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Climate change impacts on crop yields across Madagascar and household-informed adaptation strategies

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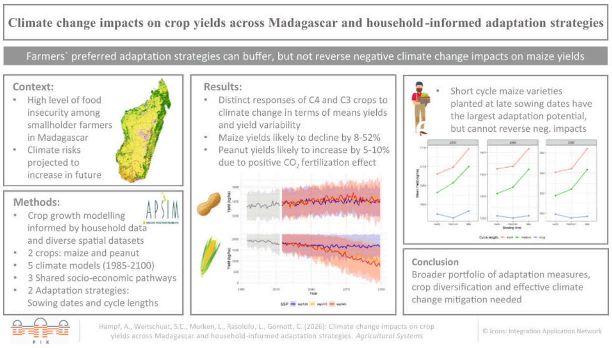
HIGHLIGHTS

- Primary household data was used to inform crop management and adaptation strategies.
- Maize yields are projected to decrease by 8–52%, depending on SSP and period.
- Peanut yields are likely to increase by 5–10%, driven by CO_2 fertilization effect.
- Late-sown short-cycle maize cultivars show the greatest adaptation potential.
- Adaptation strategies can buffer but no reverse negative CC impacts on maize yields.

GRAPHICAL ABSTRACT



Climate change impacts on crop yields across Madagascar and household-informed adaptation strategies

Farmers` preferred adaptation strategies can buffer, but not reverse negative climate change impacts on maize yields

Context:
- High level of food insecurity among smallholder farmers in Madagascar
- Climate risks projected to increase in future

Methods:
- Crop growth modelling informed by household data and diverse spatial datasets
- 2 crops: maize and peanut
- 5 climate models (1985-2100)
- 3 Shared socio-economic pathways
- 2 Adaptation strategies: Sowing dates and cycle lengths

Results:
- Distinct responses of C4 and C3 crops to climate change in terms of means yields and yield variability
- Maize yields likely to decline by 8-52%
- Peanut yields likely to increase by 5-10% due to positive CO_2 fertilization effect

- Short cycle maize varieties planted at late sowing dates have the largest adaptation potential, but cannot reverse neg. impacts

Conclusion
Broader portfolio of adaptation measures, crop diversification and effective climate change mitigation needed

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ABSTRACT

Context: Madagascar is one of the most food-insecure countries globally, with 40% of the population undernourished and 90% unable to afford a healthy diet. Smallholder farmers rely primarily on low-yielding, rainfed subsistence farming and are highly vulnerable to climate change due to their dependence on seasonal rainfall and limited adaptive capacity.

Objective: The objective of this study was to quantify climate change impacts on maize and peanut yields across Madagascar and to evaluate the effectiveness of low-cost adaptation strategies informed by household survey data.

Methods: Crop simulations were conducted with the Agricultural Production Systems Simulator (APSIM) for a historical baseline and future periods up to 2100 under three socio-economic pathways (SSP1–2.6, SSP3–7.0, SSP5–8.5). High-resolution climate projections (CMIP6/ISIMIP3b), diverse spatial datasets and household survey data from 624 farmers informed the modelling framework and guided the selection of adaptation strategies. For maize, the adaptation potential of different sowing dates and crop cultivars was tested; for peanut, the CO_2 fertilization effect was isolated by comparing increasing versus constant atmospheric [CO_2].

Results and Conclusion: Madagascar is projected to undergo substantial warming during the main cropping season, accompanied by shifts in rainfall patterns. Maize yields are likely to decline by −8% to −52%, with losses

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intensifying under higher emissions and later periods. In contrast, peanut yields are projected to increase by +5% to +10%, primarily due to the CO_2 fertilization effect; without it, yields would decline, highlighting the severity of future climatic stress. Moreover, yield variability is projected to increase for maize but remain stable for peanut. Among adaptation strategies, short-cycle cultivars sown late performed best for maize under future climates, yet no tested combination could reverse negative yield impacts. Our findings underscore the distinct responses of C_4 and C_3 crops to climate change and the growing risks for food security, given farmers' limited coping mechanisms.

Significance: This study provides the first national-scale assessment of climate change impacts on maize and peanut in Madagascar. It demonstrates the added value of combining household survey data with process-based crop models and emphasizes that that a broader portfolio of accessible and effective adaptation measures is needed to sustain smallholder livelihoods under climate change.

1. Introduction

Madagascar ranks among the most food-insecure countries globally, with 40% of its population undernourished and 90% unable to afford a healthy diet (FAO et al., 2024). The majority of the population relies on agriculture for their livelihood, predominantly practicing rainfed subsistence farming with low yields. This high dependence on agriculture, physical isolation and lack of access to safety nets, leaves Malagasy farmers highly vulnerable to any climatic and economic shocks (Harvey et al., 2014; World Bank, 2024). Between 2019 and 2024, this vulnerability became particularly evident in South Madagascar (Grand Sud), where prolonged below-average rainfall triggered one of the worst droughts in the country's history (Harrington et al., 2022). Drought-induced crop and livestock losses, paired with the restrictions of the Covid-19 pandemic and pest infestations, resulted in acute food insecurity (IPC Level 3 or above) for over a million people in the region (IPC, 2021).

Climate projections from the Intergovernmental Panel on Climate Change (IPCC) indicate that crop production in Madagascar is likely to face increasing challenges under future climate conditions (Masson-Delmotte et al., 2021; Tadross et al., 2008). For instance, the projected shortening of the rainy season in large parts of the country could hinder growing rice crops twice a year (Randriamarolaza and Aguilar, 2023). Key climate risks include more frequent and prolonged droughts, shorter rainy seasons, intensified cyclones, rising temperatures as well as heavy precipitation and pluvial flooding (Masson-Delmotte et al., 2021; Tadross et al., 2008). In the Grand Sud, a significant rise in drought frequency per decade is projected from mid-century onward, posing a severe threat to crop production and food security in the region (Rabezanahary Tanteliniaina and Andrianarimanana, 2024).

Adapting farming systems to these changing climate conditions is urgently needed to keep or even increase the current production level. This requires identifying adaptation strategies that not only effectively reduce the adverse impacts of climate change but are also practicable and affordable for smallholder farmers with limited resources. The overall objective of this study was to identify such adaptation strategies by incorporating primary household data from smallholder farmers in Southeast Madagascar into a process-based crop modelling framework. The specific objectives of the study were to

(i) Analyze projected changes in temperature and precipitation across Madagascar during the main cropping season;
(ii) Make use of primary household survey data from 624 smallholder farmers to inform crop management practices and adaptation strategies;
(iii) Simulate climate change impacts on maize and peanut yields and yield variability across Madagascar using diverse spatial datasets and high-resolution climate data for three shared socio-economic pathways;
(iv) Evaluate the effectiveness of adaptation strategies, namely modified sowing dates and varieties of different cycle lengths, in buffering adverse climate impacts.

Household survey data collected from more than 600 households in three southern regions was used to complement information on crop management practices and to align our modelling exercise with the realities of smallholder farming systems. In addition, the survey provided insights into farmers' perceptions of climate risks, their current responses to weather extremes, and the types of adaptation measures they consider feasible within their local context. Maize (*Zea mays*) and peanut (*Arachis hypogaea*) were selected as focus crops for this study because they are among the ten most widely cultivated crops in the country by harvested area (SI-Fig. 1) and due to their particular relevance to smallholder farmers in Southern Madagascar (NITADAE and MINAE, 2023). Additionally, the two crops exhibit contrasting physiological responses to climate change: while carbon fixation in maize follows the so called C4 photosynthesis pathway, which makes efficient use of current atmospheric [CO_2] level, peanut converts carbon via the C_3 photosynthesis pathway, which is still limited by current CO_2 levels (Toreti et al., 2020; Vanuytrecht and Thorburn, 2017). As a result, C3 crops are generally expected to benefit more from rising CO_2 concentrations than C4 crops.

This study was motivated by a substantial research gap in climate impact assessments and adaptation strategies for Madagascar's agricultural sector. To date, only a limited number of crop modelling studies have been conducted for the country. For instance, Vololona et al. (2013) projected an overall decline in maize yields across Madagascar by 2050 compared to 2000, with some localized yield increases, using downscaled climate data under the A1B scenario. More recently, Tomalka et al. (2020) reported results for Madagascar of the global LPJmL model (Schaphoff et al., 2018) and ISIMIP2b (Frieler et al., 2017) climate projections to estimate a slight national-scale decline in maize yields by 2080 relative to 2000. Yields of C_3 crops, such as sugarcane and rice, on the other hand, remain stable or slightly increase, depending on the selected representative concentration pathway (RCP) shown by Tomalka et al. (2020). However, this study reports results from a global analysis, offering limited insights into sub-regional yield variability. Furthermore, neither study integrated insights from household data into the model set-up nor addressed potential adaptation strategies, leaving a critical gap in understanding how smallholder farmers might respond to future climatic challenges.

2. Methods and materials

2.1. Study area

Madagascar covers an area of approximately 587,000 km^2, of which 56% is grassland, 23% forest, 12% shrubland, and 6% annual cropland (Zanaga et al., 2022, Fig. 1 a). The island's main crops in terms of harvested area are rice, maize, cassava, sweet potato, coffee and peanut (FAO, 2025; SI-Fig. 1), while vanilla and cloves are important export products (Garruchet et al., 2023). Maize and peanut are cultivated across the entire country, with production hotspots in the regions of Atsimo-Andrefana and Vakinankaratra (INSTAT, 2009, 2012, SI-Fig-2). While maize production almost halved from 450,000 tons in 2012 to 225,000 tons in 2020 following a severe locust invasion, peanut production increased steadily—primarily due to cropland expansion driven by rising export demand from Asian markets—reaching nearly 60,000 tons in 2023 (FAO, 2016, 2025). Despite their importance for both human consumption and livestock feed (NITADAE and MINAE, 2023), average maize and peanut yields remain low, achieving only 1.81 t/ha and 0.89 t/ha, respectively, in 2023 (FAO, 2025).

The island exhibits diverse climatic conditions, from humid tropical zones in the east to semi-arid areas in the southwest, with a pronounced rainfall gradient from over 3500 mm annually in the northeast to as little as 400 mm in the south (Randriatsara et al., 2022). The primary rainy season, lasting from November to April, aligns with the main growing period for most annual crops (Randriamarolaza and Aguilar, 2023). Madagascar's dominant soil types are ferralsols, cambisols, and luvisols, which cover 29%, 14%, and 10% of the country, respectively (Poggio et al., 2021). One important constraint to crop production is the generally low fertility of these soils and their high phosphorus retention potential by oxide minerals (Batjes, 2011).

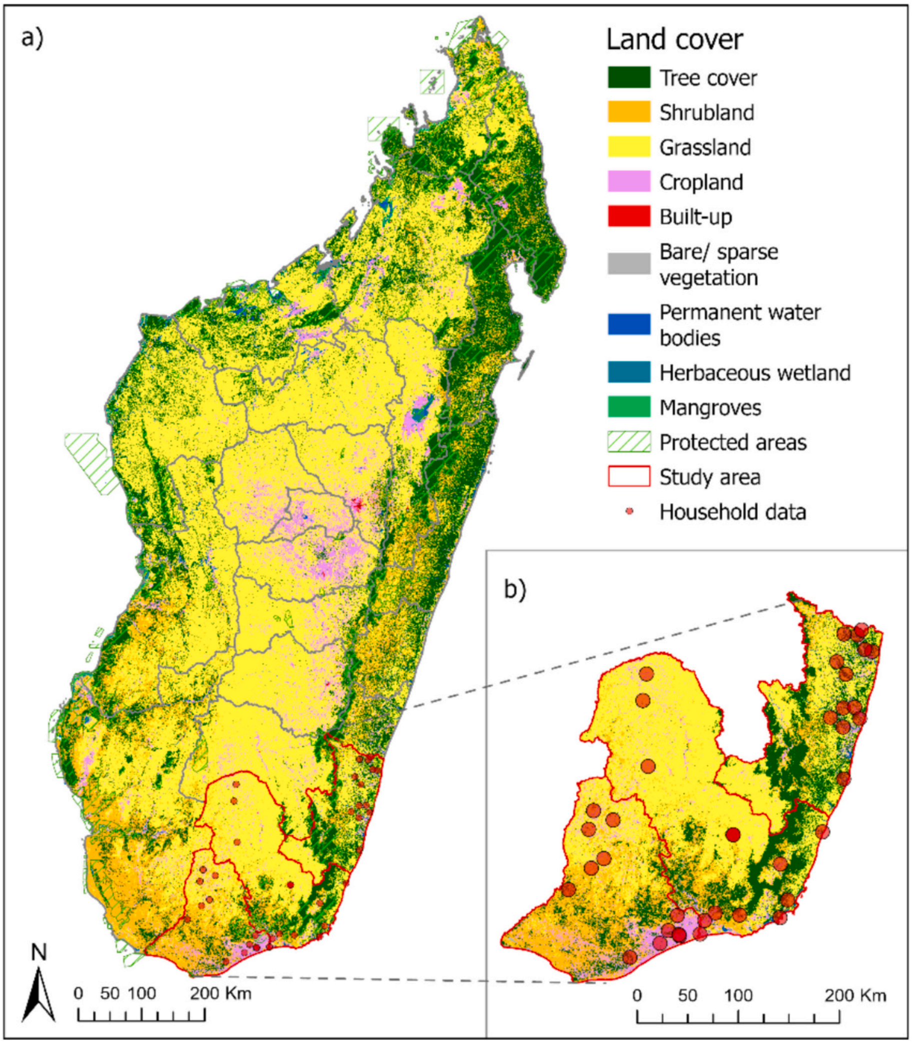

Fig. 1. *(a)* Location of Madagascar and its major land cover types. *(b)* Locations of villages (fokontany) where household data was collected during 2023–2024. Land cover data source: ESA WorldCover 10 m 2021, v 200 (Zanaga et al., 2022).

2.2. Household data

Household survey data were used to capture smallholder farmers' preferences regarding adaptation strategies and to complement information on crop management where such data were not available at the national scale. Although the survey is not representative of the entire country, it helped align the modelling exercise with the realities of Malagasy smallholder farming systems. The survey was conducted in May/June 2023 with a representative sample of 624 smallholder farmers across 39 fokontany in three regions (Androy, Anosy, Atsimo-Atsinanana; Fig. 1b). The household sampling procedure is described in detail in the Supplementary Information (SI-Text 1).

Nearly half of the surveyed farmers (48%) reported growing maize, peanuts, or both, pointing to the high relevance of these crops in Madagascar's Southeast. The survey revealed that the use of mineral fertilizers is very limited (1%). However, 73% of the surveyed farmers reported to also keep livestock, indicating that manure may serve as an important alternative nutrient source for sustaining crop production. All farmers practice rainfed agriculture, highlighting their dependence on seasonal rainfall. Planting and harvesting schedules reflect this reliance: 76% of maize farmers sow in October/November at the onset of the rainy season and harvest between February and April, while 74% of peanut farmers plant in November/December and harvest from March to May. The majority of maize and peanut farmers rely on traditional seeds without specific selection (64% and 53%, respectively), while the remainder largely uses some form of improved seeds,[1] highlighting both potentials but also limitations to the adoption of improved seeds.

The survey further provided insights into farmers' experiences with and responses to climate risks, which helped to identify plausible bottom-up adaptation strategiess (see Fig. 2). A large majority of maize and peanut farmers (86%) reported to have experienced a weather shock in the 12 months prior to the survey, mainly drought (75%), poor rainfall (55%), and cyclones (18%). In addition, 94% perceived changes in weather patterns over the past five years compared with 10–20 years ago. Despite these challenges, only 25% had adopted adaptive measures, with financial constraints (60%) and lack of knowledge (45%) cited as the main barriers. Among those who did adapt, the most common strategies were off-farm employment (62%), adjustments in agricultural practices (14%), and increased savings (14%).

Looking ahead, about half of the respondents expressed interest in adopting or intensifying adaptation measures in future. Their preferred strategies include modifying agricultural practices (32%) and pursuing off-farm employment (31%). Out of those who would like to change their agricultural practices, the most popular options in order of importance are: changing the crop variety, changing to a different crop, implementing soil improvement techniques, and changing planting and harvesting dates.

2.3. Crop growth model

Crop yields were simulated with APSIM next generation (APSIM, version 2025.2.7670.0), a process-based crop model that simulates the growth and development of various crop species in response to management under diverse environmental conditions (Holzworth et al., 2014, 2018). It has been widely used and tested in various studies, including those of the Agricultural Model Intercomparison and Improvement Project (Asseng et al., 2013; Basso et al., 2014; Müller et al., 2017). Among various available process-based crop models, we decided to use APSIM, given its capability to simulate farming systems in tropical environments and in representing farming practices of smallholder systems. We used the maize module further described in Soufizadeh et al. (2018) and the peanut plant module developed by Robertson et al. (2002).

2.4. Model calibration and evaluation

The following sections describe the field experimental datasets used for model calibration, the calibration procedure, and the subsequent model evaluation using independent datasets at regional and national scales.

2.4.1. Field experimental data

APSIM was calibrated to local field conditions using data from field experiments provided by the National Center for Applied Research in Rural Development (FOFIFA). Maize field trial data were obtained from experiments conducted at a research station and on farmers' fields in Andranomanelatra (19°47′S, 47°06′E; 1640 m elevation.), located in the Vakinankaratra region. The experiments were carried out over three consecutive growing seasons (2013/14–2015/16) to assess the effects of conservation agriculture and improved manure management in rice–maize systems (Rasolofo et al., 2018). The local early-maturing maize variety Tombontsoa (vegetative cycle <90 days), which is widely cultivated in southern Madagascar, was used throughout. Recorded data include sowing and harvest dates, as well as grain and straw yields at maturity, across four fertilization regimes and two crop management practices (conservation and conventional), resulting in a total of 96 observations for each variable. For model calibration, only data obtained under conventional management were used. Weather data were recorded on-site by a dedicated weather station (SI-Fig. 3).

The second field experiment, aimed at assessing peanut growth and yield, was conducted at the CPSA seed production center (25°01.8′S, 46°21.6′E; 80 m elevation) in the Anosy region of southeastern Madagascar (Rabenjanahary, 2022). The trial evaluated three peanut varieties (*Boha*, *Kanety* and *Fleur 11*) under varying management regimes, including irrigation and was carried out over three consecutive cropping seasons (2018/19 to 2020/21). Recorded data included phenological stages, leaf area index, and pod yield. For the purpose of this study, only observations for the cultivar *Kanety* were used, a traditional cultivar with a medium cycle length of 90–120 days. Due to the absence of data from a weather station at field experimental site, we used data from ERA5 (SI-Fig. 4), a reanalysis dataset providing global weather records with a spatial resolution of 0.25° (Hersbach et al., 2023).

Soil data for both field experiments were sourced from the ISRIC database to ensure consistency with the soil input used in the gridded crop growth simulations. A table with the most relevant soil physical and chemical properties at each site is provided in the Supplementary Information (SI-Table 2 and SI-Table 3).

2.4.2. Calibration procedure

Model calibration followed the soil–crop model calibration protocol proposed by Wallach et al. (2024) and was implemented in R, using, among others, the *apsimx* package (Miguez, 2024). Calibration was conducted sequentially by first optimizing parameters related to phenology (e.g. thermal time requirements for different developmental phases), followed by parameters controlling biomass accumulation (e.g. radiation use efficiency, RUE), and finally those related to yield formation (e.g. grain number and grain size). Default cultivar parameters were taken from the *mwi_local* cultivar for maize and *VB97* for peanut, as preliminary simulations indicated that these provided the closest agreement with the target cultivars in terms of cycle length and yield. The optimisation algorithm used was the gradient-based L-BFGS-B method and parameter bounds were set to ±25% of the default values. The cultivar parameters adjusted during the calibration procedure, together with their default and optimized values, are listed in the Supplementary Information (SI-Table 4 and 5).

2.4.3. Model evaluation

While model calibration relied on field experimental data, model evaluation was conducted at broader spatial scales to evaluate the model's ability to reproduce temporal and spatial yield variability across Madagascar. Following calibration, gridded crop growth simulations were conducted using the optimized cultivar parameters and the input data described below. Subsequently, the outputs of the baseline gridded simulations were aggregated to regional and national levels and compared with independent yield datasets. The model's ability to capture temporal yield trends was assessed using annual FAO yield records for the baseline period from 1985 to 2014 (FAO, 2025). To isolate interannual variability, yield anomalies were calculated by subtracting a 5-year moving average from each annual value, following the approach of Müller et al. (2017). Spatial validation was conducted by aggregating simulated yields to the subnational level (23 regions) and comparing them with reported yields from the HarvestStat dataset, available for the period 1990–2010 (Lee et al., 2025). Prior to computing performance metrics, simulated and reported yields were standardized using z-score

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[1] This relatively high share of farmers who report using some form of improved seeds was recorded in April 2023. We collected follow-up data over the course of 2023/2024 from the same households and found much lower instances of improved seeds use in subsequent interviews/plantings. A potential explanation for the relatively wide-spread use of improved seeds in April 2023 may be a seed distribution program in the previous year, with some development organizations focusing efforts on improved access to quality seeds in Madagascar. Observations from April 2023 may thus not indicate consistent high use of improved seeds. The measure of improved seeds reported above includes recycled seeds.

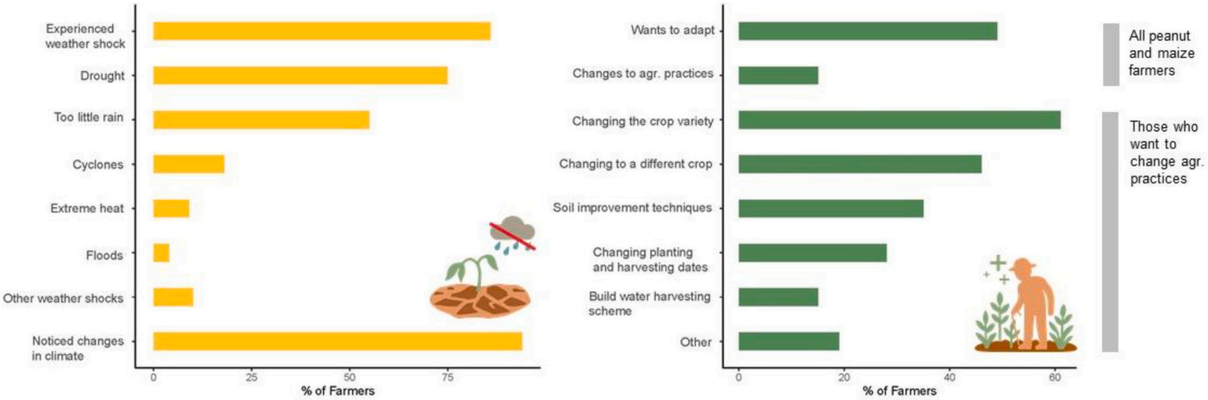

Fig. 2. Weather shock experience (a) and adaptation intentions (b) among surveyed smallholder maize and peanut producers in South-East Madagascar. Data source: AGRICA Madagascar baseline survey.

transformation. Model performance was quantified using Willmott's index of agreement (d).

2.5. *Input data for gridded simulations across Madagascar*

The following section outlines the input data used for running crop growth simulations for maize and peanut across Madagascar. Simulations were carried out on a grid level to capture spatial climate and soil variability across the country. The spatial resolution of the grid was 0.125° which corresponds to approximately 12.5 × 12.5 km near the equator. Simulations were carried out for a baseline period centered on the year 2000 (1985–2014) and for a future period (2015–2100). To facilitate the interpretation of climate change impacts, future outcomes were analyzed across three time horizons: the near-term (around 2030; 2015–2044), the mid-term (around 2060; 2045–2074), and the long-term (around 2090; 2075–2100). Crop growth simulations for the future were conducted under three Shared Socioeconomic Pathways (SSPs): SSP1–RCP2.6, SSP3–RCP7.0, and SSP5–RCP8.5, further referred to as SSP1–2.6, SSP3–7.0, and SSP5–8.5. These scenarios were selected to capture a broad range of plausible future conditions, spanning low-, medium-, and high-emission pathways and thereby enabling an assessment of crop responses under contrasting socio-economic trajectories and mitigation efforts.

2.5.1. *Climate data*

APSIM was run with climate data of simulation round 3b of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3b). ISIMIP3b provides bias-corrected CMIP6 climate forcing for historical, SSP1–2.6, SSP3–7.0, and SSP5–8.5 conditions (Frieler et al., 2025; Lange and Büchner, 2021). Five primary and five secondary climate models were selected to be part of the ISIMIP3b ensemble, as they were found to be a good representation of the whole CMIP6 ensemble in terms of climate sensitivity. A detailed description of the model selection process can be found in Lange (2021a). As part of the ISIMIP project, the simulations from these climate models have been bias-adjusted and downscaled to a spatial resolution of 0.5° × 0.5° using ISIMIP3BASD (Lange, 2019, 2021b).

However, the climate of Madagascar and in particular precipitation varies on smaller scales due to its complex topography. For the purpose of this study, the output of the five primary models (GFDL-ESM4, MPI-ESM1–2-HR, MRI-ESM2–0, UKESM1–0-LL, IPSL-CM6A-LR) was therefore further downscaled to a spatial resolution of 0.125° × 0.125° using the same ISIMIP downscaling method as described in Lange (2019, 2021b). The downscaling algorithm is a trend-preserving quantile mapping, which has been found to perform well in preserving spatial variability and extremes (ibid.). The high-resolution observational dataset used to perform the downscaling of the model simulations is CHELSA-W5E5 (Karger et al., 2023). In order to perform the downscaling, CHELSA-W5E5 was remapped from 1 km to 0.125° × 0.125° resolution using first-order conservative remapping.

Finally, the processed climate data were converted from netcdf into APSIM-compatible weather files (.met). One weather file was generated for each grid cell, containing daily records of precipitation (mm), maximum and minimum temperature (°C), solar radiation (MJ/m2/day) and atmospheric [CO_2] (ppm). For each SSP, we used the corresponding CO_2 concentrations, which increase at different rates over time depending on the scenario, as shown in the Supplementary Information (SI-Fig. 5).

2.5.2. *Soil data*

APSIM requires a detailed set of soil parameters to simulate crop growth and soil processes accurately. For this study, soil data were sourced from the International Soil Reference and Information Centre (ISRIC), which provides global gridded soil maps known as SoilGrids (Poggio et al., 2021). These maps include a wide range of soil properties (e.g. total nitrogen, soil organic carbon) and are derived from approximately 230,000 soil profile observations in the World Soil Information Service (WoSIS) database (Batjes et al., 2020, 2024). To prepare the soil data as an input to APSIM, we first identified the dominant soil type within each grid cell using a soil classification map based on the World Reference Base for Soil Resources (presented in the Supplementary Information as SI-Fig. 6). Then we extracted the soil properties for the dominant soil type in each grid cell using functions provided in the R package *apsimx* (Miguez, 2024).

2.5.3. *Cultivated land and protected areas*

Crop growth simulations were conducted only for grid cells where maize or peanut is currently cultivated and that lie outside protected areas. Cropland distribution was identified using the CropGrid dataset (Tang et al., 2024). To convert the continuous cropland fractions into a binary mask for the simulations, a crop was considered present in a grid cell if at least 0.1% of the cell area was under cultivation, thereby accounting for potential future cropland expansion. This threshold was selected as it provides a reasonable balance between retaining sufficient grid cells for a meaningful country-level assessments and excluding cells with only negligible crop presence. Applying this threshold resulted in 18.5% of grid cells being included in the maize simulations and 13% in the peanut simulations. Protected areas were excluded from the simulations under the assumption that they will not be converted to cropland. As of 2016, Madagascar's protected area network comprised 122 terrestrial sites covering 7.1 million hectares (Gardner et al., 2018). A map showing the grid cells included in the simulations is presented in the Supplementary Information (SI-Fig. 7).

2.5.4. *Sowing dates and cycle lengths*

The household survey revealed that farmers align their sowing dates with the onset of the rainy season. Given the substantial spatial variation in sowing and harvest dates across Madagascar and the fact that the survey was representative only for the southern regions, we complemented these insights with crop calendar data for the 2022–23 and 2023–24 (MINAE et al., 2024). The calendars contain sowing windows (start, mid and end date) for maize and peanut cultivars of different cycle lengths (short, medium, long) for Madagascar's 23 regions, resulting in a total of 207 cycle length × sowing dates combinations per crop. For this study, the calendars were digitized and spatially harmonized to match the extent and resolution of the simulation grid (presented in the Supplementary Information as SI-Fig. 8). In general, short-cycle varieties have a larger sowing window and can be sown later in the season as medium- and long-cycle varieties, whose drought sensitive development stages may coincide with the dry season if sown too late. Fig. 3 shows the length of the sowing window for maize and peanut cultivars of different cycle lengths.

2.5.5. *Fertilization and irrigation*

As evidenced by the household survey data and global gridded fertilization datasets (Coello et al., 2025), the use of mineral fertilizers by maize and peanut producers in Madagascar is minimal. However, since a substantial proportion of surveyed farmers reported owning livestock, the simulations incorporated an application of 5 t/ha of manure prior to the onset of the maize growing season, consistent with the rate used in the field experiment in Vakinankaratra (Rasolofo et al., 2018). As a legume capable of fixing atmospheric nitrogen (Giller, 2001), peanut did not receive any fertilizer in the simulations, neither mineral nor organic. All simulations were performed under rainfed conditions to align with local agricultural practices reported in the survey.

2.6. *Baseline and adaptation scenarios*

The baseline and adaptation scenarios are based on the gridded input data described above, with variations in sowing dates and crop cycle lengths. These two adaptation strategies were chosen to reflect the findings from the household survey, which identified “adjusting planting dates” and “changing crop varieties” as popular adaptation options. Moreover, both practices are also highlighted as priorities in Madagascar's National Adaptation Plan (MEDD, 2021). In the baseline scenario, sowing dates were set to the midpoint of the sowing windows recommended for each of the 23 regions, reflecting the assumption that farmers aim to avoid the risks associated with sowing too early or too late. The crop cultivars used in the baseline scenario correspond to those used in field experiments.

Adaptation scenario I examined the potential benefits of adjusting sowing dates by setting them to either the first or last day of each region's recommended sowing window. Adaptation scenario II evaluated the effect of varying crop cycle lengths. For maize, this involved cultivars differing in thermal time requirements for the vegetative phase from the end of the juvenile stage to floral initiation. The growing degree-days for this phase were set to 180, 225, and 270, representing early-, medium-, and late-maturing varieties, respectively. Since interaction effects between adaptation scenario I and II were expected, these were combined into nine possible combinations of crop cycle lengths (short, medium, long) and sowing dates (early, medium, late).

Adaptation strategies were applied only to maize under SSP5–8.5, as preliminary simulations indicated that peanuts consistently benefited from climate change without additional adaptation measures. Peanut crop growth simulations were instead conducted under two conditions: one with a constant atmospheric [CO_2] fixed at 360 ppm (~corresponding to levels around the year 2000), and another incorporating annually changing [CO_2] with variations according to the SSP scenario.

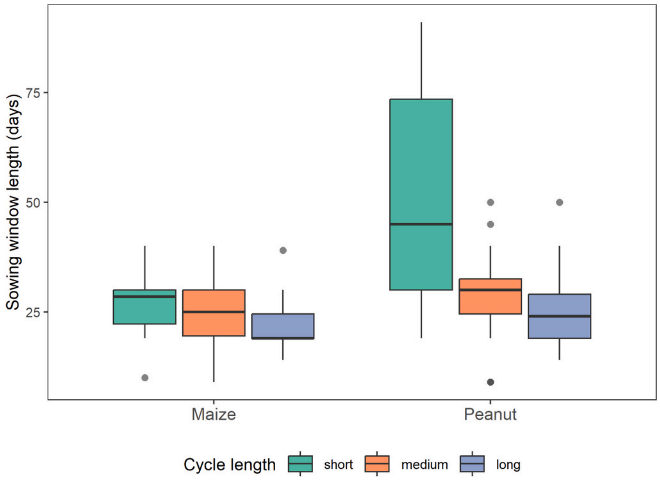

Fig. 3. Length of sowing windows in days for maize and peanut cultivars of different cycle lengths. Data source: MINAE et al., 2024.

3. Results

3.1. *Model performance*

A comparison of simulated yields with reported yields indicates that the calibrated APSIM model can reproduce both reported temporal and spatial yield patterns, albeit with certain limitations. Simulated mean maize and peanut yields during the baseline period (1.86 t/ha and 1.49 t/ha, respectively) exceed the corresponding FAO-reported values (1.22 t/ha and 0.73 t/ha). This discrepancy is likely due to the model's limited ability to account for biotic stress factors, such as pests, diseases, and weeds, as well as its limited representation of phosphorus constraints and extreme weather events.

Analysis of yield anomalies (Fig. 4) indicates that the model reasonably reproduces interannual variability but fails to capture years with extreme yield deviations (e.g., 2002–2004 for maize and 2013–2015 for peanut). When these exceptional years are excluded, the Willmott's index (d) is 0.46 for maize and 0.48 for peanut, suggesting an acceptable performance. Spatial validation against subnational yield data from the HarvestStat dataset (Lee et al., 2025) further suggests that the model captures broad spatial yield gradients, with Willmott's d values of 0.47 for maize and 0.44 for peanut.

3.2. *Projected temperature and precipitation change during cropping season*

The main cropping season for most annual crops in Madagascar extends from mid-October to mid-April, coinciding with the rainy season. In the baseline period (1985–2014), Madagascar saw an average precipitation of about 1200 mm during these six months, though with substantial spatial variation—from as little as 160 mm in the southwest to as much as 3360 mm in the northeast. Baseline mean temperatures also varied considerably, ranging from 16.8 °C in the central highlands to 29.3 °C in warmer lowland areas, with a national average of 24.5 °C (shown in SI-Fig. 9).

Projected future changes indicate a clear warming trend (Fig. 5a). Under the low-emissions scenario (SSP1–2.6) and in the near-term future (around 2030), mean temperatures are expected to rise by approximately +0.78 °C compared to the baseline period. Temperature increases intensify to +1.16 °C in the mid- and long term (around 2060 and 2090, respectively). Under the high-emissions scenario (SSP5–8.5), warming is more pronounced, with increases of +0.9 °C in the short term, +2.3 °C in the mid-term, and nearly +4.0 °C in the long term. The intermediate scenario (SSP3–7.0) projects temperature increases ranging from +0.81 °C to +3.17 °C. These temperature increases are

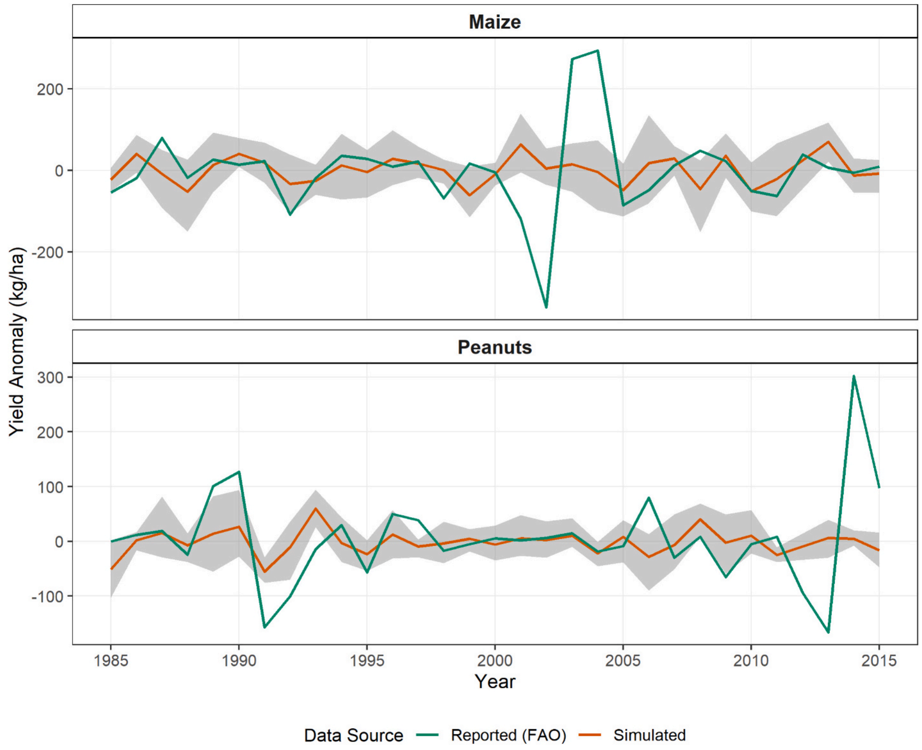

Fig. 4. Annual yield anomalies for maize and peanut in Madagascar during the baseline period (1985–2014). Solid lines show reported FAO yields and the ensemble mean of simulated yields, while shaded bands represent the inter-model spread (10th–90th percentile) across five global climate models. Data source for reported values: FAO (2025).

spatially consistent, affecting the entire country in a broadly uniform manner (shown in SI-Fig. 10).

Projected changes in mean precipitation relative to the historical baseline are generally small, ranging from slight decreases (−1%) to modest increases (+3%), depending on the scenario and period (Fig. 5b). However, spatial variability is substantial. The North and Northeast are projected to experience precipitation declines of up to −10% under SSP5–8.5, whereas the Southeast is likely to become wetter, with increases of up to +24% (shown in SI-Fig. 11). This indicates that currently dry regions are projected to become wetter, while currently wet regions are expected to become drier.

3.3. Simulated crop yields in baseline scenario

In the baseline scenario, simulated mean yields across Madagascar are 1.86 t/ha for maize and 1.49 t/ha for peanut. Simulated maize yields vary between 0.9 and 2.1 t/ha, with the highest values in the central highlands and a gradual decline toward the western and northwestern coasts. Peanut yields range from 1.2 to 1.8 t/ha, also peaking in the central highlands but showing a more pronounced decline in the lowland areas of the east, south, and northwest (Fig. 6).

3.4. Climate change impacts on crop yields

3.4.1. Maize

Simulated maize yield changes in Madagascar show consistent declines across all scenarios and time horizons, with the magnitude of impact increasing over time and under more severe emission pathways (Fig. 7). In the near-term, projected percentage yield losses compared to the baseline period range from −7.8% under SSP1–2.6 to −8.7% under SSP3–7.0 and − 8.4% under SSP5–8.5. By mid-century, the yield decline intensifies, reaching −13% under SSP1–2.6, −25% under SSP3–7.0, and − 27.6% under SSP5–8.5. The most severe losses are projected for the late-century, particularly under high-emission scenarios, with maize yields projected to decrease by −42.3% under SSP3–7.0 and − 51.8% under SSP5–8.5. Even under the low-emission SSP1–2.6, late-century losses still reach −12.5%.

Spatial patterns of simulated maize yield change reveal pronounced regional heterogeneity across Madagascar (Fig. 8). The most severe yield declines are projected in the lowland areas, particularly in the West, but also in parts of the South and along the East coast. In the near term, maize yields in the central highlands remain relatively stable, with only minor differences across emission scenarios. By mid-century, however, yield losses begin to emerge in the highlands under high-emission pathways, and these declines intensify toward the end of the century. In several western and southern regions, maize yields are projected to fall by up to 100% under late-century high-emission scenarios, suggesting that maize cultivation may no longer be viable in these areas.

3.4.2. Peanuts

In contrast to the projected declines in maize yields, simulations indicate a consistent increase in peanut yields across all SSPs and time periods in Madagascar (Fig. 9). In the near-term, percentage yield gains are modest but positive, ranging from +4.6% under SSP1.2–6 to +5.0% under SSP5.8–5. These gains become more pronounced by mid-century, with yields increasing by +7% under SSP1.2–6 and 9% under SSP3.7–0 and SSP5.8–5. The largest increases are projected for the late-century under high-emission scenarios, with yield gains of +10% under SSP3.7–0 and SSP.5–85, while SSP1.2–6 maintains a more moderate increase of +6%.

When atmospheric [CO_2], however, is fixed to a constant level of 360 ppm, the picture reverses and peanut yields are projected to decline by −4 to −6% in the short term, −6 to −13% in the mid-term and − 6 to −23% in the long term, with the largest losses occurring under high-emission scenarios toward the end of the century. A figure showing peanut yield changes under fixed [CO_2] is presented in the Supplementary Information (SI-Fig. 12).

Spatial patterns of projected peanut yield changes across Madagascar

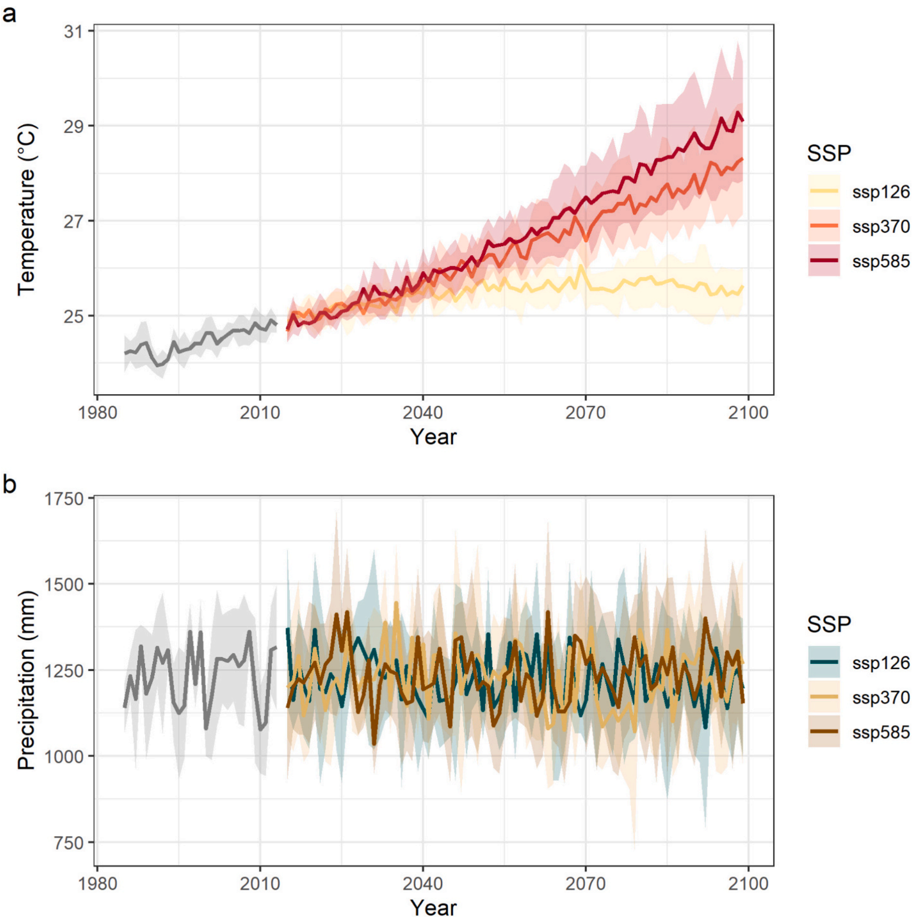

Fig. 5. Projected annual (a) mean daily-mean temperatures and (b) total precipitation during maize cropping season averaged across Madagascar, showing the multi-model mean value (line) and the full range of the model ensemble (shading) for the downscaled ISIMIP3b climate model data.

reveal widespread and largely positive impacts (Fig. 10). In the near-term, most regions—particularly the central parts of the country—show moderate yield increases of 4–5%. These gains become more pronounced by mid-century, with the central highlands showing the strongest improvements across scenarios. By the late-century, however, regional yield declines emerge in the northwestern and western parts of the island, particularly under SSP3–7.0 and SSP5–8.5. In contrast, under the low-emission SSP1–2.6 scenario, spatial variability across yield changes remains low.

3.5. *Climate change impacts on interannual yield variability*

Climate change affects not only average yields but also interannual yield variability. Our analysis indicates that year-to-year variability is projected to increase over time under high-emission scenarios for maize, while remaining largely stable for peanuts across periods (Fig. 11). In the historical baseline, the standard deviation of interannual yield variability was 2.6 for maize and 2.4 for peanuts. By mid-century, it rises to approximately 6.0 under high-emission scenarios, and by the end of the century, it reaches 10.7 under SSP3–7.0 and 13.1 under SSP5–8.5 for maize. Such increases in variability could exacerbate the vulnerability of smallholder farmers, who rely on consistent yields for food security and income stability.

3.6. *Evaluation of adaptation strategies on maize yield*

Simulation results show that adjusting sowing dates and switching crop varieties provide only limited potential to offset the negative impacts of climate change on maize yields under the high-emission scenario (SSP5–8.5). Relative to the baseline—the short-cycle variety sown at medium dates—the room for improvement remains modest. Across all periods, the most effective strategy is to use a short-cycle variety sown toward the end of the recommended window (Fig. 12). The results also highlight a strong interaction between crop variety and sowing date: selecting the optimal combination has a substantially greater impact on yield than modifying either factor alone. Moreover, the benefits of adaptation increase over time. While the yield gains from the best sowing date–variety combination are relatively small in the near term, they become more pronounced in the mid- and long-term periods.

4. Discussion

This study is among the first to model climate change impacts on smallholder agriculture in Madagascar, where quantitative evidence remains limited. By using household survey data to inform crop management practices and to identify farmers' preferences regarding adaptation strategies, we capture both the biophysical responses of crops and socio-economic dimensions of smallholder farming systems. This integration allowed us to evaluate the feasibility and effectiveness of farmers' preferred adaptation measures, offering insights that purely model-driven approaches cannot provide. Moreover, by considering both a C_4 crop (maize) and a C_3 crop (peanut), our analysis moves beyond crop-specific results and offers broader insights for the agricultural sector and adaptation planning.

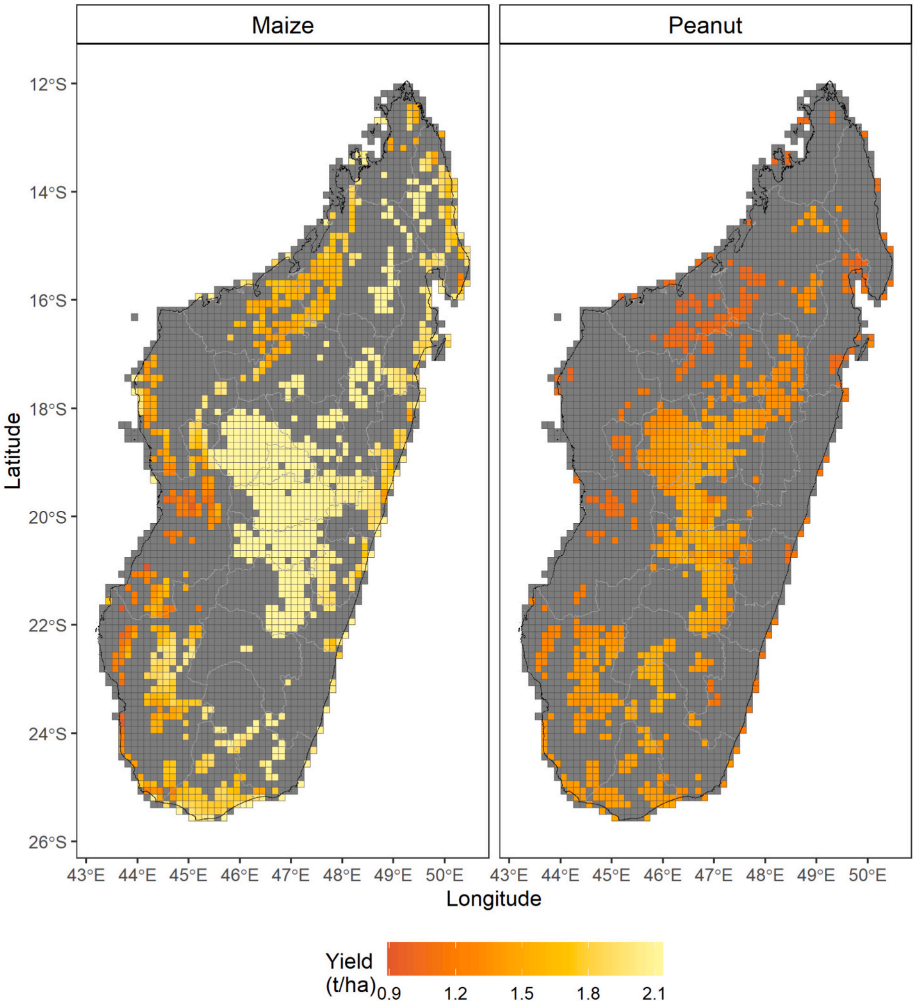

Fig. 6. Simulated mean maize and peanut yields across Madagascar for the baseline period 1985–2014.

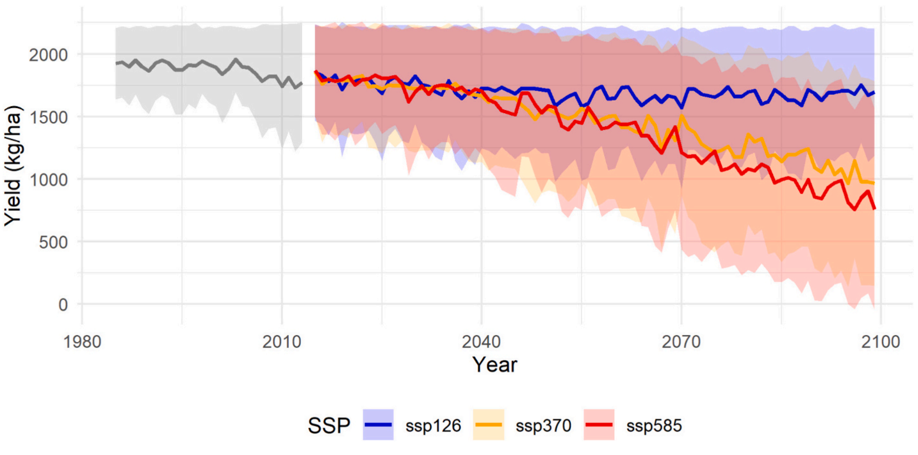

Fig. 7. Simulated mean maize yields across Madagascar from 1985 to 2100 under three SSPs (SSP1–2.6, SSP3–7.0, and SSP5–8.5). Solid lines represent the national mean yield for each scenario, while shaded areas indicate the standard deviation across grid cells and GCMs, capturing both regional and inter-model variability.

4.1. Projected climate change impacts on crop yields and interannual yield-variability

Simulated climate change impacts on maize (C_4) and peanut (C_3) reveal markedly different responses between the two crops, both in terms of mean yields and interannual yield variability. Maize is projected to experience yield declines across all scenarios and time horizons, accompanied by increasing interannual variability. In contrast, peanut is projected to show moderate yield increases across all scenarios and periods and relatively stable yields throughout the century. These differences can be attributed to the distinct photosynthetic pathways of C_3 and C_4 crops, with C_3 crops benefiting more from elevated

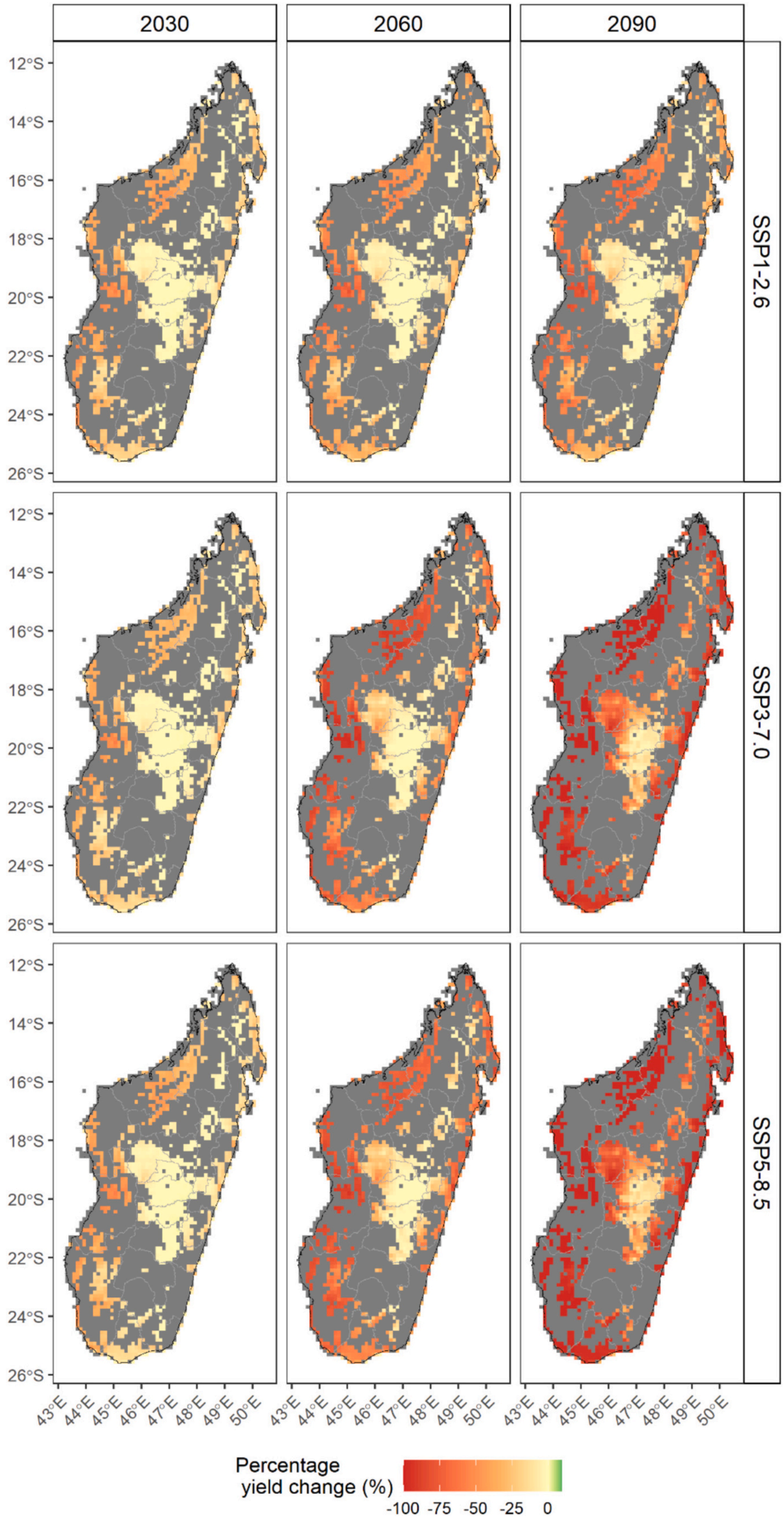

Fig. 8. Simulated percentage changes in maize yields across Madagascar under three Shared Socioeconomic Pathways (SSP1–2.6, SSP3–7.0, and SSP5–8.5) for three future periods centered around 2030 (2015–2044), 2060 (2045–2074), and 2090 (2075–2100), relative to the historical baseline (1985–2014).

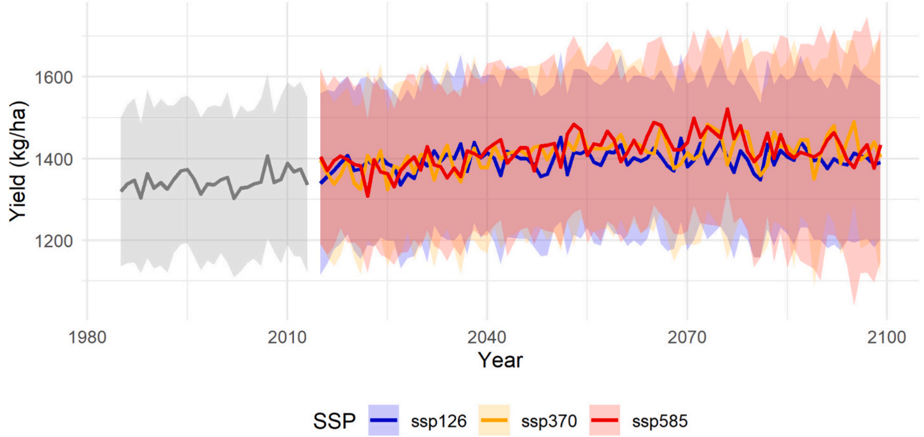

Fig. 9. Simulated peanut yields across Madagascar from 1985 to 2100 under three SSPs (SSP1–2.6, SSP3–7.0, and SSP5–8.5). Solid lines represent the national mean yield for each scenario, while shaded areas indicate the standard deviation across grid cells and GCMs, capturing both regional and inter-model variability.

atmospheric [CO_2], whereas C_4 crops only benefit under drought stress (Rezaei et al., 2023).

The projected maize yield losses in our study exceeds those reported in global assessments (Jägermeyr et al., 2021; Tomalka et al., 2020) and studies based on earlier CMIP phases (Vololona et al., 2013). This likely reflects our use of low-input conditions consistent with smallholder farming practices, as well as the calibration of our crop model to local field experimental data. Moreover, it has been shown that agricultural impacts are likely to emerge earlier under CMIP6 (Jägermeyr et al., 2021). Simulated peanut yield changes are consistent with Faye et al. (2018), who reported peanut yield increases in Senegal of 2–8% during the dry season, and 11–19% during the rainy season when increasing [CO_2] is taken into account.

The simulation results of our study are concerning, as they suggest that climate change could simultaneously reduce maize productivity and increase its year-to-year variability, while offering only modest gains for peanut. Although not the most important crop for Malagasy diets, maize is a key staple for many smallholder farmers, playing a critical role in household food security (Rigden et al., 2022). Moreover, yield stability is as important as absolute yields for smallholder farmers, who have limited financial resources, restricted access to credit or insurance, and few alternatives to buffer against poor harvests (Madembo et al., 2020; Menesch et al., 2023).

4.2. Buffering potential of adaptation strategies

Simulation results show that adaptation measures preferred by farmers can buffer, but not reverse the negative impacts of climate change on maize yields. The highest adaptation potential was found for short-cycle varieties sown at late sowing dates. This finding aligns with Randriamarolaza and Aguilar (2023), who reported that the rainy season is likely to start later and end earlier, leading to a shortened growing period. Such a contraction in the rainy season explains why late sowing combined with short-cycle cultivars provides the largest benefit: it reduces exposure to early-season stress while avoiding peak late-season stress. Moreover, shorter growth cycles may better align crop water and nutrient requirements with seasonal resource availability, thereby reducing stress during critical developmental stages compared with longer-cycle cultivars.

Our selection of adaptation strategies was guided by insights from the household survey and can be considered “best-fit” options—strategies that farmers are most likely to adopt given their current circumstances. These differ from “best-bet” practices, which are known to enhance crop productivity but face limited uptake due to financial, technical, or socio-economic barriers. Survey results highlighted “limited financial resources” and “lack of knowledge” as the principal constraints to adaptation, consistent with Harvey et al. (2014), who identified resource and capacity limitations as key reasons why few farmers have adjusted their practices in response to climate change. Exploring other best-fit options, such as soil improvement techniques or crop varieties adapted to the low phosphorus availability of Malagasy soils, could offer promising pathways to strengthen resilience. In addition, more resource-intensive measures—such as mineral fertilizer application or irrigation—may ultimately be required to safeguard future food production.

4.3. Limitations of the study and scope for further research

The results and findings presented in this study are subject to several limitations and uncertainties. A primary source of uncertainty in simulation results stems from the climate projections used as inputs to the crop model. Although we employed projections from multiple GCMs, uncertainties remain—particularly for rainfall projections, which are subject to greater variability across climate models than temperature. Another limitation is the reliance on a single crop model. Model intercomparison studies have shown that crop model uncertainty can exceed that of climate models (Jägermeyr et al., 2021; Wallach et al., 2023) and that the use of multi-model ensembles is preferable (Martre et al., 2015), which, however, was beyond the scope of this study. Similarly, soil data quality is a limiting factor. The WoFIS database used here includes only ~180 soil observations for Madagascar, restricting the representation of local heterogeneity and potentially reducing the reliability of yield projections at finer scales. In addition, the gridded crop growth simulations used in this study represent a simplification of the diverse cropping systems and management practices across Madagascar. While spatial variability was partially accounted for through downscaled climate data, soil information, and spatially varying sowing dates, other management factors—such as fertilization—were assumed to be uniform across regions and over time. Model calibration was further constrained by reliance on data from multiple seasons but only a single site per crop, while model evaluation was limited by the availability of subnational yield statistics.

Future research could address these limitations by expanding calibration datasets to include additional sites and years, and by employing multiple crop models to better capture structural uncertainty. Also, a sensitivity analysis prior to model calibration could help to further improve simulation accuracy, as previous studies have shown that the sensitivity of APSIM-Maize cultivar parameters can vary substantially under different climatic conditions, particularly with respect to rainfall and temperature variability (Yang et al., 2025). Moreover, evaluating a broader set of adaptation strategies—both “best-fit” options that are locally feasible and “best-bet” practices that may offer higher

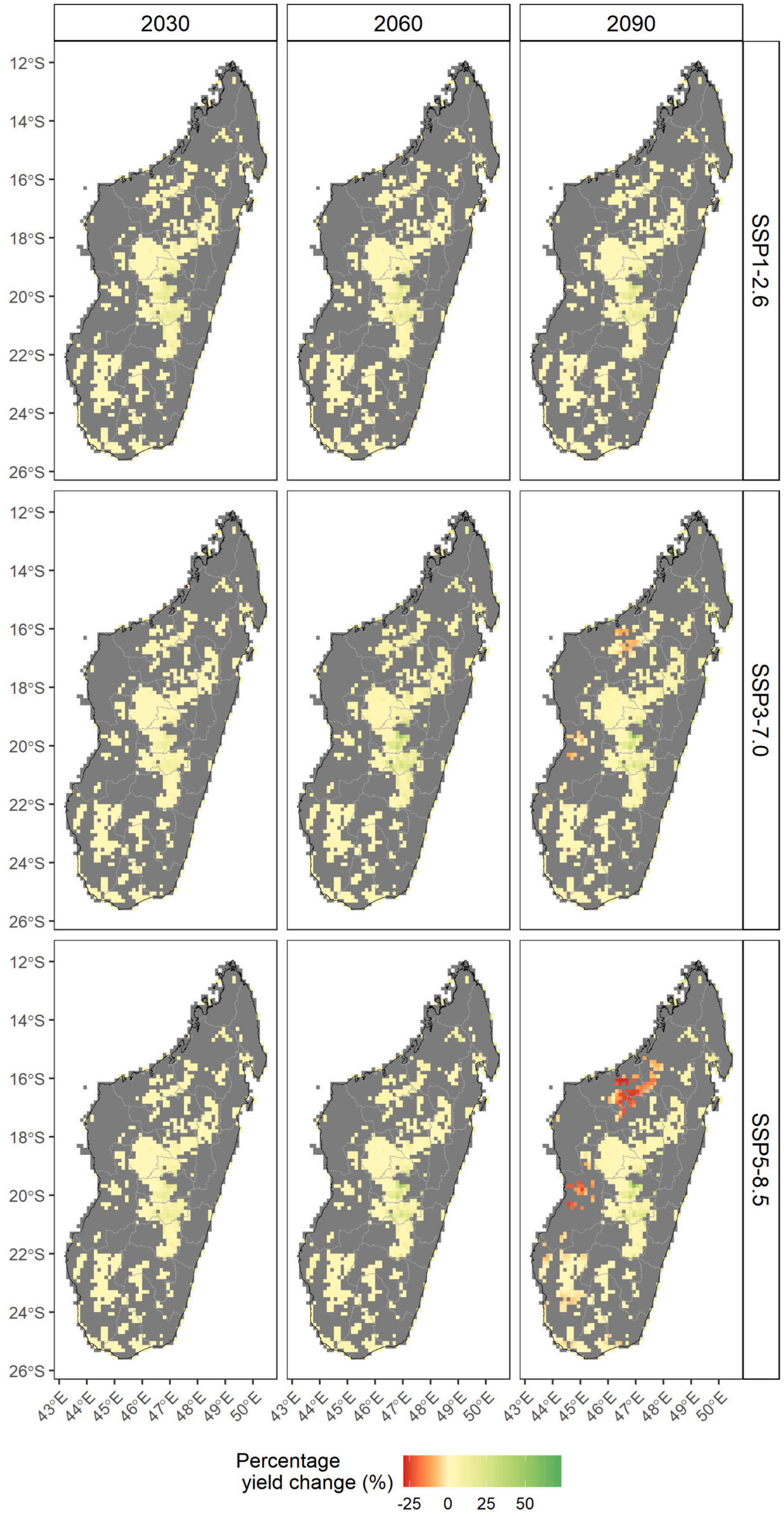

Fig. 10. Simulated percentage changes in peanut yields across Madagascar under three Shared Socioeconomic Pathways (SSP1–2.6, SSP3–7.0, and SSP5–8.5) for three future periods centered around 2030 (2015–2044), 2060 (2045–2074), and 2090 (2075–2100), relative to the historical baseline (1985–2014).

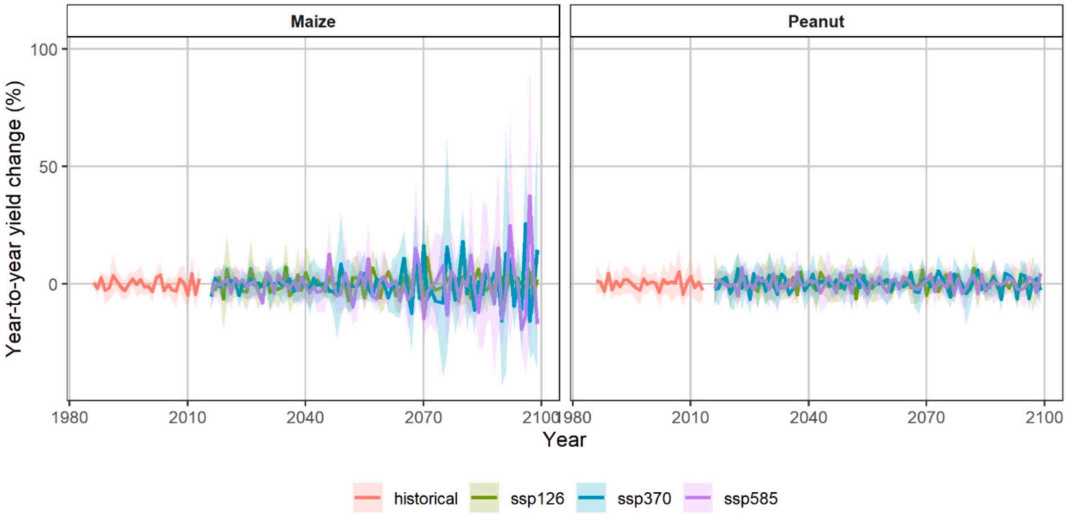

Fig. 11. Projected interannual maize and peanut yield variability over time and according to different SSPs.

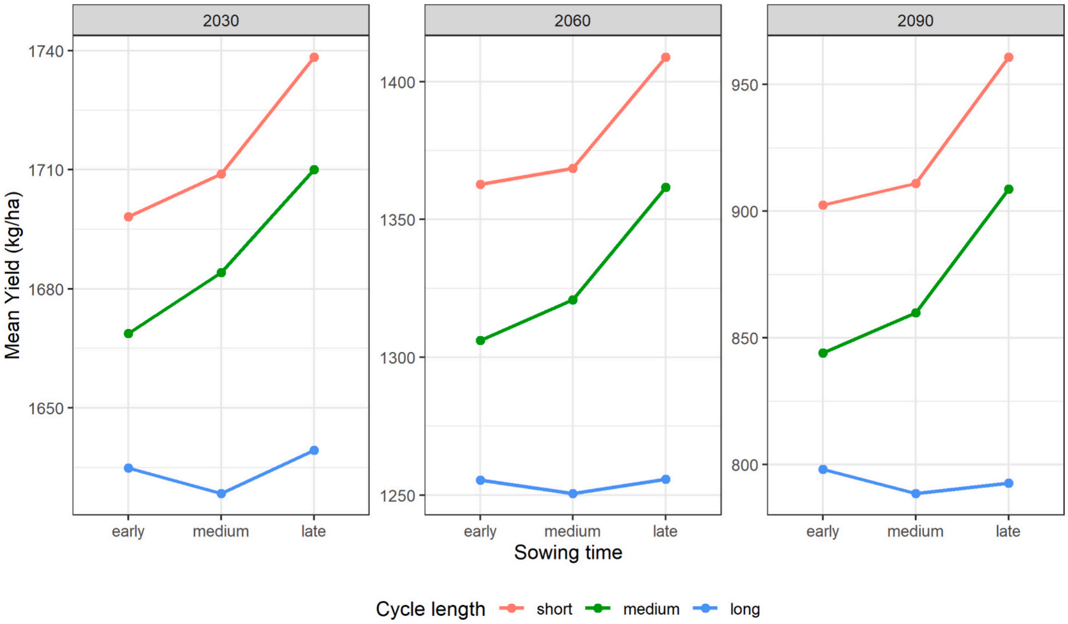

Fig. 12. Interaction effects of crop cycle length (short, medium, long) and sowing dates (early, medium, late) on maize yields across Madagascar during three future periods (2030, 2060, and 2090) under the high-emission scenario SSP5–8.5.

productivity gains—would help to identify a wider portfolio of affordable and effective measures, potentially reducing the need for farmers to abandon agriculture in favor of off-farm employment. More broadly, greater attention is needed to climate change impacts and adaptation strategies in low-input smallholder farming systems and how climate-induced yield changes translate into effects on household income and food security, particularly in regions beyond the current research focus.

5. Conclusion

This study highlights the profound challenges that climate change poses for smallholder farming systems in Madagascar and underscores the different response of C_4 and C_3 crops to changing climatic conditions both in terms of mean yields and interannual yield variability. As a C_4 crop, maize is projected to decline under future climates, with increasing interannual yield variability, whereas peanut is projected to benefit moderately from elevated [CO_2]. Beyond the specific yield projections for maize and peanut, this study demonstrates the added value of integrating household survey data with process-based crop models. By evaluating adaptation strategies informed by household survey data, we provide a more realistic assessment of both the feasibility and effectiveness of farmers` driven interventions to buffer against climate-induced yield losses. Although short-cycle maize cultivars sown at late planting dates offer some buffering potential, none of the tested strategies can fully offset projected maize yield losses, suggesting that more resource-intensive measures may ultimately be required to safeguard food production. Overall, our findings emphasize that a broader portfolio of accessible and effective adaptation measures is needed to ensure that agriculture remains a viable livelihood for Malagasy smallholder farmers under a rapidly changing climate.

CRediT authorship contribution statement

Anna Hampf: Writing – review & editing, Writing – original draft,

Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Chiara Sophia Weituschat:** Writing – review & editing, Investigation, Data curation, Conceptualization. **Lisa Murken:** Writing – review & editing, Visualization, Resources, Investigation, Data curation, Conceptualization. **Laingo Irintsoa Rasolofo:** Writing – review & editing, Data curation. **Christoph Gornott:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization.

Code availability

All custom code used for simulation, data analysis, and visualization is available from the corresponding author upon reasonable request.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used generative AI and AI-assisted technologies in order to improve the readability and language of the manuscript. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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Declaration of competing interest

The authors declare that they have no competing interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2026.104834.

Data availability

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

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