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Limited environmental and yield benefits of intercropping practices in smallholder fields: Evidence from multi-source data

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A R T I C L E I N F O

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A B S T R A C T

Context: To ensure food security in sub-Saharan Africa, it is necessary to improve crop yields while minimizing environmental impacts. Intercropping has been demonstrated to deliver such outcomes, but their performance in smallholder fields has received limited attention therefore insufficient to capture the complexity of real-world crop fields run by smallholder farmers.
Objective: This study examines the benefits and management of intercropping practices in real smallholder fields in Malawi.
Methods: We collected field data on intercrop types, the number of intercropped species and maize yield in intercropped maize fields. Field data was then combined with geospatial and household survey data to investigate the yield benefits, agricultural inputs, and factors related to intercropping choices. We used Pearson correlation and Tukey's test to test the statistical significance in the difference between intercropped fields and monoculture fields.
Results: We found that more intercrops were planted in fields with smaller sizes, drier conditions, and higher soil erosion levels, with adoption rates increasing from 75 % in 2010 to 84 % in 2020. In addition, our field data shows that intercropping is associated with reduced primary maize yield (2.7 t/ha) compared to pure maize yield (3.8 t/ha). Conversely, satellite data demonstrates an improvement in overall field yield in intercropped fields. Meanwhile, intercropped fields require higher labor inputs (11 h more per season) and increased weeding times than monocultures, however agrochemical inputs (fertilizers and pesticides) do not necessarily decrease in intercropped fields compared to monocultures.
Conclusions: Our results suggest that while smallholder farmers in Malawi adopt intercropping to improve land use efficiency, drought resilience, and soil fertility, they are not realizing the full benefits observed in experimental trials.
Implications: More evidence on the benefits and best practices of intercropping in smallholder fields is necessary in order to better understand this practice as an option for sustainable intensification.

1. Introduction

Ensuring food security in sub-Saharan Africa is a top priority, particularly given the projected tripling of food demand by 2050 (van Ittersum et al., 2016). However, achieving higher crop production in the region is challenging due to adverse effects of climate change, degraded

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soil fertility, and low inputs (Hoffman et al., 2018; Jayne et al., 2019). While intensive agriculture is necessary to meet the growing population's food demands, agricultural expansion and intensification have significant environmental impacts, such as biodiversity loss (Zabel et al., 2019), higher greenhouse gas emissions (Searchinger et al., 2015), and water and air pollution caused by excessive use of fertilizers and pesticides (Tilman, 2020). Therefore, to ensure long-term food security in sub-Saharan Africa, it is imperative to increase crop production sustainably while taking into account environmental impacts.

Crop diversification, which involves increasing the diversity of crops through crop rotation, multiple cropping, or intercropping, has been considered an important strategy to minimize environmental impacts while improving agricultural productivity and stability (Christian and Blessing, 2022; Hufnagel et al., 2020). Intercropping practices, involving the planting of multiple crops within the same field, have been considered one of the important ways to foster crop diversity and promote sustainable intensification in sub-Saharan Africa (Garnett et al., 2013; John et al., 2021; Tilman, 2020). Specifically, intercropping practices have received strong support and promotion from governments, local and international agricultural development agencies, and donors (Corbeels et al., 2020; Giller et al., 2021), through setting up promotion programs and working groups to advocate technical and policy interventions (Chinseu et al., 2022).

The promotion of intercropping is based on the benefits it brings, including enhancing crop yield (Li et al., 2020; Stratton et al., 2022), reducing the risks of climatic shocks, improving soil fertility (Mazzafera et al., 2021), controlling pests and diseases (Mazzafera et al., 2021; Silberg et al., 2017), and lowing agrochemical inputs (Li et al., 2021). This promotion specifically targets the low-input systems of smallholder fields in sub-Saharan Africa (Gitari et al., 2020; Namatsheve et al., 2020), where practices and adoption may vary to suit local conditions, needs, and challenges. However, it is important to note that the benefits and positive yield responses of intercropping mentioned above are mainly observed in controlled experimental trials and subsequent meta-analyses. These experimental settings often simplify cropping systems (Corbeels et al., 2020) and may not reflect the actual cropping system dynamics and resource allocation choices made by farmers who need to balance various pressures such as climate change, soil conditions, market prices, and labor inputs (Krupnik et al., 2019). For instance, field experiments have been designed to investigate optimal crop species combinations and rotation strategies (Gwenambira-Mwika et al., 2021; Li et al., 2020; Li et al., 2021), as well as evaluate impacts on stability and income gain (John et al., 2021). These experiments are often conducted on small plots and few sites in research stations, which may not accurately represent farm-scale functioning (Krupnik et al., 2019). Consequently, these findings may have limitations in terms of their applicability to larger scales, such as at the country level (Rusinamhodzi et al., 2012; Silberg et al., 2017).

Although intercropping practices have been extensively studied for their effects on crop yield and soil fertility in experimental trials, their performance in real smallholder fields has received less attention, leaving little evidence on the benefits of intercropping in these settings. Understanding the performance of intercropping in smallholder fields is crucial to optimize the yield response and inputs required as these can vary between experimental trials and on-farm management practices. Intercropping, particularly the practice of growing legumes in maize fields, is widely adopted by smallholder farmers in sub-Saharan Africa (Brooker et al., 2015; Gitari et al., 2020; Himmelstein et al., 2017; Okigbo and Greenland, 1976), making it an ideal opportunity to investigate yield benefits and environmental trade-offs of intercropping practices, such as agrochemical inputs, in real-world settings. This study offers a complementary approach to assess the performance of intercropping by conducting on-farm observations at a national scale.

For studying intercropping practices in smallholder fields across the entire country and over longer time-scales, acquiring field data on crop yield, field characteristics, and management strategies is key, but also challenging for sub-Saharan African regions. However, the growing availability of geospatial and household survey data, in combination with field measurements, makes large-scale research on smallholder fields possible. In this case, this paper makes two novel contributions. Firstly, it investigates intercropping practices in fields that are owned and operated by smallholder farmers, which reflects the real-world costs and benefits of this practice. Secondly, it uses multimodal datasets, including field measurements, surveys, and long-term (2010–2020) satellite data that cover large environmental and management gradients, to investigate the yield benefits, agricultural inputs, and factors related to intercropping choices. This study focuses on Malawi as an example to evaluate the performance of intercropping practices in smallholder farmers' fields and provide guidance on promoting the positive effects of crop diversification in sub-Saharan Africa (Brooker et al., 2015).

2. Data and methods

2.1. Setting and study site

This study focuses on intercropping practices in maize fields, as maize is the primary staple food grown by 97 % of farming households in sub-Saharan Africa (Denning et al., 2009) and intercropping in maize fields is the most common means of crop diversification. To characterize intercropped maize fields, we used data on crop diversity (i.e., the number of intercropped species) and crop stand type (i.e., mixed, strip, row, and relay), as these two variables reflect complexity and the level of cost in field management.

Malawi was selected as a case study because its small-scale farming sector is characterized by poverty and chronic food insecurity (Bezner Kerr et al., 2019) and it heavily relies on rain-fed maize production (John et al., 2021). The agricultural production in the country faces multiple challenges, such as poor soil fertility and high climatic variability. The Southern region of Malawi is the most populated and has the majority of croplands but is also prone to climatic hazards, such as droughts, dry spells, and localized floods (Sato et al., 2020). To address these challenges, sustainable intensification and crop diversification programs have been promoted for several years in Malawi (John et al., 2021; Snapp et al., 2010). We selected maize fields in the Phalombe District of Southern Malawi (Fig. 1a) to measure maize yield, the number of intercropped species, and intercrop stand type (Fig. 1c) to understand maize yield response to intercropping at the local scale.

Additionally, we investigated the overall field yield in intercropped fields at the national scale using a satellite data-based proxy (Fig. 1b) and the number of intercropped species from long-term (2010, 2016, 2020) Integrated Household Survey (IHS) data. Using the household survey data, we further investigated inputs (i.e., labor, fertilizer, and insecticide) of intercropping and changes in its adoption. Finally, we combined survey data on plot size, soil erosion level, and a satellite data-based drought index to evaluate the factors that correlate with the adoption of intercropping practices.

2.2. Field investigation on maize yield and intercropping management practices

Field data was collected in 2020 and 2021, including plot GPS location, intercrop type, and maize yield from 162 maize-dominated fields belonging to 150 households. This was done to capture yield and management variability within the study area, guided by local stakeholders' expertise. GPS coordinates of the four corners of all fields were recorded. Maize yield was measured during the harvest season in late March following standard crop cut measurements (Carletto et al., 2015). To sample the fields, three subplots of 2 m x 2 m were selected according to the FAO guidelines (FAO, 2018). Stratified random sampling techniques were employed in each field to capture yield variation and represent the entire field. To obtain the average yield for each field, each

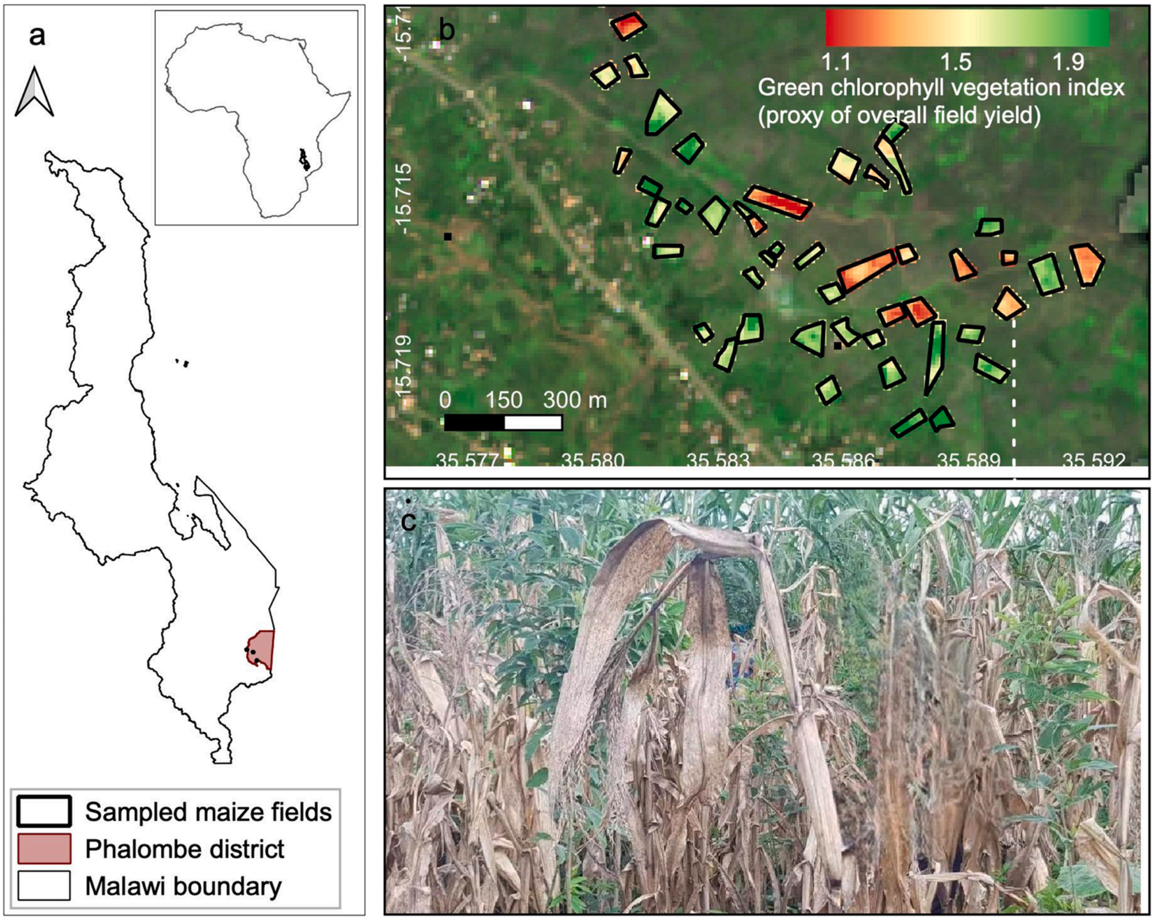

Fig. 1. (a) Malawi country location in Africa (inset); location of Phalombe district in Southern Malawi and selected intercropped maize fields in the Phalombe district; b) overall field yield variation of the subset of selected fields estimated by Sentinel-2 seasonal mean green chlorophyll index (CIgreen) (November 2020 to April 2021), with background Sentinel-2 RGB image; c) field photo showing an intercropped field with a spatially random mixed relay stand type where maize reaches harvest stage while legume crops are at the growing stage.

field was divided into high, middle, and low yield sections based on visual inspection, with one subplot randomly placed in each section. The mean value of the three subplots was then calculated. The selection of the number and size of subplots was based on consulting with local stakeholders and previous studies (Jain et al., 2019), as well as taking into account practical logistic trade-offs.

In each subplot, maize grain was shelled from the cob, weighed, and its moisture content was measured using a grain moisture meter (Armstrong et al., 2017) – MC 7825 G. The maize yield was adjusted to 12 % moisture content based on fresh weight and moisture content (Ngoune Tandzi and Mutengwa, 2020). Intercrop yields were not measured in this study due to the difficulty of measuring them logistically. However, the presence of intercropped fields and monoculture maize fields was recorded, with intercropped fields accounting for 80 % (130) and monoculture maize fields for 20 % (32) of the selected 162 field plots. In intercropped fields, intercrop types and the number of intercropped species were recorded, with the majority of fields (68 %) planted with maize and 1–2 intercrops. The variables measured in the field are listed in Table 1.

2.3. Overall field yield proxy using satellite data

To estimate overall field yield, including maize and intercrops, we utilized satellite measures of canopy greenness as a proxy. Specifically, we calculated the Normalized Difference Vegetation Index (NDVI) and green chlorophyll vegetation index (CIgreen) from Sentinel-2 L2A surface reflectance data. These indices have been proven to be effective in estimating crop yield in smallholder fields in sub-Saharan Africa (Burke and Lobell, 2017; Jin et al., 2017; Lambert et al., 2018; Li et al., 2022). We developed a calibration model to determine the extent to which these vegetation indices could accurately estimate overall field yield as measured at the field level.

For this study, we used the Sen2Cor algorithm (Magdalena et al., 2017) to correct the Sentinel-2 data and masked out cirrus clouds and cloud shadows using cloud mask bands. We selected a sample of 32 monoculture maize fields to investigate the relationship between vegetation indices and overall field yield, while the remaining 130 intercropped fields were excluded due to the difficulties in measuring intercrop yields. Seasonal mean and maximum values were calculated for the entire growing season from November 2020 to April 2021 to develop a linear empirical model. Mean values of pixels within each plot were also calculated to account for within-field variation.

To evaluate model accuracy, we used several metrics, including the coefficient of determination (R^2), p-value, root mean square error (RMSE), and normalized RMSE (nRMSE: RMSE divided by observed yield difference). The vegetation index that showed the strongest relationship with maize yield was selected as the proxy of overall field yield. We calculated the mean values of the selected index for the entire maize fields across the Malawi using the Maize Mask Datasets in 2019 developed by the World Bank (Azzari et al., 2021) and aggregated them at the traditional authority administrative level. We then investigated the relationship between the satellite proxy of overall field yield and the number of intercropped species based on household surveys to understand yield responses of intercropping practices. The Sentinel-2 satellite

Table 1
Dataset used in this study.

Field data				
Variables	Number of plots	Time	Spatial scale	Data sources
Maize plot coordinates	162	2020–2022	Southern Malawi Phalombe district	Collected from this study
Number of intercropped species				
Maize yield				
Malawi integrated household survey (IHS)				
Variables	**Number of surveys available**	**Time**	**Spatial scale**	**Data sources**
Crop stand type (Q1)	6477	2020	National scale (Malawi)	Worldbank LSMS program
Number of intercropped species in maize fields (Q2)	6477,6369, 6713	2010, 2016, 2020		
Plot size (Q3)	6619,7584	2010, 2020		
Weeding times (Q4)	6166	2016, 2020		
Labor inputs (Q5)	7052, 6715,6477	2010, 2016, 2020		
Fertilizer applied (Q6)	9962	2010, 2016, 2020		
Pesticides/ herbicides usage (Q7)	7052, 6715, 6477	2010, 2016, 2020		
Soil erosion level (Q8)	6163	2020		
Changes in soil erosion in the past 5 years (Q9)	647	2010		
Spatial dataset				
Variables	**Spatial resolution (m)**	**Time**	**Spatial scale**	**Data sources**
Maize Mask dataset	30	2019	National scale (Malawi)	World Bank Data Catalog
Changes in NDVI (MOD13Q1)	250	2010–2020		Google Earth Engine data catalog
NDVI from Sentinel-2	10	2020		
Palmer Drought Severity index (PDSI)	4000	2010, 2016, 2020		

data were obtained and further analyzed using the Google Earth Engine platform (Gorelick et al., 2017).

2.4. Integrated household survey on intercropping management practices

The Malawi Integrated Household Survey (IHS) conducted by the Malawi National Statistical Office, as part of the World Bank's Living Standard Measurement Study, was utilized to examine intercropping practices of smallholders throughout the country. The survey employed a stratified sampling technique that covered the three major regions of Malawi (Northern, Central, and Southern), encompassing 28 administrative districts and 256 traditional authorities to provide a representative sample of the nation. For this study, data pertaining to intercropping and management practices during the rainy season were extracted from the survey for the years 2010, 2016, and 2020, with approximately 6500 household surveys conducted each year across the country (Table 1).

All crop species planted within the field plots were included in the survey information utilized for this study. The planted crop species were differentiated between main crops and intercrops, enabling the identification of monoculture and intercropped fields, as well as calculation of crop diversity within each field. Other survey variables utilized in this study included crop stand type (mixed, row, strip, and relay), weeding times, labor inputs, fertilizer application, pesticide usage, soil erosion levels, and changes in soil erosion from 2005 to 2010. These variables were used to understand: (1) the extent of intercropping and its adoption changes from 2010 to 2020, (2) the factors related to its adoption, such as plot size, soil erosion level, and (3) the management input differences (weeding times, labor inputs, fertilizer application, and pesticide usage) between monoculture and intercropped fields. The correlation between the number of intercropped species and the aforementioned variables was based on 263 administrative units of traditional authorities, aggregated from approximately 6500 surveys per year. In each administrative unit, the mode values of the number of intercropped species were calculated from roughly 25 surveys to represent the number of intercropped species for the entire administrative unit. The analyses were focused on maize fields, which are the primary crop type in Malawi. Table 1 lists all survey variables and their counts, along with the original questionnaires related to each variable in the supplementary file (Table S1).

2.5. Monitoring cropland degradation and drought using spatial datasets

We utilized changes in the Normalized Difference Vegetation Index (NDVI) as a long-term indicator for monitoring cropland productivity and degradation, which has been widely used in previous studies (Wessels et al., 2004; Easdale et al., 2018; Gichenje and Godinho, 2018; Barbier and Hochard, 2018). We combined this information with household survey data on soil erosion levels to investigate the relationship between changes in NDVI trends and the number of intercrop species, aiming to uncover farmers' choice of intercropping on degraded land. Specifically, we utilized the MODIS NDVI data (MOD13Q1) (Didan, 2015) at a spatial resolution of 250 m to calculate changes in NDVI during the crop growing season (November-April) from 2010 to 2020 by applying a linear regression model. Positive slope values indicate an enhancement in cropland productivity, while negative values show a reduction in cropland productivity, indicating cropland degradation. We extracted significant slope values and calculated the mean value for the traditional authority level. The slope value was further correlated with crop diversity (number of intercropped species) to investigate the relationship between changes in cropland productivity and intercropping practices adoption.

Additionally, we utilized the Palmer Drought Severity Index (PDSI) dataset to investigate whether the adoption of intercropping practices is correlated with drought conditions. The PDSI dataset utilizes readily available temperature and precipitation data to estimate relative dryness (Abatzoglou et al., 2018). PDSI is a standardized index that generally ranges from -10 (dry) to $+10$ (wet) and has been successful in quantifying long-term drought (Dai, 2013). In this study, we presented a box plot of the above variables (plot size, drought index, etc.) and visually demonstrated the differences between monoculture maize fields and intercropped fields. We also used Pearson correlation and ANOVA to calculate the P value of the linear regression function, as well as Tukey's test, to test the statistical significance in the difference between intercropped fields and monoculture fields. All statistical analyses were conducted using the R Statistical Computing software. The spatial satellite data and drought index data were accessed and processed in the cloud-based platform Google Earth Engine (Gorelick et al., 2017).

3. Results

3.1. Changes in intercropping practices and spatial variation in Malawi

Intercropping is a widely adopted practice in Malawi, with an average of 80 % of maize fields across the country being intercropped according to the IHS survey dataset from 2010, 2016, and 2020 (Fig. 2a, Fig. S1). The spatial distribution of intercropping shows a strong pattern,

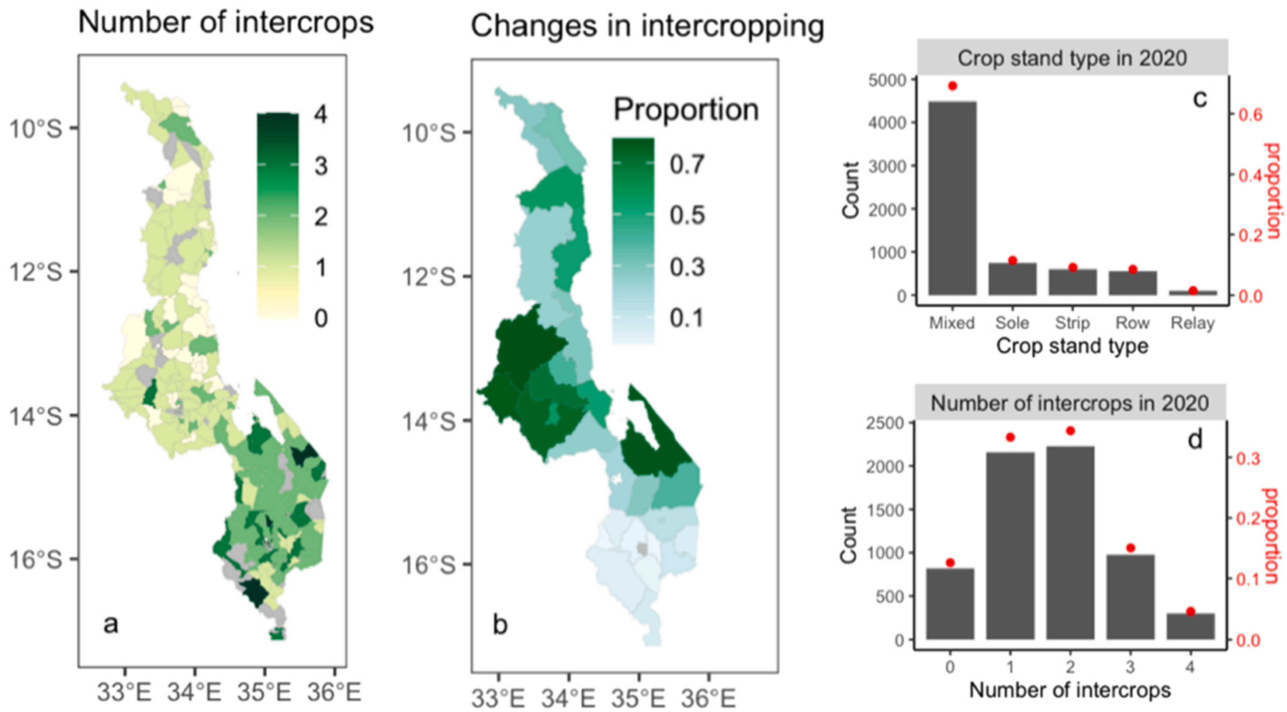

Fig. 2. (a) Average number of intercropped species in maize fields at the 263 traditional authority administrative units in 2020, through data aggregation of the most frequent value within each region, gray color shows areas with NA values; (b) changes in intercropping proportion in maize field from 2010 to 2020 at the district level; (c) histogram distribution of crop stands types including mixed, sole, strip, row and relay in 2020; (d) histogram distribution of number of intercropped species in 2020. The above dataset is based on ~6500 integrated household surveys in Malawi for year 2010 and 2020.

with the Southern Region having the highest proportion of intercropping at 95 % in 2020, compared to 70 % and 73 % in the Northern and Central Regions, respectively (Fig. 2a). The most common intercropping practice across the country is spatially mixed intercropping, which accounts for 67 % of maize fields according to 6476 surveys conducted by the IHS in 2020 (Fig. 2c). In contrast, strip and row intercropping, where intercrops are grown in different rows or multiple rows combined in strips, accounts for 17 % of maize fields, while relay intercropping, where intercrops are planted after maize to complement its growth cycle, accounts for 2 % of maize fields (Fig. 2c). Maize-legume intercropping, particularly with pigeon bean, is the most common intercrop type, planted in 62 % and 57 % of maize fields at the local scale of Southern Malawi and the national scale, respectively (Fig. S2). The adoption of intercropping has increased from 2010 to 2020 (Fig. 1b), with 75 % of maize fields being intercropped in 2010, compared to 84 % in 2020, with the majority of fields planted with 1–2 intercrop types (Fig. S1, Fig. 2d). This increase is most noticeable in the Northern and Central Regions (Fig. 2b).

3.2. *Determinants of intercropping choice*

Our analysis revealed correlations between intercropping practices and various factors including plot size, climate conditions, and soil quality (Table 2). Specifically, we found that smaller plot sizes were associated with a greater number of intercropped species in 2010, 2016, and 2020 (Fig. 3a), indicating a negative correlation between the two (Table 2). On average, monoculture maize was grown on plots of 0.44 ha in size across Malawi, whereas intercropped fields had an average size of 0.38 ha. We also observed a negative correlation between the number of intercropped species and drought index values (Table 2), indicating that intercropping was more prevalent in areas experiencing more severe drought conditions in all three years (Fig. 3b). The average PDSI was −0.9 in monoculture fields compared to −1.4 in intercropped fields.

Furthermore, our analysis showed that intercropping was more common in fields with higher soil erosion levels in 2020 (Fig. 3a, Table 2). On average, 32 % of monoculture fields were reported to have soil erosion based on survey data from 2010, 2016, and 2020, while this number increased to 43 % in intercropped fields (Fig. 4a). Looking back at earlier years (2005–2010), we found a similar trend, with more intercrops being planted in fields with worsened soil erosion (Fig. 4b), although this correlation was not statistically significant (Table 2). Our analysis of long-term satellite data also revealed a similar pattern, with intercropping being more prevalent in fields with negative trends of NDVI from 2010 to 2020, while monoculture was practiced in fields with increasing NDVI trends at the national scale in 2020 (Fig. 4c, Table 2). When we examined these correlations at the regional scale, we found similar patterns in the central and southern regions, indicating that intercropping was more common in less productive fields. However, opposite results were observed in the northern region (Fig. S3). Overall,

Table 2
Correlation between number of intercropped species and determinant of intercropping choice.

Continuous variables	Pearson correlation with number of intercropped species		P value (ANOVA)
Drought index	-0.41		$p < 0.001$*
Plot size	-0.16		$P < 0.05$*
Changes in NDVI	-0.32		$P < 0.001$*
Categorical variables		**Average number of intercrops**	**P value (TUKEY)**
Soil erosion level	No Erosion	1.484	$P < 0.001$*
	Low, middle, high erosion level	1.642	
Changes in soil erosion level	Better	1.67	$p > 0.1$
	Same	1.62	
	Worse	1.53	

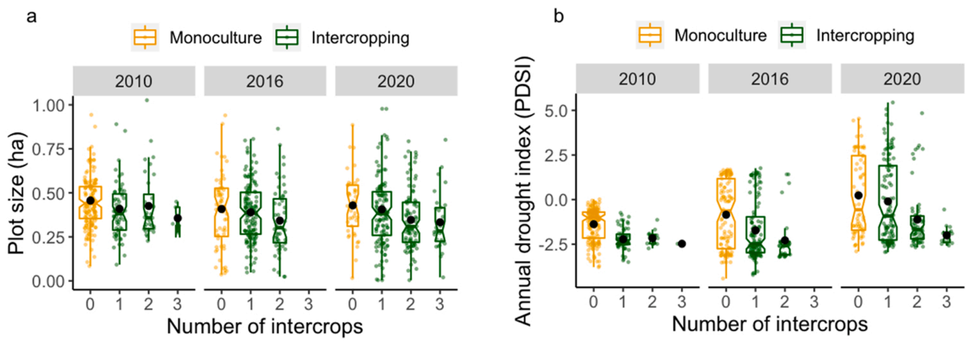

Fig. 3. Plot size and drought index comparing maize monoculture and intercropped maize fields with varying levels of crop diversity (number of intercropped species). (a) Plot size and the number of intercropped species at the traditional authority administrative level (263 units) aggregated from approximately 20,000 surveys (IHS) across Malawi for three years (2010, 2016, 2020); (b) average PDSI derived from the gridded meteorological dataset at the 4 km spatial resolution and the number of intercropped species at the traditional authority administrative level across Malawi for the three years (2010, 2016, 2020). Black dots indicate mean values; the box extents represent the range from 25th to 75th percentile; the whiskers extend to 1.5 * the Interquartile range (IQR) (the box); notches (1.58* IQR / sqrt(n)) of different groups were also shown; bar width indicates the relative proportion of each group.

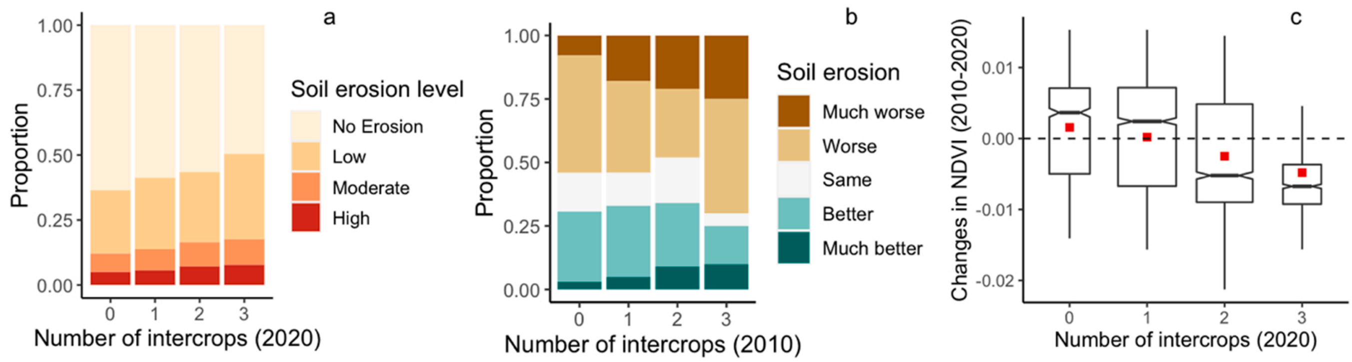

Fig. 4. Soil erosion level and changes in cropland productivity comparing monoculture and intercropped maize fields with varying levels of crop diversity (number of intercropped species). a) Proportion of soil erosion in monoculture and intercropped fields calculated from 6163 surveys (IHS) in 2020; b) changes in soil erosion level from 2005 to 2010 in monoculture and intercropped fields according to available 647 surveys (IHS) on farmers' perception; c) changes in cropland productivity in monoculture and intercropped fields calculated at administrative level of traditional authority, cropland productivity was represented by slope values of linear regression of seasonal (November - April) mean NDVI (MODIS satellite data) in 2010–2020, and the number of intercropped species were calculated at the administrative level cross Malawi for 2020. Red dots indicate mean values; the box extents represent ranges from 25th to 75th percentile; the whiskers extend to 1.5 * the Interquartile range (IQR) (the box); notches (1.58 * IQR / sqrt(n)) of different groups were also shown; bar width indicates the relative proportion of each group.

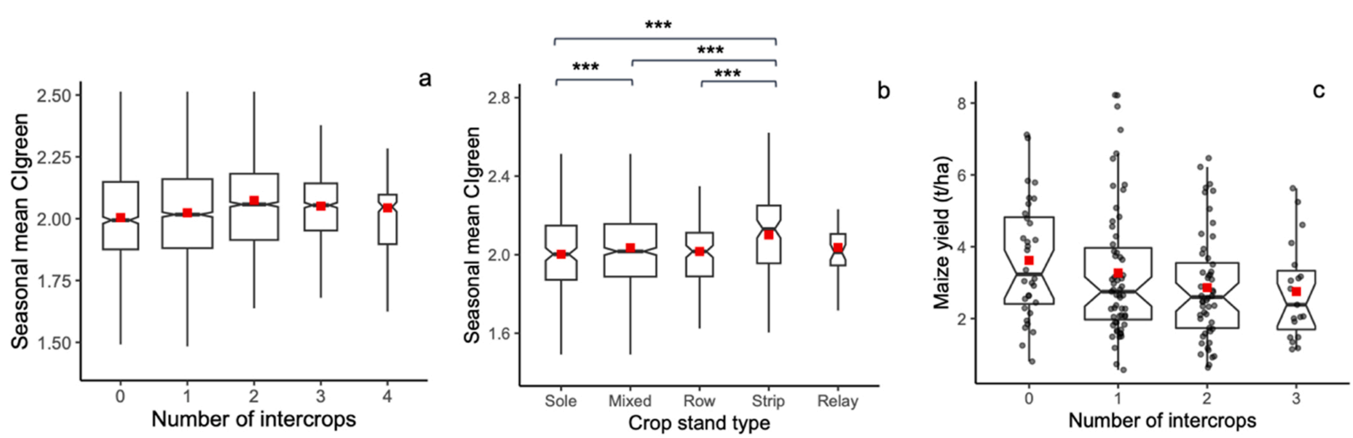

Fig. 5. Yield difference comparing monoculture and intercropped fields with varying crop dstand type. Whole field yield (use satellite data of green chlorophyll vegetation index as a proxy) in monoculture and intercropped maize fields with (a) varying level of crop diversity (number of intercropped species) and (b) different stand types for year 2020. The number of intercropped species and crop stand type were retrieved from 6163 household surveys, *** indicates that the difference between two groups is significant; (c) maize yield difference in monoculture and intercropped maize fields measured from 161 field plots in Southern Malawi in 2020. Red dots indicate mean values; the box extents represent the range from 25th to 75th percentile; the whiskers extend to 1.5* the interquartile range (IQR) (the box); notches (1.58* IQR / sqrt(n)) of different groups were also shown; bar width indicates the relative proportion of each group.

our results suggest that intercropping may be more prevalent in degraded cropland, as long-term persistent decline of NDVI is correlated with cropland degradation (Barbier and Hochard, 2018).

3.3. Yield response and inputs (agrochemical and labor)

Our findings showed that Sentinel-2 measures of vegetation indices provide a moderate accuracy in estimating field yield for monoculture maize fields (Fig. S4 and Table S2). The green chlorophyll vegetation index, calculated from seasonal mean, outperformed NDVI in estimating field yield ($R^2 = 0.64$, nRMSE = 21.7 %) and was therefore used as a proxy for overall field yield in maize-dominated intercropped fields in Malawi.

Although satellite data showed a slightly higher field yield in intercropped fields compared to monoculture fields (Fig. 5a), the potential gain in yield was weak, with a Pearson correlation coefficient of 0.1 (Table 3). Our analysis further revealed that the greatest overall field yield gain occurred in fields with a strip intercropping pattern, followed by relay fields (Fig. 5b). In contrast, mixed fields exhibited a lower potential for yield gain compared to the strip stand type. As intercropped fields allocate less land for primary crop (maize) production, average maize yield decreased with an increased number of intercropped species (Fig. 5c), and this decline was significant between monoculture and intercropped fields (Table 3). Specifically, our field data from Southern Malawi showed that maize yield (2.7 t/ha) was lower in intercropped fields compared to pure maize yield (3.8 t/ha) in 2020 (Fig. 5c).

We also observed a positive correlation between increased overall field yield in intercropped fields and higher labor inputs: fields with more intercrops consistently required more labor inputs in 2010, 2016, and 2020 (Fig. 6a, Table 3). On average, labor inputs were 487 h per season in monoculture fields, which increased to 498 h per season in intercropped fields. Additionally, our analysis showed that increased weeding times were necessary in more intercropped fields compared to pure maize fields at the national scale (Fig. 7b, Table 3).

We did not observe a significant difference in fertilizer application between monoculture and intercropped fields at the national scale. On average, farmers applied 307.8 kg/ha (including both organic and inorganic fertilizers) in monoculture maize fields, while slightly more fertilizer (308.2 kg/ha) was applied in intercropped fields, according to the combined three-year household surveys dataset (2010, 2016 and 2020) (Fig. 7a, Table 3). The amount of fertilizer applied varied across years; in 2010, the same amount of fertilizer was applied in monoculture and intercropped maize fields, while in 2016, farmers applied an average of 42 kg/ha more fertilizer in intercropped fields, and in 2020, they applied 13 kg/ha less in intercropped fields compared to monoculture fields (Fig. 7a).

Our findings suggest that pesticide application rates are not necessarily lower in intercropped fields, with a similar proportion of households applying pesticides in intercropped (2.41 % of 5489 households) and monoculture fields (2.4 % of 4751 households) (Fig. 7b, Table 3). Although the use of pesticides increased in 2020 (5 % of 6477 households) (Fig. 7b), many smallholder farmers in Malawi have limited access to pesticides. For example, in 2010 and 2016, only 0.7 % and 1.2 % of households, respectively, reported accessing pesticides among the surveyed households of 7052 and 6175. We have summarized the main findings on the determinants of intercropping choice, input use, and yield response in Fig. 8.

Table 3
Correlation between number of intercropped species and yields, inputs (agrochemical and labor).

Continuous variables	Pearson correlation with number of intercrops		P value (ANOVA)
Overall field yield (proxy from satellite data)	0.1		$p < 0.001$*
Mazie yield	-0.18		$P < 0.05$*
Labor inputs	0.02		$p < 0.05$*
Weeding times	0.04		$P < 0.001$*
Total fertilizer inputs	0.003		$P = 0.8$
Categorical variables		**Average number of intercropped species**	**P value (ANOVA)**
Pesticide application	Yes	1.45	0.0016*
	No	1.31	

4. Discussion

4.1. Widespread intercropping and its management in Malawi

In this study, we examined the yield performance of intercropping in smallholder farms across Malawi and assessed the factors that determine its adoption. Our findings suggest that farmers' intercropping choices are associated with plot size, climate conditions, and soil quality (Table 2). We observed that smallholder farmers use intercropping as a means of maximizing land use efficiency and mitigating the negative impacts of adverse climatic conditions and soil degradation. We found a positive correlation between intercropping and smaller field sizes (Fig. 3a), higher drought severity (Fig. 3b), and greater soil erosion and reduced productivity (Fig. 4), although these correlations do not necessarily indicate causality, and regional differences also suggest other factors are at play (Fig. S3). A possible interpretation is that population growth results in reduced field sizes and an increased number of land-constrained households that are more economically disadvantaged. Such households may tend to intercrop to maximize returns from land on small farms (Silberg et al., 2017; Sirrine et al., 2010; Waldman et al., 2016). As such, it has been shown that field size and total land holdings have been determinants of smallholder cropping decisions (Marenya and Barrett, 2007). In addition, existing studies have stated that intercropping practices also be adopted to reduce the risk of climatic shocks such as drought or dry spells and become an important climate-change adaptation strategy for ever-drier regions of the world (Pittelkow et al., 2015). Similarly, studies in Malawi have found that intercropping practices have been adopted as a way to mitigate deteriorating soil erosion levels through legumes filling the gap between maize plants and reducing the adverse impacts of raindrops (Stefani et al., 2020; Zougmore et al., 2000).

The widespread adoption of intercropping practices among farmers indicates their awareness and recognition of the benefits of intercropping, particularly in mitigating the effects of climate change and soil degradation. However, farmers often fail to plan and arrange crops spatially, which can limit their efficiency in achieving optimal yields. Our findings suggest that fields with randomly mixed crop patterns have lower yield potential (Fig. 5b) compared to those with strip and relay stand types. Previous research has also shown that spatially arranged strip intercrops are more effective in achieving yield gain (Yin et al., 2020) and offer significantly greater benefits than fully mixed intercrops (Li et al., 2020). However, we found that only a limited number of households (15 %) have adopted strip and relay intercropping practices in Malawi, indicating a need for improved intercrop management among smallholder farmers.

4.2. Yield response with high labor inputs

This study aimed to compare yield performance between monoculture and intercropping systems by measuring both maize yield and overall field yield (yield of maize and all intercrops combined). To estimate overall field yield in intercropped fields, we used the green chlorophyll index from satellite data as a proxy. We found that using the chlorophyll vegetation index to estimate overall field yield in intercropped fields is feasible, with good accuracy ($R^2 = 0.64$, nRMSE = 21.7 %) when field-measured maize yield from 32 monoculture maize fields.

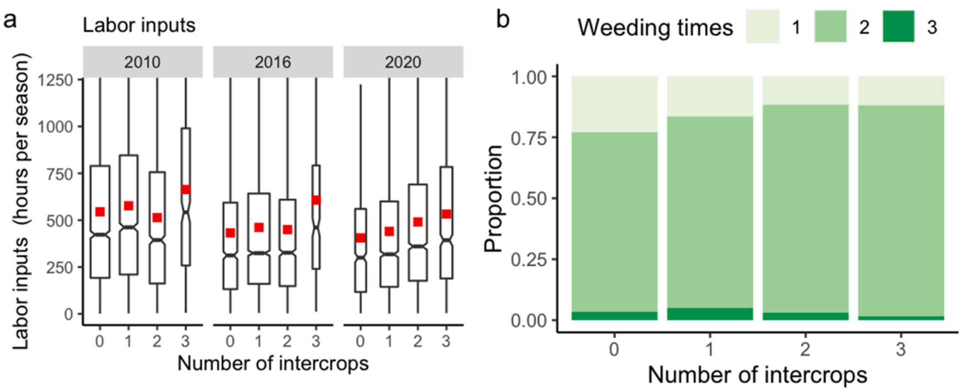

Fig. 6. Labor inputs and weeding times difference comparing monoculture and intercropped maize fields with varying level of crop diversity (number of intercropped species). (a) Labor input difference in 2010, 2016, and 2020 based on approximately 20,000 surveys (IHS) across the whole of Malawi; (b) proportion of weeding time for monoculture and intercropped fields based on 6166 surveys in 2016 and 2020 across the whole of Malawi. The red dots in (a) indicate mean values; the box extents represent the range from 25th to 75th percentile; the whiskers extend to 1.5 * the Interquartile range (IQR) (the box); notches (1.58* IQR / sqrt(n)) of different groups were also shown; bar width indicates the relative proportion of each group.

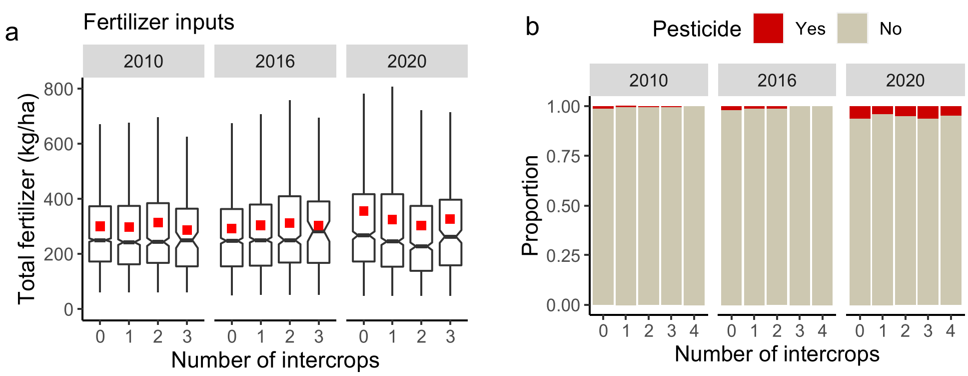

Fig. 7. Fertilizer and pesticide inputs in monoculture and intercropped maize fields with varying level of crop diversity (number of intercropped species). Fertilizer inputs (a) and pesticide application proportion (b) for 2010, 2016 and 2020 at the national scale based on 9962 surveys. The red squares in (a) indicate mean values; the box extents represent range from 25th to 75th percentile; the whiskers extend to 1.5* the Interquartile range (IQR) (the box); The black dots in (a) indicate mean values; the box extents represent the range from 25th to 75th percentile; the whiskers extend to 1.5* the Interquartile range (IQR) (the box); notches (1.58* IQR / sqrt(n)) of different groups visually show the difference of the medians of distributions and if the notches do not overlap, this is evidence that the medians are different; bar width indicates the relative proportion of each group.

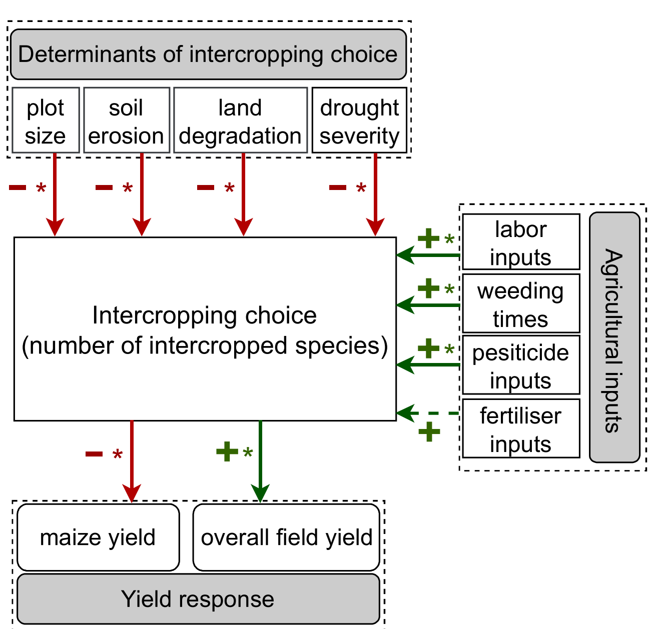

Fig. 8. Diagram showing correlation between number of intercropped species and its determinants, yield response and agricultural inputs. Green lines represent positive correlations while red lines represent negative relationships. * indicates significant differences between intercropped fields and monoculture fields, while dashed lines indicate insignificance in differences (Tukey's or ANOVA P > 0.05).

This result gives us good confidence that seasonal mean values of green chlorophyll vegetation index could be used as a proxy of overall field yield in intercropped fields including both maize and intercrops. Because the use of seasonal mean vegetation index from November to April can capture greenness information from intercrops towards the end of March and early April, when maize reaches harvesting stage and intercrops dominate field greenness, as demonstrated by our field photo (Fig. 1c). However, this method also has limitations, including cloud coverage and contributions from photosynthetically active weed biomass (Rudorff and Batista, 1990), as well as difficulties in differentiating intercrops and maize in small plots. In any case, we found a weak positive correlation (Pearson correlation: 0.1) between yield and number of intercropped species when using satellite data as a proxy of overall field yield. This finding is consistent with previous studies (Beillouin et al., 2019; Li et al., 2020; Martin-Guay et al., 2018) which showed that intercropping generally leads to yield gains. However, our field crop-cutting measurements in southern Malawi revealed that this yield gain comes at the expense of the primary crop (maize) yield.

Although improved overall field yield in intercropping fields have the potential to provide a protein-rich food source from legume plants (Place et al., 2003), our findings showed a reduction in maize yield, which indicates limited benefits for household staple food availability as maize is the primary staple food. While previous studies found that legume intercrops in maize fields can provide additional yield benefits without negatively affecting maize (Waddington et al., 2007) and can even maintain or enhance maize yields (Gwenambira-Mwika et al., 2021) through improved soil fertility and biological nitrogen fixation (Giller and Cadisch, 1995; Gwenambira-Mwika et al., 2021; Rusinamhodzi et al., 2012). Our study argues that intercropping has limited benefits in terms of yield gain for smallholder fields, as also stated in other studies (Ngwira et al., 2012; Thierfelder et al., 2012; Zhang et al., 2016), particularly compared to other types of crop diversification such as crop rotation, which provided more pronounced yield benefits (Christian and Blessing, 2022; Gwenambira-Mwika et al., 2021). Therefore, we suggest that more evidence on the benefits and best practices of intercropping is needed for smallholder farmers to better recognizing its opportunities for the sustainable intensification, given that farmers tend to prioritize short-term yield gains over longer-term sustainability (Christian and Blessing, 2022). Our results support the argument that sustainable intensification options such as crop diversification are generally promoted with little regard to context and support for smallholder farmers, making it difficult to attain the proclaimed benefits (Chinseu et al., 2022; Giller et al., 2021).

4.3. Limited environmental benefits

Our study revealed that agrochemical inputs (pesticide and fertilizer) were not necessarily reduced in intercropped fields compared to monoculture fields. This suggests that the environmental benefits of reduced usage of agrochemical inputs are not clear in intercropped fields managed by smallholder farmers. While previous research showed that smallholder farmers apply more fertilizer to their intercropped fields relative to their maize-only fields (Silberg et al., 2017), our data indicate that this difference is not significant in smallholder fields at the national scale. In addition, intercropping has been observed (Tilman, 2020) to reduce disease incidence, our results show that pesticide application is not necessarily reduced in smallholder intercropped fields. However, since only a few households applied pesticides in both intercropped and pure maize fields (Fig. 7b), the benefits of reducing pesticide use are not clear from this study. Moreover, our study demonstrated that weeding times increased in intercropped fields. This correlation may have two possible explanations: first, the effectiveness of intercropping practices in reducing weed populations may not be clear in real smallholder fields in Malawi, which differs from experimental trial results that demonstrated the effectiveness of intercropping practices in suppressing weeds (Li et al., 2020; Stefani et al., 2020; Stoltz and Nadeau, 2014). Second, farmers may plant more intercrops on fields with weed problems to help reduce weeds. Regardless of the reason, increased weeding time is associated with increased labor inputs, indicating that intercropped fields require more complicated management strategies.

We argue that the limited benefits of intercropping practices in fields managed by smallholder farmers may be attributed to inadequate management strategies. The implementation of intercropping management practices requires specialized knowledge (Silberg et al., 2017), which can be challenging for smallholders in sub-Saharan African countries, particularly in the face of climate change and land degradation. Previous studies have shown that yields may be significantly reduced under suboptimal component plant densities and layouts in intercropped fields (Rusinamhodzi et al., 2012; Yin et al., 2020). Therefore, we posit that the observed limited benefits of intercropping in smallholder fields in Malawi may be related to management practices (e.g. farmers using spatially mixed intercropping patterns without any specific arrangement). However, field experimental trials were well managed by agronomy researchers with sufficient knowledge of crop collocation, manure/fertilizer application rates, and application timing (Silberg et al., 2017), therefore enabling the maximum benefits of intercropping. In any case, our study highlights the need for smallholder farmers to adopt better management practices to realize the potential benefits of intercropping practices. Increased research is required to examine detailed performance differences in intercropping practice and to identify key management drivers that explain performance, which would help to better advancing the sustainable intensification of agriculture in sub-Saharan Africa.

Using multi-source datasets of field measurements, survey data, and satellite data, our study provides a framework for assessing intercropping practices in smallholder fields over a large region, finding limited yield gains and environmental benefits. However, it is important to note that the yield response and inputs of intercropping may vary at the local scale, and further research is needed to investigate the performance of intercropping practices in other smallholder fields in sub-Saharan Africa beyond Malawi.

5. Conclusion

Although field trials have shown clear benefits of intercropping practices, our study revealed that these benefits are not apparent in real-world smallholder farming fields in Malawi, based on evidence from field data, household survey data, and satellite data. Due to limited inputs in technology, infrastructure, extension services, and the adverse effects of climate change across sub-Saharan African countries, we speculate that similar limited benefits of intercropping may be observed outside of Malawi, but this assumption requires further investigation. Our findings suggest that despite 80 % of maize smallholder farmers applying intercropping practices, they did not observe noticeable benefits. Therefore, more evidence on the benefits and best practices of adopting intercropping practices for smallholder fields is needed.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2023.108974.

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