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Reshaping agricultural production systems: Trade-offs and implications for sustainable intensification and environment management

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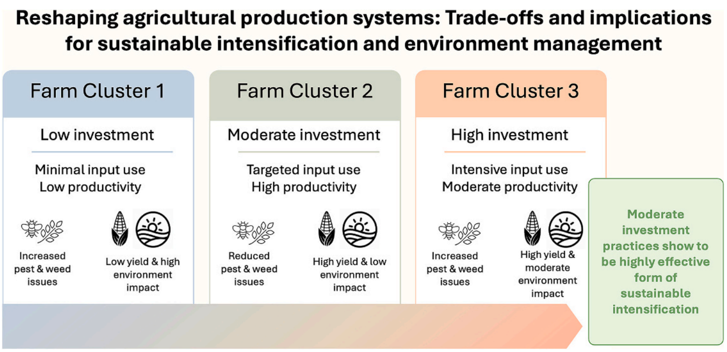
HIGHLIGHTS

- Environmental, agronomic, and economic stresses threaten to the sustainability and resilience of agricultural systems.
- Supporting smallholders in sustainable intensification improves impr food security, income, and environmental sustainability.
- Innovative financing mechanisms, climate-resilient infrastructure, and extension services help overcome adoption barriers.
- Moderate-investment practices were the most effective, balancing productivity and environmental sustainability.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: As global food production is projected to double to meet future food demand, reshaping agricultural systems to balance productivity with environmental sustainability is a critical challenge. Cambodia, where smallholder farming dominates and rural communities face increasing socioeconomic and environmental pressures.

OBJECTIVE: This study aims to provide empirical evidence on viable intensification strategies for smallholders in Northwest Cambodia which enhance food security, reduce poverty, and promote environmental sustainability, offering practical insights to address these global priorities through locally grounded solutions.

METHODS: This study integrates demographic-socioeconomic data from a census of 997 upland households and farming practices from 46 maize plots to assess trade-offs and to navigate pathways for sustainable and resilient agricultural production.

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RESULTS AND CONCLUSIONS: The analysis reveals moderate-investment practices, defined by targeted and efficient input application, were highly effective, achieving yields comparable to high-investment practices (characterised by intensive chemical application), while significantly reducing environmental costs (US$134.79 per hectare) compared to low-investment practices (which applied inputs minimally). If extended, this reduction could translate to annual environmental cost savings of US$700,597 in Cambodia and US$1.16 billion across Southeast Asia. Additionally, these practices reduced production costs by US$116 per hectare and increased profits by US$23 per hectare, resulting in annual profit gains of US$707,200 in Cambodia and US$198 million across Southeast Asia. Both low- and high-investment strategies exhibited inefficiencies and higher environmental costs, underscoring the importance of balanced resource use. The analysis further uncovers critical challenges faced by smallholders, including financial constraints, climate variability, and technical knowledge gaps, which hinder their capacity to adopt sustainable practices.

SIGNIFICANCE: This study contributes to the global discourse on sustainable intensification by demonstrating moderate-investment practices can optimise farm profitability and environmental sustainability. By addressing the triple challenges of climate variability, resource constraints, and technical knowledge gaps, these findings offer actionable strategies for policymakers, practitioners, and researchers aiming to develop sustainable and resilient agricultural systems that align with global sustainability goals.

1. Introduction

Sustainable intensification in agriculture has emerged as a central focus in the global discourse on poverty alleviation, food security, and environmental sustainability (Jat et al., 2020; Jhariya et al., 2021; Melland et al., 2014; Zhen et al., 2006). The global food production system faces increasing challenges, such as land degradation, socioeconomic and market uncertainties, that are projected to worsen with the growing impacts of climate change further undermining smallholders' adaptive capacity (Birkmann et al., 2022; IPCC, 2022; Touch et al., 2024b). "Business as usual" agriculture is deemed unable to sustainably meet the needs of the growing global population, which is anticipated to grow by over 2 billion by 2040, with these pressures further intensified by the escalating effects of climate change (Kc et al., 2018; Stringer et al., 2020). The necessity for transformative change is evident, requiring a future where food security, climate change mitigation, and livelihood aspirations are realised through the implementation of multifunctional landscapes and broader economic development strategies (Stringer et al., 2020; Willett et al., 2019). Such a transformation is unlikely to be straightforward or smooth. Achieving such a vision demands radical, systemic shifts in values, beliefs, social behaviours, and governance. Recognising that no singular transformation pathway will suit all contexts, it is challenging to generalise from one farmer's experience to another (Stringer et al., 2020). This underscores the importance of multidisciplinary and multi-stakeholder interventions that can navigate different pathways and address smallholder farmers' diverse needs and aspirations for improved agricultural production, economic viability, and environmental sustainability.

Smallholder farmers (hereafter smallholders) are central to global development policies, notably the Sustainable Development Goal (SDG) target 2.3, which aims to enhance their productivity, incomes, and access to land (Gil et al., 2019). Additionally, the UN COP21 climate agreements, formulated by more than 100 countries during the 2015 UN Conference of the Parties on Climate Change, aim to strengthen the adaptive capacity of smallholders (Guja and Bedeke, 2024; Wollenberg et al., 2016). Numerous scholars argue that supporting smallholders as they transition toward sustainable intensification is a crucial aspect of meeting the objectives of increased agricultural production efficiency, environmental sustainability, and socioeconomic outcomes (Adolph et al., 2021; Helfenstein et al., 2020). Despite growing research and development support for sustainable intensification, debate over the performance of smallholding farms, particularly concerning productivity, resource efficiency, biodiversity, and greenhouse gas emissions, continues (Ricciardi et al., 2021; Touch et al., 2024b). For instance, Adolph et al. (2021) argues that smallholders are discouraged from focusing on long-term sustainability because they have limited resources to meet both farming and livelihood needs. Agricultural policies often push for rapid increases to productivity, developing and deploying interventions that encourage smallholders to adopt new practices, often ignoring differences among farming households and farms. For Mouratiadou et al. (2021), because agricultural production is part of complex social, economic, and natural systems, the success of sustainable intensification policies and practices depends on specific situations that change over time.

Existing literature highlights significant discrepancies in the performance and sustainability of smallholder farming systems. For instance, Helfenstein et al. (2020) suggest that pathways and strategic interventions can drive sustainable intensification, aligning agricultural productivity with environmental sustainability. Similarly, Tilman et al. (2011) underline the importance of integrated soil fertility and pest management practices in enhancing soil health and productivity. Nevertheless, limited access to resources and financial constraints often compels smallholders to adopt low-input farming strategies, resulting in reduced yields and profit margins (Chen et al., 2020; Khan et al., 2024). On the other hand, over-application of inputs, such as fertilisers and pesticides by higher-input smallholders, can lead to environmental degradation, inefficiencies, and financial losses (Elahi et al., 2019; Onwuchekwa-Henry et al., 2022). These dual challenges underscore the need for context-specific strategies to balance input use and achieve sustainable intensification. Despite these insights, substantial knowledge gaps persist, particularly regarding the complex, interrelated effects of household demographics, socioeconomics, and applied farming practices. These interactions will differ by place, requiring in-depth, place-based analyses to establish the costs, benefits, and sustainability of intensification, while still offering valuable insights into how different intensification strategies affect yield, profitability, and environmental outcomes in smallholder agricultural systems.

Cambodia provides a compelling case for exploring transformation pathways toward sustainable and resilient intensification among smallholders. Approximately 80 % of the population resides in rural areas, where livelihoods and food security are closely tied to agriculture (Touch et al., 2024b). These rural communities contribute significantly to Cambodia's socioeconomic outcomes, underscoring the critical role of agriculture in national development. The country's tropical monsoon climate, characterised by distinct wet and dry seasons, shapes cropping calendars and agricultural practices, making climate-adaptive farming essential (Touch et al., 2024a). An ongoing shift in agricultural practices, driven by socioeconomic development, technological advancements, and increasing climatic challenges, highlights the dynamic nature of the sector (Cook et al., 2024). To design effective and sustainable development policies, these dynamics necessitate a deeper understanding of the local context, including smallholders' perceptions, resources, constraints, and capacities. Context-specific knowledge is particularly important to ensure that interventions support smallholders in adopting sustainable agricultural practices and environmental management strategies without endangering their lives and livelihoods.

Maize smallholders in Northwest Cambodia exemplify the complexities and opportunities of agricultural transformation (Montgomery et al., 2016; Montgomery et al., 2017). Their dependence on agriculture for livelihoods and food security, combined with exposure to climatic variability, socioeconomic pressures, and growing incidence of debt-driven land dispossession in the area (Green, 2024), makes them an ideal focus for studying sustainable intensification. The insights gained from this study are not only applicable to the smallholders studied but are also relevant for a broader range of smallholders in Cambodia and Southeast Asia.

This study investigates the complex interactions between demographic-socioeconomic factors and agricultural practices to assess the trade-offs faced by maize smallholders in Northwest Cambodia under the context of intensification pressures. The empirical findings contribute in several important aspects. First, the study offers actionable insights for policy, practice, and research by identifying evidence-based entry points for promoting sustainable agricultural intensification, resource-efficient technologies, and supportive institutional frameworks. Second, it offers scalable recommendations that can be adapted to similar contexts, contributing to progress toward Sustainable Development Goals (SDGs) related to zero hunger, poverty reduction, and climate action. Third, by addressing these interconnected challenges, the study underscores the transformative potential of inclusive and sustainable agricultural strategies to enhance the resilience and livelihoods of smallholders.

2. Summarised methodology description

The study employed a multi-stage sampling procedure, beginning with high-level consultations involving agricultural research and development experts with extensive experience in Cambodia, as well as with local government officials. This resulted in the selection of two provinces (Battambang and Pailin) in Northwest Cambodia (Fig. 1). The climate in these provinces is influenced by the Southeast Asian Monsoon, characterised by a six-month wet season (May to October) and a six-month dry season (November to April) (Fig. 2.c). March and April are the hottest months, while December and January are the coolest (Fig. 2.a-b). For further details on the local climate see Appendix A.1.

Selection criteria for the villages were established using academic literature (Norman et al., 1995; Touch et al., 2024b), including the presence and absence of farmer groups/associations/cooperatives, various rural livelihood activities, and locations in upland villages, leading to the selection of four upland villages (for further details regarding the sampling procedure, see Appendix A.2). Included in the selection process, the selected villages were mapped, and an upland household census was conducted using in-person interviews with 997 household representatives from July 2022 to February 2023. The household census was designed to gain insights into household demographic and socioeconomic characteristics. The household census questionnaire covered nine thematic areas: 1) household settlement history; 2) household composition, living arrangements, relationships, education, and livelihoods (including non-farm activities); 3) migration and remittances; 4) housing ownership and assets; 5) income, expenses and credit; 6) aspirations and subjective economic well-being; 7) land and agricultural production; 8) social capital, trust and access to agricultural information; and 9) accessibility and connectivity.

Following the household census of 997 (upland households), a matched-pair sampling approach was used to select a targeted subset of 46 upland maize smallholders for in-depth monitoring. The aim was to examine farming practices, input use, and environmental impacts across households with similar structural characteristics but differing livelihood outcomes. Households were matched in pairs based on predicted income and well-being, using regression models that accounted for key farm-level variables, including total landholding, proportion of irrigated land, and crop-specific income shares. Within each pair, one household exhibited high actual income or well-being, and the other lower, despite

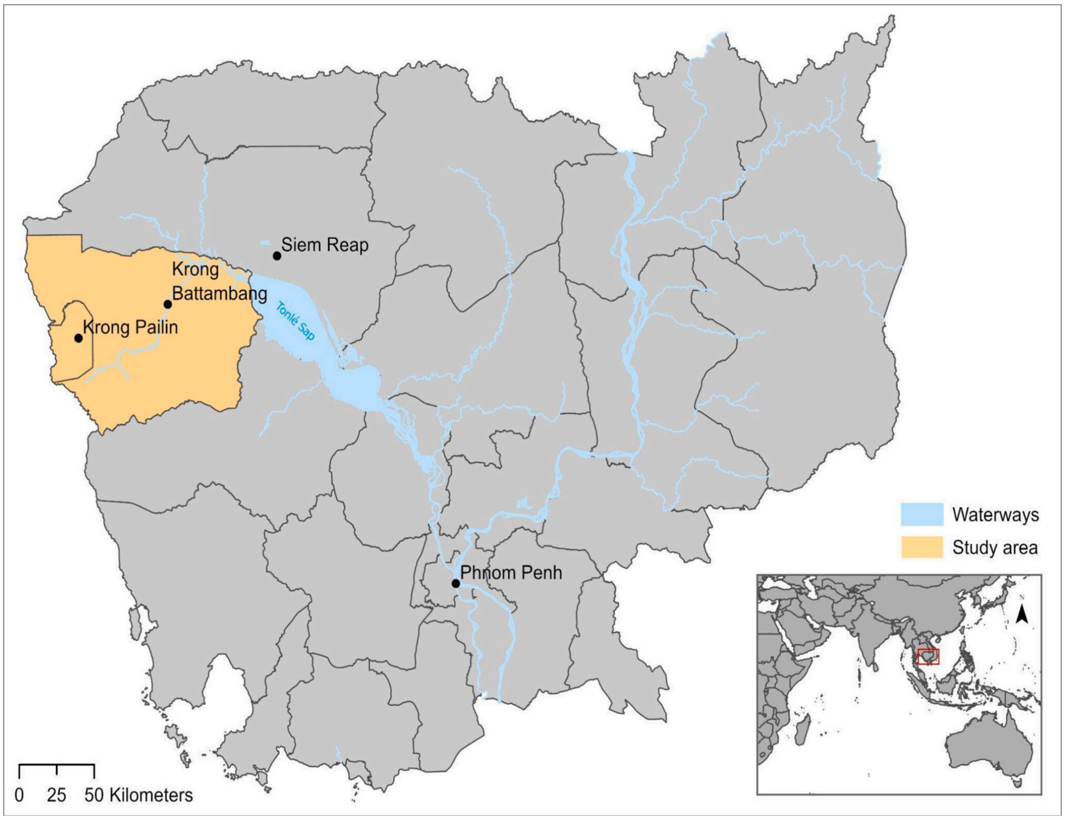

Fig. 1. Study areas in Battambang and Pailin provinces of Northwest Cambodia.

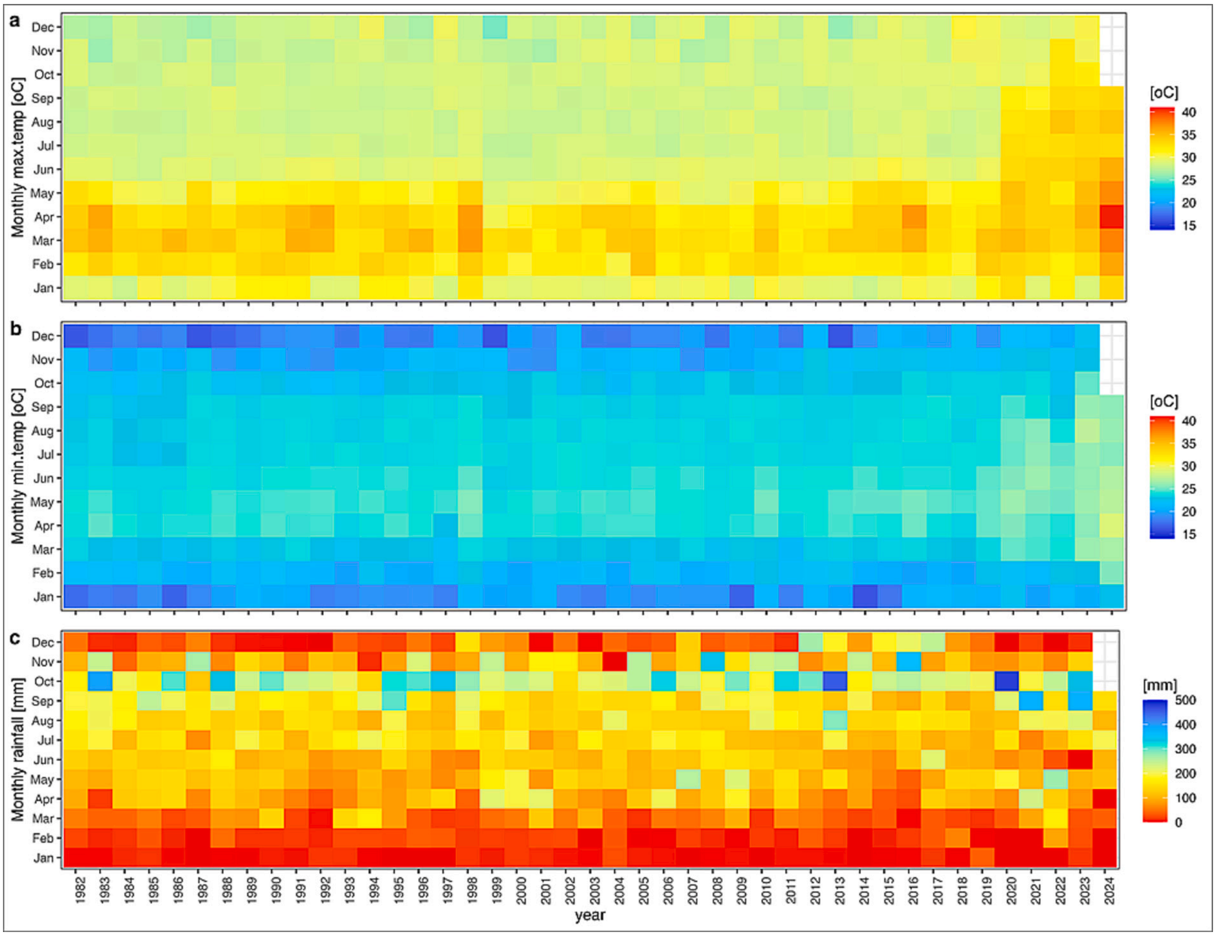

Fig. 2. Heatmap of long-term historical climate averages for Battambang and Pailin in Northwest Cambodia: (a) rainfall, (b) maximum temperature, and (c) minimum temperature.

similar predicted profiles. This design allowed us to isolate differences in performance and decision-making under comparable socioeconomic and agroecological conditions.

This targeted selection strategy served multiple analytical purposes. First, it enabled high-resolution, season-long data collection on farming operations, biophysical field conditions, and cost structures. Collecting this level of detail across the full census data would have been logistically and financially infeasible. Second, the matched-pair design facilitated comparative insights into the drivers of productivity, profitability, and sustainability by controlling for key confounding factors. Third, the selected households were situated in upland maize systems that exemplify the intensification and environmental pressures commonly faced by rainfed smallholders in Cambodia and other regions with similar agro-ecological conditions. This enhances the broader relevance and applicability of the findings.

From June 2023 and February 2024, crop growth monitoring and farming practice documentation were conducted on these 46 maize farm plots. Data collected includes: 1) farming operational activities, such as land preparations, planting methods, crop varieties, seeding rates, fertilisation, management practices for insects, pests, diseases, and weeds, harvesting, and sales; 2) biophysical information, such as soil fertility, soil moisture, and the presence and management of weeds, insect pests, and diseases; and 3) production costs, entailing comprehensive tracking of all costs involved in crop production for the main plots. This data was used to analyse the effectiveness and efficiency of different farming practices and their impacts on crop production, profit margins, and the environmental impacts. For further detail regarding data collection see Appendix A.3.

To further contextualise the impact of farm production, an additional analysis estimated the environmental costs of maize production on a per-hectare basis. In the absence of data on environmental externalities, we utilised cost estimations from peer-reviewed literature (see Appendix A.5) to develop a framework for quantifying costs. The analytical framework integrates direct and indirect environmental externalities, offering an assessment of the trade-offs between environmental and economic outcomes in maize production. For detailed descriptions of the framework, including assumptions and computation, see Appendix A.5.

The CommCare mobile data platform was used to digitally record data from the household census, crop growth monitoring, and farming practice documentation. Additionally, R statistical programming was employed to perform statistical modelling and multivariate analyses of the quantitative data. For detailed data analysis methods and procedures see Appendix A.3.

3. Results and discussion

3.1. Socioeconomic and demographic profiles

The analysis of socioeconomic and demographic characteristics (based on the census of 997 upland households, see Table 1) reveals that, on average, crop production accounts for approximately 37 % of total household income, with the remainder coming from casual labour, and other sources such as off-farm employment, small business, and remittance. While crop income represents a notable share of household income, most smallholders exhibit low-income diversification and minimal annual savings (mean = 7 %, median = 0 %). These financial

Table 1

Descriptive statistics of selected household socioeconomic and demographic characteristics of the respondents (n = 997).

Variable	Unit description	Mean	Media	Std Dev
Total annual income	USD	5668	3500	9334
Annual savings	Percent (of total income)	7.10	0	41.02
Annual crop income	Percent (of total income)	36.55	30.00	36.98
Annual livestock income	Percent (of total income)	3.26	0	11.96
Aquaculture income	Percent (of total income)	0.30	0	4.67
Employment income	Percent (of total income)	7.44	0	21.14
Business income	Percent (of total income)	11.90	0	26.51
Remittance income	Percent (of total income)	7.62	0	22.07
Other income	Percent (of total income)	31.85	15.00	37.13
Total farmland	Hectare	3.68	2.50	4.23
Owned farmland	Percent (of total farmland)	92.68	100	19.45
Irrigated farmland	Percent (of total farmland)	0.88	0	2.06
Residency duration in village	Year	16.95	20.00	8.10
Household size	Number of people	3.99	4.00	1.47
Ordinary phone	Number of phones	0.23	0	0.48
Smartphone	Number of phones	1.97	2.00	1.33
Motorbike	Number of motorbikes	1.10	1.00	0.76
4WD tractor	Number of 4WD tractors	0.07	0	0.28
2WD tractor	Number of 2WD tractors	0.30	0	0.70
House-to-market distance	Travel time spent in minutes	12.56	8.00	13.15
House-to-health facility distance	Travel time spent in minutes	22.61	20.00	14.82
House to agri-govt office distance	Travel time spent in minutes	27.70	30.00	15.46

constraints hinder their capacity and willingness to invest in alternative agricultural practices, such as reduced tillage, green manure cropping, and other agroecological approaches that conserve, restore, and improve natural resources, as they must also weigh upfront costs and potential economic shocks in their decision-making. Similar findings by Dhillon and Moncur (2023), Ruzzante et al. (2021) and Shiferaw et al. (2009) emphasise that smallholders often operate under significant economic stress, making it challenging for them to adopt new practices and technologies that require upfront investments. Research by Kassie et al. (2013); Mutyasira et al. (2018a) demonstrate that building financial resilience among smallholders is a critical enabler of changed farming practices. Without addressing these constraints, smallholders risk becoming trapped in a cycle of low investment and low returns, which may reinforce practices that continue to contribute to environmental degradation and constraint sustainability overtime (Touch et al., 2024b).

The analysis also indicates that the average landholding is 3.22 ha, reflecting a moderate scale of farming operations. The high rate of land ownership (Mean = 93 %, Median = 100 %) provides security and autonomy, which are argued to be crucial for intensification (Kolapo et al., 2022; Mutyasira et al., 2018b; Pretty et al., 2018; Winters et al., 2018). However, access to irrigated farmland is extremely low (Mean = 0.88 % of total farmland, Median = 0 %), underscoring a heavy reliance on rainfed agriculture, which is said to inhibit intensification (Palsaniya et al., 2023; Prasad et al., 2022). This dependence increases vulnerability to climate variability, adversely impacting productivity and resilience (Yadeta et al., 2024). Additionally, low levels of mechanisation, with tractor ownership at less than 1 %, constrain the efficiency and scalability of farming operations, limiting intensification potential.

Demographic data reveal that participating smallholders have long residency in their villages (Mean = 19 years, Median = 20 years). The average household size is 3.61 people (Median = 4), which provides potential labour supply for farming operations. While ordinary phone ownership per household is low (Mean = 0, Median = 0), smartphone ownership is moderate (Mean = 1.85, Median = 2), suggesting potential for digital tools to disseminate information on sustainable practices.

3.2. *Identifying opportunities for sustainable agricultural intensification*

The farm typology developed in this study enables unpacking the complex nature of farm production among smallholders, allowing creation of farm clusters to deepen and broaden the analysis. Given the heterogeneity in farming practices, resource availability, and demographic-socioeconomic conditions, a one-size-fits-all approach to agricultural development is unlikely to be effective. The analysis identified three distinct farm clusters based on their unique characteristics (Fig. 3; see Appendix A.4 for the method of farm typology development), each reflecting a different level of input investment and associated outcomes. Broadly, Cluster 1 consisted of low-investment farms with minimal input use and low productivity; Cluster 2 represented moderate-investment farms with more efficient input use and balanced returns; and Cluster 3 comprised high-investment farms that applied inputs intensively but experienced diminishing economic returns and greater environmental risks (see the comparison of production and environment costs in Figs. 4 and 5). These farm clusters reveal significant disparities in agronomic practices, input use, productivity, and environmental impact, as outlined below.

Farm Cluster 1 (low-investment) operated on land with moderate soil fertility and moisture levels but invested minimally in farm inputs. This limited investment led to significant challenges with insect infestation (35 % of the total score out of 100) and weed infestation (45 % of the total score out of 100), resulting in productivity losses. Smallholders in Cluster 1 achieved only 36 % of the maximum observed on-farm yield, that was calculated relative to the highest yield recorded in the monitoring dataset (8.93 tons per hectare), despite low disease infestation (6 % of the total score out of 100). Total production costs were relatively low at 48 % of the maximum observed production costs (US$730 per hectare), reflecting limited financial resources that constrained the adoption of more intensive or yield-enhancing practices. Farm Cluster 2 (moderate-investment) operated on land with similar fertility and moisture conditions to Farm Cluster 1 but achieved notable gains in productivity through targeted and strategic investments in land preparation, seed, planting, fertiliser, and pest management. Weed infestation was slightly reduced (43 %), insect infestation fell to 30 %, and disease infestation remained low at 7 %. Smallholders in Cluster 2 achieved 67 % of the maximum on-farm yield while incurring production costs equivalent to 70 % of the maximum. These outcomes suggest that moderate, well-targeted investments can enhance both resource use efficiency and economic returns, offering a more sustainable intensification pathway. In contrast, Farm Cluster 3 (high-investment) operated on land with higher soil fertility and moisture levels, enabling the highest yields among the clusters (76 % of the maximum yield). However, this cluster also incurred the highest production costs, at 84 % of the maximum. Despite the yield advantage, gross margins in Cluster 3

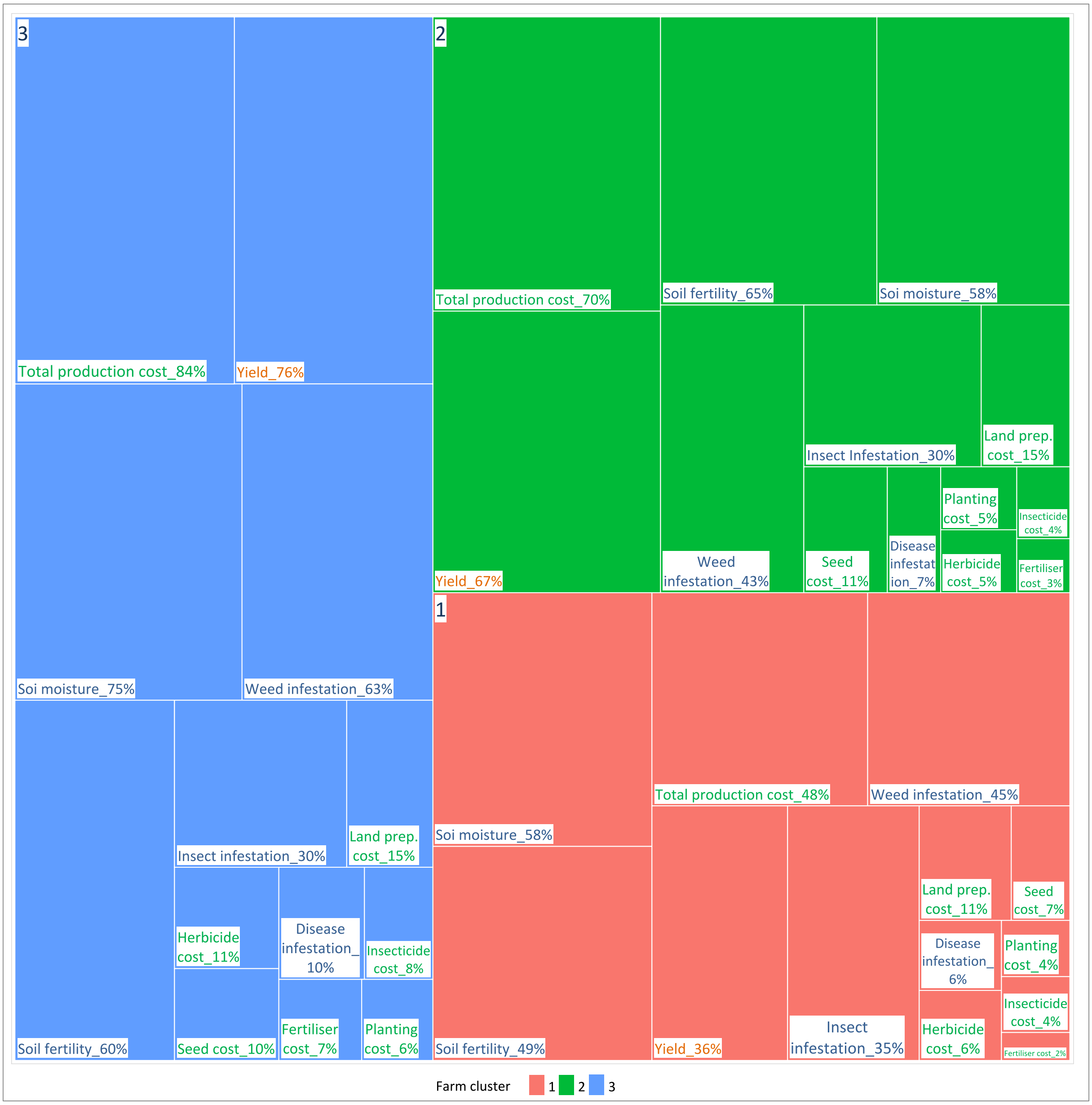

Fig. 3. Tree-map visualisation of key agronomic, cost, and environmental variables by farm cluster. Each square represents one variable, and its area is proportional to the variable's value relative to the maximum observed across the sample (e.g., 76 % yield = 76 % of the maximum observed yield of 8.93 t/ha).

were comparable to those of Farm Cluster 2, indicating reduced economic returns to further intensification. While some smallholders in this cluster adopted intensification-related practices such as more intensive investments in land preparation and seed use, these were often applied alongside blanket input use rather than precision or conservation-oriented strategies. The heavy use of inputs in Farm Cluster 3 raises concerns about environmental sustainability, including risks of fertiliser runoff, soil degradation, and greenhouse gas emissions, which could undermine long-term productivity gains (Hossain et al., 2022). These findings suggest that sustainable intensification is not solely determined by financial condition. While affordability shapes investment capacity, the adoption of more efficient, lower-cost strategies observed in Cluster 2 may also reflect enabling factors such as better access to technical knowledge, informal peer learning, or a greater openness to adopting new practices. Although these factors were not directly measured in this study, their potential influence underscores the importance of supportive environments – including extension services, training programs, and reliable input access – to foster the uptake of resource-efficient technologies among smallholders. Further research would be required to confirm this potential influence.

A comparison across the three clusters reveals important differences in the marginal returns to investment. Cluster 2, which made moderate but targeted investments, achieved a 31-percentage point increase in yield compared to Cluster 1 (67 % vs. 36 % of the maximum), while only increasing production costs by 22 percentage points (70 % vs. 48 %). In contrast, Cluster 3 increased production costs by 14 percentage points over Cluster 2 (84 % vs. 70 %) but achieved only a 9-percentage point gain in yield (76 % vs. 67 %), along with heightened environmental concerns associated with more intensive input use. These comparisons suggest that moderate investment strategies offer better cost-efficiency and environmental sustainability per unit of output than high-input approaches.

These findings have implications for policies, practices, and research aimed at promoting sustainable agricultural intensification. First, policies should prioritise moderate-investment strategies that optimise resource use and minimise environmental costs. Targeted financial

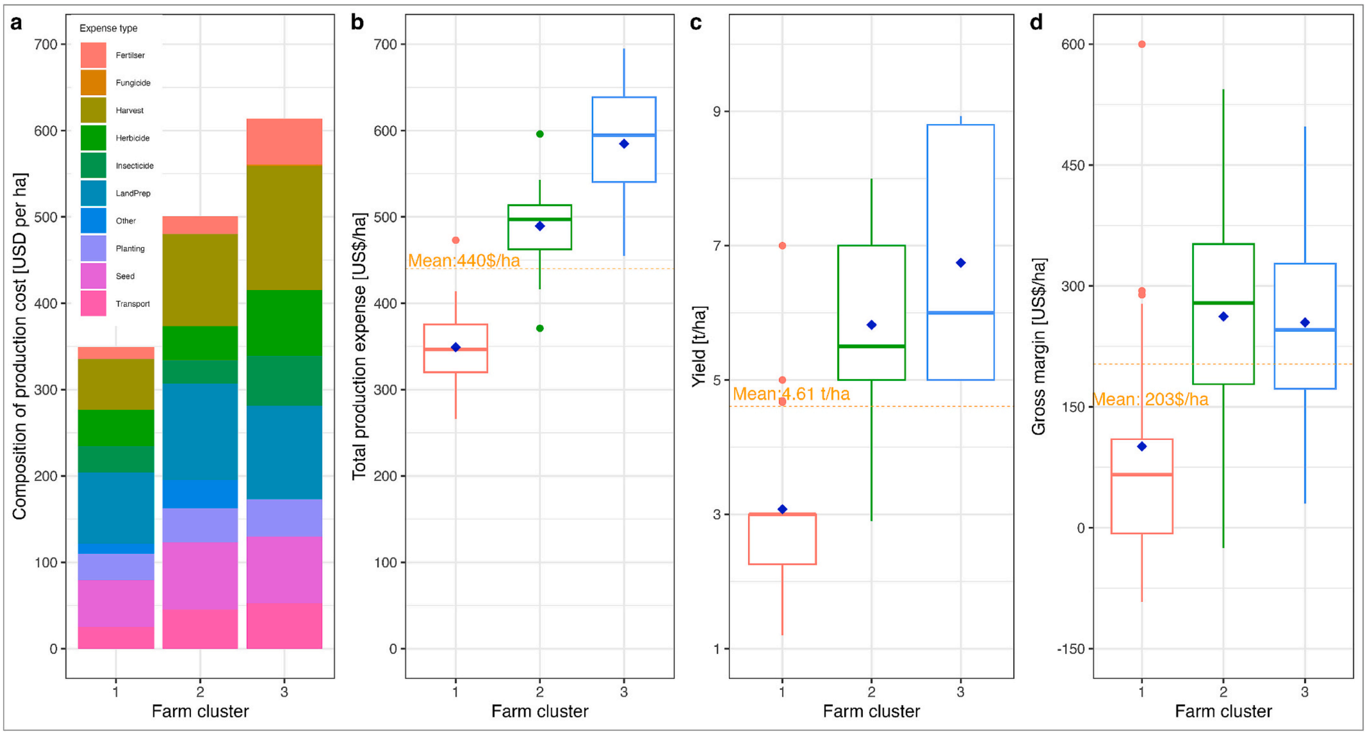

Fig. 4. Comparison of maize production by different farm clusters: (a) Composition of production expenses; (b) Distribution of total production expenses; (c) Distribution of crop yields; and (d) Distribution of gross margins. The diamond in the box plot represents the average value for each farm cluster, while the dashed line indicates the overall average value across all farm clusters.

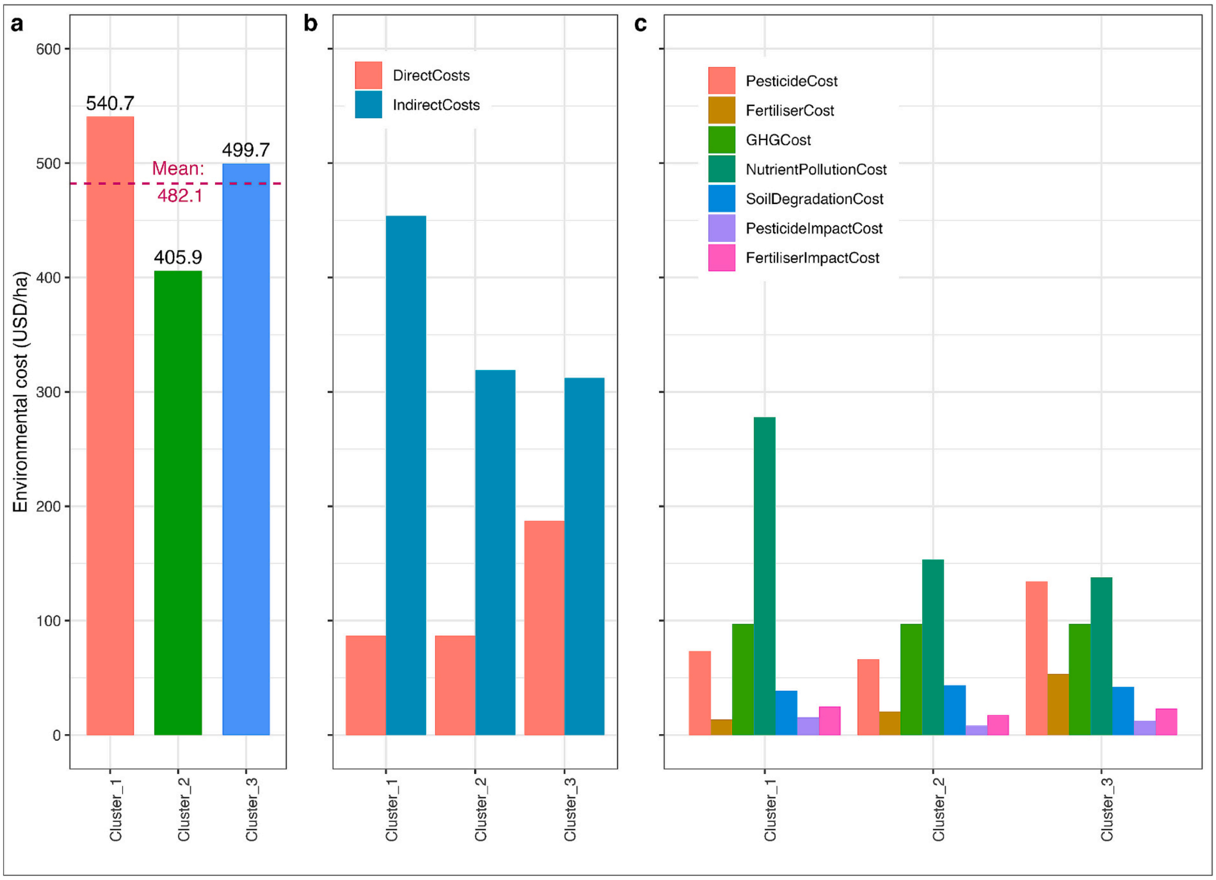

Fig. 5. Visualisation of environmental cost summaries cross farm clusters.

subsidies, technical support, and farmer training programs can potentially encourage the adoption of resource-efficient technologies and alternative agricultural practices, such as integrated pest management (IPM) (Deguine et al., 2021), precision fertilisation (Haneklaus and Schnug, 1998), conservation agriculture (Pretty et al., 2018) and other climate-smart practices. Second, investments in research and extension services are essential for developing and disseminating context-specific, affordable technologies tailored to smallholder needs. While knowledge-sharing often occurs informally through neighbours and local networks, formal extension services can play a complementary role by supporting these networks and ensuring access to updated, evidence-based practices (Tran and Touch, 2024). For instance, innovations in low-cost irrigation systems (Mashnik et al., 2017) and improved mechanisation access (Van Loon et al., 2020) could address the productivity constraints observed in Farm Cluster 1 and mitigate inefficiencies in Farm Cluster 3. Digital platforms can also be leveraged to provide smallholders with timely agricultural advice, market access information, and environmental management strategies, particularly given the moderate smartphone ownership rates observed in this study. Third, integrating environmental sustainability into agricultural intensification strategies is crucial.

3.3. *Environmental costs*

In this section, we sought to compute the direct and indirect environmental costs of maize production per hectare for each farm cluster using peer-reviewed data. Direct costs include expenses on pesticides and fertilisers, while indirect costs account for externalities such as greenhouse gas (GHG) emissions, nutrient runoff, soil degradation, pesticide impacts, and fertiliser impacts (refer to Appendix A.5 for further detailed descriptions of the framework). By quantifying these costs for each farm cluster, the analysis uncovers differences in cost structures, which carry implications for environmental sustainability and economic viability (Fig. 5).

Direct costs represent the immediate, localised impacts of maize production and exhibit substantial variability among the farm clusters (Fig. 5.b-c). Farm Cluster 3 (high-investment) incurs the highest direct cost (US$187.37 per hectare), primarily driven by high pesticide costs (US$134.14 per hectare) and fertiliser expenses (US$53.22 per hectare). In comparison, Farm Cluster 1 (low-investment) (US$86.73 per hectare) and Farm Cluster 2 (moderate-investment) (US$86.67 per hectare) have considerably lower direct costs but exhibit differing input patterns. Farm Cluster 1 allocates nearly 85 % of its costs to pesticides (US$73.13 per hectare), while Farm Cluster 2 demonstrates a more balanced distribution between pesticides (US$66.29 per hectare) and fertilisers (US $20.38 per hectare). The Farm Cluster 3's reliance on chemical inputs, without significant yield benefits over Farm Cluster 2 (Fig. 4.c), suggests inefficiencies in input use. In contrast, the balanced approach in Cluster 2 highlights potential efficiencies through optimised input use.

Indirect costs, reflecting broader environmental externalities, also show significant differences across farm clusters (Fig. 5.b-c). Farm Cluster 3 incurs the lowest indirect costs (US$312.34 per hectare), benefiting from efficient nutrient use, which minimises nutrient pollution costs (US$138 per hectare) despite heavy reliance on agrochemicals. Similarly, Farm Cluster 2 achieves relatively low indirect costs (US $319.23 per hectare), driven by reduced nutrient pollution costs (US $153.34 per hectare) and minimal pesticide impact costs (US$8.21 per hectare). In contrast, Farm Cluster 1 exhibits the highest indirect cost (US$453.96 per hectare), largely attributable to high nutrient pollution costs (US$277.91 per hectare). These findings align with Pandey and Diwan (2018), who emphasise that poorly managed nutrient applications in low-input systems can lead to substantial environmental externalities. However, the efficient nutrient management observed in Cluster 2 aligns with the arguments of Zhang et al. (2012), who identify optimised fertiliser use as a critical pathway for reducing agricultural pollution. Nutrient pollution emerges as the largest contributor to environmental costs across all clusters, underscoring the importance of fertiliser management. The ability of Farm Cluster 2 to achieve low nutrient pollution costs while maintaining cost efficiency and yields demonstrates the potential of precision nutrient management, as emphasised by Raza et al. (2023). In contrast, Farm Cluster 3's high pesticide costs reveal opportunities for adopting integrated pest management (IPM) approaches, as discussed by Dhawan and Peshin (2009), to reduce chemical dependence without compromising productivity.

From an environmental perspective, a scenario-based illustration of scaling the resource-efficient practices observed in Farm Cluster 2 suggests significant potential for improving sustainability (Fig. 5.a). In Cambodia, where approximately 5200 ha of maize are cultivated annually (NIS, 2021), adopting the efficient practices observed in Farm Cluster 2 could reduce total environmental costs by US$134.79 per hectare compared to Farm Cluster 1. This would represent an illustrative reduction of US$700,597 in environmental costs. Extending this scenario to the Southeast Asian maize area, estimated at 8.6 million hectares (FAO, 2022), suggests a hypothetical potential reduction of up to US $1.16 billion in environmental costs. While this scaling exercise relies on several assumptions, it serves to highlight the potential magnitude of environmental benefits if resource-efficient practices were adopted more widely across the region. These findings align with broader evidence from Southeast Asia. For example, a recent study in Vietnam by Chau and Ahamed (2022) found that mixed-cropping systems, improved organic fertiliser use, and access to irrigation significantly enhanced technical efficiency and yields in smallholder rice production. The study underscores the importance of targeted government support to optimise input use, particularly for smallholders with reliable irrigation. Similarly, research in Laos by Laing et al. (2018) showed that mechanised dry seeding in rice systems improved water-use efficiency and profitability while reducing production costs. Together, these examples reinforce the value of well-targeted investment strategies in achieving productivity gains without incurring excessive environmental trade-offs. At the same time, they highlight the need to tailor interventions to local agroecological and socioeconomic conditions.

This study highlights that judicious input management – balancing fertiliser efficiency, reduced pesticide use, and targeted nutrient application – can achieve intensification while minimising environmental impacts. These findings provide actionable insights for policymakers and practitioners to design tailored interventions for diverse farming systems. Investments in research, capacity-building, and performance-based incentives could further accelerate the transition toward sustainable and resilient agricultural systems.

3.4. *Underlying factors affecting crop yields and profit margins*

The correlation matrix, statistical modelling, and factor analysis reveal interactions between household characteristics, farming practices, and crop productivity, providing insights into the trade-offs that shape production, profitability, and environmental outcomes (Fig. 6.a-b).

First, demographic factors such as household size and the age of the household head significantly influence economic investments and farming decisions (Fig. 6.a). For example, the age of the household head negatively correlates with insect infestation ($r = -0.35$), indicating that older smallholders adopt better pest management practices, resulting in higher yields. Larger households, however, exhibit higher spending on land preparation ($r = 0.41$), which drives up overall production costs ($r = 0.56$). While extensive land preparation may improve initial soil conditions, it reduces soil moisture content (McGarry, 1987; Montgomery et al., 2016; Montgomery et al., 2017; Querejeta et al., 2000), necessitating higher seeding rates to compensate for reduced germination. This relationship is evident in the negative loading factor of soil moisture (−0.1) and the positive loading factor of seeding rate (0.35) in Fig. 6.b. Higher seeding rates increase seed expenditure ($r = 0.37$), moderately contributing to total production costs ($r = 0.36$). These

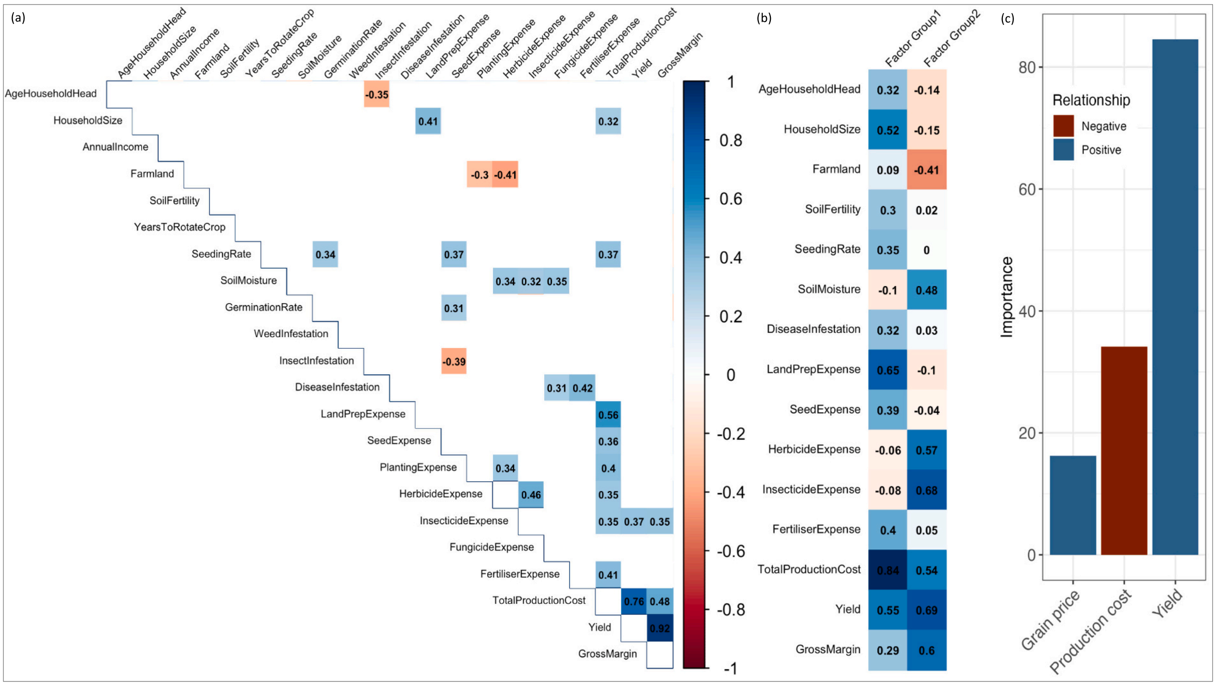

Fig. 6. Heat map of the correlation matrix (a) showing the strength and direction of relationships and loading factors from Factor Analysis (b) indicating the contribution of each measured variable to each factor group. Based on the variable characteristics of each factor group, Factor Group 1 is named as 'inefficient farm practices,' while Factor Group 2 is named as 'efficient farm practices'. The bar plot (c) presents the variable importance of grain yield, grain price and total production in affecting the gross margin of maize production. This variable importance was quantified through standardised coefficients that are used to compare the importance of variables that are on different scales. They are obtained by standardising both the predictors and response variable to have a mean of zero and a standard deviation of one before fitting the model. Our computation involved employing a multiple linear regression model, then we standardised coefficients by scaling the input data to have zero mean and unit variance, finally we computed the importance value of each variable by the magnitude of its standardised coefficient. Larger absolute values indicate higher importance.

patterns underscore inefficiencies in input management, particularly among smallholders employing resource-intensive practices.

Second, socioeconomic factors, particularly farm size, also influence cost efficiency and resource utilisation (Fig. 6.a). Larger farms benefit from reduced per-unit expenses for planting ($r = -0.30$) and herbicide use ($r = -0.41$), likely due to economies of scale. However, reduced herbicide application correlates with lower soil moisture content ($r = 0.34$), suggesting that weeds are more prevalent in wetter fields. This trade-off is particularly pronounced in inefficient farming practices, where excessive land preparation depletes soil moisture, increases seeding rates, and contributes to higher overall production costs.

Third, farm inputs are shown to play a pivotal role in determining productivity. Strong correlations between total production costs and yields ($r = 0.76$) and between yields and gross margins ($r = 0.92$) confirm that investments in inputs – fertilisers, seeds, and pest control – are fundamental to achieving higher crop yields (Fig. 6.a). However, while higher production costs lead to increased yields, they do not always translate into improved gross margins (Fig. 4.d). For instance, increased fertiliser expense correlates with higher disease infestations ($r = 0.42$), suggesting that improper fertiliser application exacerbates crop vulnerabilities and reduces profitability. This finding aligns with the study by Onwuchekwa-Henry et al. (2022), which demonstrated that a higher incidence of crop diseases is associated with increased fertiliser application.

Fourth, regression analysis is used to assess the relative influence of crop yield, grain price, and production cost on gross margins (Appendix A.6.), offering insights into how each factor contributes to the observed variation in farm-level performance. The model produced an R^2 value of 0.9955 and an adjusted R^2 of 0.9952, confirming the strong explanatory power of these predictors, which is expected, given that gross margins are a function of yield, price, and cost. However, the variable importance analysis (Fig. 6.c) reveals that crop yield is by far the most influential driver of gross margins, well above total production costs and grain prices. This finding reinforces the notion that enhancing yields, particularly through efficient and strategic input use, offers the greatest leverage for improving profitability. For instance, although Cluster 3 achieved the highest average gross margin (US$326 per ha), it did so with the highest production cost (US$614 per ha). By contrast, Cluster 2 achieved a nearly equivalent gross margin (US$303 per ha) while spending 22.5 % less on inputs. These findings suggest diminishing economic returns to high-input intensification and highlight the potential of moderate, well-targeted investments to support both economic and environmental sustainability.

Fifth, factor analysis identifies two distinct farming approaches with significant implications for economic viability and environmental impacts (Fig. 6.b). Smallholders in Factor Group 1 (inefficient farm practices) invest heavily in land preparation, reducing soil moisture retention and necessitating higher seeding rates to offset germination losses, aligning with the studies of Yu et al. (2019) and Shittu et al. (2017). This approach increases fertiliser use, which exacerbates pest infestations and leads to higher pesticide application. These cumulative costs reduce profitability and contribute to environmental degradation, including soil erosion and loss of fertility (Birkás et al., 2004). In contrast, smallholders in Factor Group 2 (efficient farm practices) adopt less intensive land preparation, preserving soil moisture and enabling reduced seeding and fertiliser rates. While wetter fields necessitate greater herbicide expenditure to manage weed growth, the overall efficiency gains in input use result in higher yields and improved profit margins. These findings align with prior studies (Blanco-Canqui and Wortmann, 2020; Handiso et al., 2023; Liebhard et al., 2022), which emphasise that maintaining soil moisture and reducing input waste are critical pathways toward sustainable agricultural intensification.

Overall, these results highlight the trade-offs inherent in current farming practices, underscoring the importance of balancing agricultural production, economic efficiency, and environmental sustainability. Strategies for sustainable intensification should prioritise optimising resource use, such as reducing excessive land preparation to retain soil moisture, improving input efficiency through precision fertilisation, and promoting integrated pest and weed management. For instance, reducing land preparation can lower seed and fertiliser costs while mitigating soil erosion, contributing to long-term soil health and productivity.

3.5. Investigating smallholder problems and constraints

The analysis of household demographic and socioeconomic data reveals pervasive challenges experienced by smallholders (Fig. 7.A–B). Strikingly, 95.65 % of smallholders reported problems related to changing rainfall patterns, intensive rainfall, drought, insect pests, and lack of technical knowledge. These findings underscore the critical impact of environmental and knowledge-based factors on agricultural productivity. Similarly, 93.48 % identified crop disease, low soil fertility, and weed infestation as major concerns, while financial constraints affected 84.78 % of respondents. High labour wages and substantial loan interest rates were reported as challenges by 86.96 % of smallholders, while issues such as low harvest prices and poor-quality inputs impacted 91.30 % and 89.13 % of respondents, respectively. Interestingly, only 15.22 % of smallholders reported difficulties selling their produce, suggesting that market access, while still important, is not as pressing an issue as others. However, challenges like limited

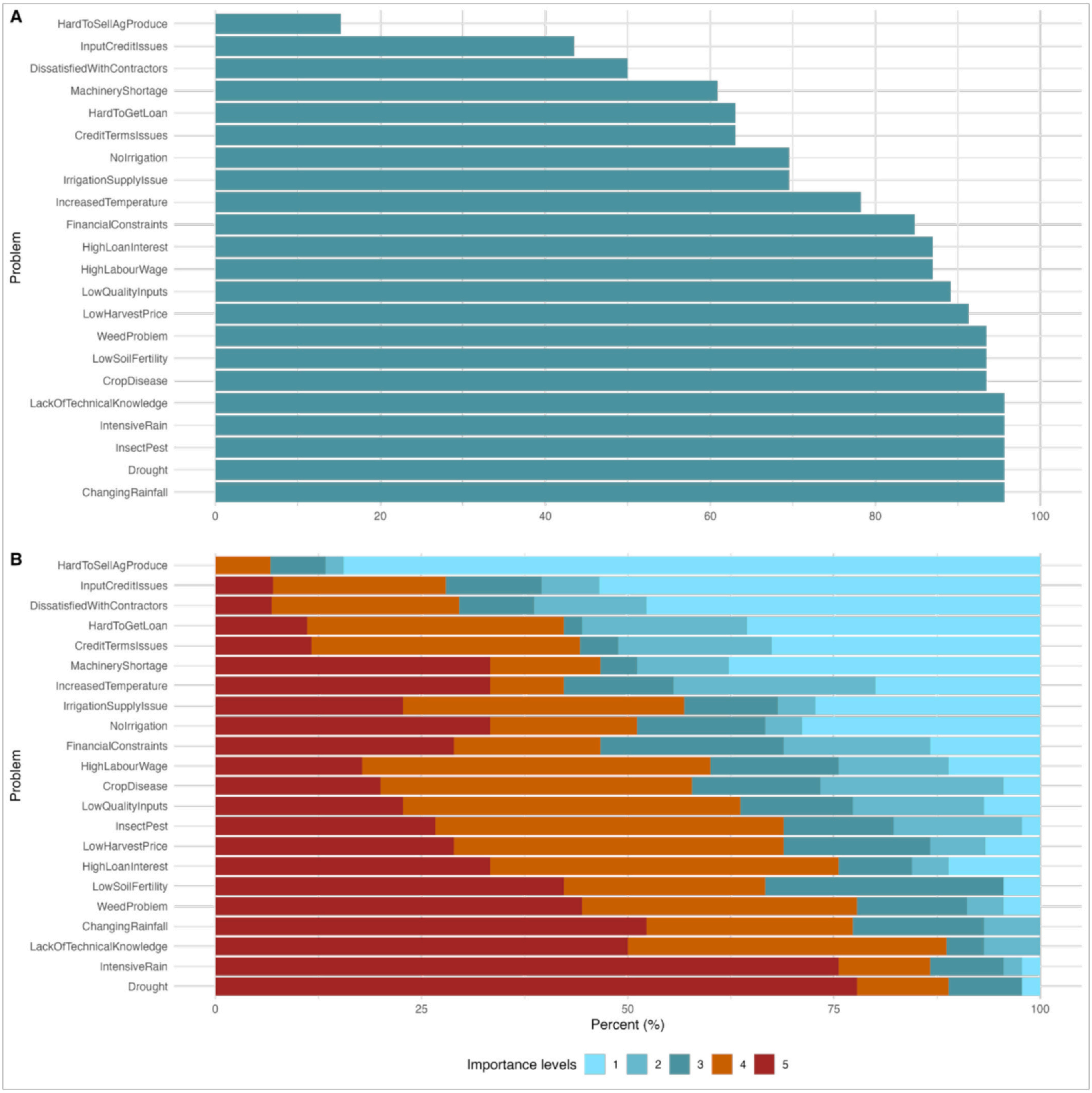

Fig. 7. Visualisation of smallholder problems and constraints: (A) presents the percentage of smallholders experiencing each problem as their own; (B) presents the importance levels of each problem (1 = Not important, 2 = Slightly important, 3 = Important, 4 = Fairly important, 5 = Very important).

irrigation supply (69.57 %) and dissatisfaction with farm contractors' services (50 %) highlight the infrastructural and operational barriers impeding productivity. In this context, farm contractors, who are commonly hired to provide mechanised services such as land preparation, planting, and harvesting, play an important operational role, especially for smallholders without their own equipment. Although contractor payments are embedded within broader cost categories (e.g., land preparation, planting, or harvesting), concerns about service quality, cost, and timeliness remain widespread among smallholders.

To better understand the relative importance of these challenges (Fig. 7.B), we computed a weighted score for each issue by multiplying the importance value (scaled from 1 to 5, where 1 signifies "Not important" and 5 signifies "Very important") by the percentage of respondents assigning each value. Key problems, such as changing rainfall patterns, drought, and intensive rainfall, had high weighted scores of 4.23, 4.62, and 4.56, respectively, highlighting severe environmental challenges that threaten farming sustainability. The lack of technical knowledge, with a weighted score of 4.32, underscores the urgent need for extension services to strengthen smallholders' knowledge and capacity. Other significant challenges included insect pests (3.76) and high loan interest rates (3.82), reflecting biological threats and financial barriers that hinder the enhanced agricultural productivity objective. Agronomic and economic stresses were also evident in the scores associated with low soil fertility (4.0), weed infestation (4.09), and low harvest prices (3.78), which could undermine agricultural production, economic viability, and environmental sustainability if left unaddressed.

Two critical findings emerge from this analysis. First, environmental challenges profoundly impact agricultural production. The near-universal concern among smallholders regarding changing rainfall patterns, drought, and intense rainfall underscores the significant threat posed by climate variability to agricultural productivity and sustainability. The high-weighted scores – 4.23 for changing rainfall patterns, 4.62 for drought, and 4.56 for intensive rainfall – underscore the severity of these issues. These findings align with previous studies (Ge et al., 2016; Meuwissen et al., 2019; Mirzabaev et al., 2023), which emphasise that climate change exacerbates such challenges, necessitating adaptive strategies to enhance resilience. For instance, climate-smart agriculture (CSA) approaches that incorporate drought-resistant crops, water management strategies, and precision farming techniques could address these challenges effectively. Second, financial constraints represent a significant barrier to sustainable agricultural practices. Approximately 84.78 % of respondents reported financial difficulties, with high labour wages (86.96 %) and substantial loan interest rates (86.96 %) compounding these challenges. Addressing these financial barriers necessitates innovative financing solutions, including policy reforms to reduce interest rates and improve access to affordable credit. Additionally, social support systems, such as subsidies for sustainable farming practices, can provide smallholders with the financial resilience needed to manage risks. These measures align with recommendations from studies by Azizi-Khalkheili et al. (2017); Onyishi et al. (2022); Siedenburg et al. (2012); and Teye and Quarshie (2022), which highlight the importance of economic resilience in fostering sustainable agricultural transitions.

Finally, exploring the interconnections between knowledge gaps, financial pressures, environmental stress, and input accessibility offers critical insight into the rationale behind smallholders' agronomic decisions. While this study did not directly ask smallholders why they adopted or avoided specific practices, the constraints identified suggest that decision-making is shaped by a complex interplay of capacity, perceived risk, and access to resources. Future research could build on these findings by employing qualitative or mixed-methods approaches to better understand how behavioural, informational, and structural factors influence smallholder decision-making across diverse agroecological and socioeconomic contexts.

4. Conclusion and recommendations

This study uncovers the interconnections between demographic-socioeconomic factors, agricultural practices, and environmental impacts, offering actionable pathways toward sustainable and resilient agricultural production among maize smallholders in Northwest Cambodia. The study demonstrates that moderate-investment practices represent a viable strategy for sustainable intensification, balancing economic viability with environmental sustainability. Efficient farm practices, characterised by optimised input use and reduced land preparation, achieved higher productivity and profitability while minimising environmental costs. Moderate-investment approaches, such as those observed in Farm Cluster 2, achieved comparable yields to high-input systems while significantly reducing nutrient pollution and pesticide reliance. In contrast, inefficient practices in Farm Cluster 1 exacerbated resource wastage, reduced profitability, and contributed to soil degradation, underscoring the importance of aligning farming practices with sustainability goals.

These findings suggest that supporting smallholders in adopting proven, cost-effective practices, such as improved land preparation methods, targeted fertiliser application, and context-specific pest management, should be a core policy priority. To accelerate their uptake, governments and development actors should invest in financial support mechanisms, including targeted subsidies and input cost-sharing schemes, to lower adoption barriers for resource-constrained smallholders. Strengthening agricultural extension systems is equally critical to ensure that smallholders receive timely, locally tailored agronomic guidance. In parallel, fostering farmer-to-farmer knowledge exchange can promote trust and peer learning, often accelerating behavioural change more effectively than top-down approaches. Finally, investments in digital advisory platforms and farmer cooperatives (Candemir et al., 2021; Kalogiannidis et al., 2024) can improve smallholders' access to affordable inputs, reduce transaction costs, and expand market opportunities, enabling broader participation in sustainable intensification efforts. While this study did not directly evaluate broader sustainability frameworks such as climate-smart agriculture, integrated pest management, or agroecological systems, these approaches may serve as guiding principles for future research and program development. However, we emphasise that scaling evidence-based, resource-efficient practices already used by smallholders in our study area offers a clear and actionable path forward.

By focusing on these grounded, achievable strategies, agricultural systems can transition toward greater resilience and sustainability, aligning agricultural intensification with environmental and economic goals. The findings of this study underscore the transformative potential of resource-efficient practices to enhance food security, reduce poverty, and minimise environmental harm. To leverage this transition, inclusive policies, targeted investments, and continued research on long-term impacts are essential to enable smallholders to intensify sustainably and equitably, contributing to the broader global sustainability agenda.

CRediT authorship contribution statement

Van Touch: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Ariane Utomo:** Data curation, Writing – review & editing, Writing – original draft, Methodology. **Nicholas Harrigan:** Methodology, Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **Caitlin Finlayson:** Writing – review & editing, Writing – original draft, Methodology, Data curation. **Andrew McGregor:** Writing – review & editing, Writing – original draft, Methodology. **Katharine McKinnon:** Writing – review & editing, Writing – original draft, Methodology. **Thong Anh Tran:** Writing – review & editing, Writing – original draft, Methodology. **Le-Anne Bannan:** Methodology, Writing – review & editing, Writing – original draft. **Daniel K.Y. Tan:** Writing – review & editing, Writing – original

draft, Methodology. **Phan Sophanara:** Writing – review & editing, Writing – original draft, Methodology, Data curation. **Panhaleak Chay:** Writing – review & editing, Writing – original draft, Methodology, Data curation. **Sophea Yous:** Writing – review & editing, Writing – original draft, Methodology, Data curation. **Kirt Hainzer:** Writing – review & editing, Writing – original draft, Methodology, Data curation. **Brian R. Cook:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors have no conflicts of interest to declare.

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Appendix A. Supplementary data

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Data availability

Data will be made available on request.

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