remains in country. The total physical area (in hectares) is also given per crop, according to the summed physical area values per country from MapSPAM (IFPRI, 2024) raster data. Note that broad beans, buckwheat, green broad beans, green beans, and string beans were NA for these countries, so are not listed here despite being listed in MapSPAM. Physical area is zero in this table if the crop was not produced during the study period in the given country.

Table S2.2. Welch's two-sample *t*-test results, comparing domestic and traded crop groupings for vertebrate species data per country with a threshold classification for crop groupings of 5%. Cells are highlighted in grey when the mean values for domestic crops exceeded those of traded crops.

Table S2.3. Welch's two-sample *t*-test results, comparing domestic and traded crop groupings for each subset of species data per country with a threshold classification for crop groupings of 15%. Cells are highlighted in grey when the mean values for domestic crops exceeded those of traded crops.

Table S8.1. Welch's two-sample *t*-test results, comparing domestic and traded crop groupings for each subset of species data per country. Cells are highlighted in grey when the mean values for domestic crops exceeded those of traded crops. These values are based on the raw values of trade-off risk and total risk potential.

Table S8.2. Summary statistics associated with the raw trade-off risk ('TOR') values shown in Figure 1 and the raw total risk potential ('TRP') values in Figure 1. 'SD' refers to standard deviation and 'Med' refers to median.

Table S8.3. Summary information associated with Figure 3.

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