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Research Paper

Crop-livestock integration provides opportunities to mitigate environmental trade-offs in transitioning smallholder agricultural systems of the Greater Mekong Subregion

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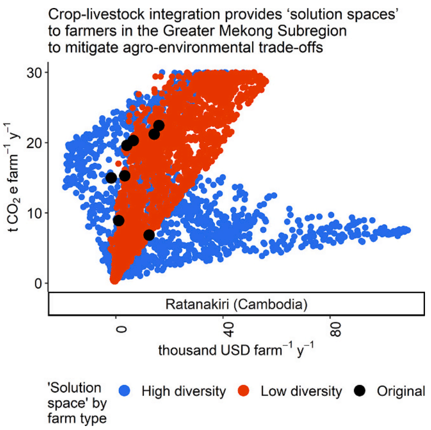
HIGHLIGHTS

- The Greater Mekong Subregion is undergoing rapid agricultural transformation, accompanied by negative environmental impacts
- This study explores the potential of crop-livestock integration to mitigate such agro-environmental trade-offs
- Nitrogen balances and greenhouse gas emissions were partly determined by transition stage, but not agricultural diversity
- Crop-livestock integration resulted in larger 'solution spaces' to mitigate trade-offs than business as usual
- Investment in research and extension is needed to develop and scale context-specific crop-livestock integration practices

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: The Greater Mekong Subregion has been undergoing rapid agricultural transformation over the last decades, as traditional diverse subsistence-oriented agriculture is evolving towards intensified commercial production systems. Negative environmental impacts often include deforestation, nutrient pollution, and greenhouse gas (GHG) emissions.

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Nutrient balances
Sustainability
Farming systems modeling

OBJECTIVE: This study aims to explore the potential of crop-livestock integration to mitigate trade-offs between economic and environmental impacts of smallholder farming systems at different stages of agricultural transition and degrees of agricultural diversity across the Greater Mekong Subregion.
METHODS: We chose a 'middle ground' between detailed modeling of few, representative farming systems and modeling of large household populations. 24 low and high diversity farms were selected in Laos (Xieng Khouang province), Cambodia (Ratanakiri province) and Vietnam (Central Highlands) from a survey dataset of 1300 households. These farming systems were simulated with the whole-farm bio-economic and multi-objective optimization model FarmDESIGN, calculating operating profit, GHG emissions and nitrogen (N) balance. Two optimizations ('business as usual' vs. 'crop-livestock integration') were performed, generating 'solution spaces' or alternative configurations aiming to maximize profitability, keep farm N balanced and minimize GHG emissions.
RESULTS AND CONCLUSIONS: Agricultural systems across the sites differed in their production orientation and management practices, representing various stages of agricultural transition. Nitrogen balances varied between sites, being negative in Ratanakiri (average − 20.5 kg N ha^{-1} y^{-1}) and Xieng Khouang (−36.5 kg N ha^{-1} y^{-1}) and positive in the Central Highlands (73 kg N ha^{-1} y^{-1}). Negative balances point to unsustainable mining of nutrients due to sale of cash crops without sufficient inputs, and positive balances to the risk of environmental contamination. Total GHG emissions ranged from 0.52–8.12 t CO_2e ha^{-1} and were not significantly impacted by stage of agricultural transformation or agricultural diversity. GHG sources in Ratanakiri and Xieng Khouang were determined by crop residue burning while in Central Highlands fertilizer and livestock were main emitters. High diversity farms obtained higher operating profits (10,379 USD y^{-1}) than low diversity farms (4584 USD y^{-1}). Crop-livestock integration, a combination of measures including introduction of improved forages grasses, manure recycling and residue feeding, and reduction of residue burning, resulted in larger 'solution spaces', thus providing farmers with more options to mitigate agro-environmental trade-offs.
SIGNIFICANCE: These findings underline the potential of crop-livestock integration to support sustainable intensification pathways in the Greater Mekong region. Public and private investment in further research and extension is needed to develop and scale context-specific crop-livestock integration practices.

1. Introduction

The Greater Mekong Subregion, comprising the countries along the Mekong River Basin in Southeast Asia, has been undergoing stark and rapid agricultural and socio-economic transformation over the last decades. Traditional diverse and subsistence-oriented agriculture is evolving towards intensified commercial production. Population is growing quickly, leading to an increased demand for crop and animal products (Quirke et al., 2003). Vietnam has shifted from a centralized to a market-oriented economy over the last 30 years. The Gross Domestic Product (GDP) per capita increased by 2.7 times between 2002 and 2018, and population increased from 60 million in 1986 to 96.5 million in 2019 (World Bank, 2021). In Cambodia, the population has increased from 14.7 million in 2013 to 15.3 in 2019 (NIS, 2019). The country reached lower middle-income status in 2015 and its economy was one of the fastest growing in the world during 1999–2018, with an average growth rate of 8% per annum (Asian Development Bank, 2019). In the Lao People's Democratic Republic (Laos), subsistence farming households have decreased from 94% to 80% (FAO, 2019), either by transitioning out of agriculture or intensifying towards market-oriented agriculture (Bouahom et al., 2004). The economic and population growth, combined with infrastructure development, improved market access and government policies, has resulted in different profound and multi-faceted transition pathways. These pathways vary in their geographic distribution, characteristics and rate of change across Vietnam, Cambodia and Laos, and represent different stages of agricultural transition (Johnston et al., 2009; Ritzema et al., 2019). They are driven by complex land use decision processes, and have generated a diverse landscape mosaic across the region (Burra et al., 2021). Rapid agricultural intensification and commercialization have often been accompanied by negative environmental impacts and increased pressure on natural resources, including loss of biodiversity, deforestation, nutrient pollution, declining forest covers, soil degradation, and greenhouse gases (GHG) emissions (Baird, 2017; Baird and Fox, 2015; Hor et al., 2014; Lin, 2011). The Green Revolution was driven by a package deal of improved seeds (breeding advances leading to high-yielding varieties of wheat, maize and rice), new inputs fueled by the development of the Haber-Bosch process (method of directly synthesizing ammonia from hydrogen and nitrogen), and availabiltiy of cheap energy from fossil fuels. Critics have been arguing that despite the economic development that the Green Revolution spurred in South-East Asia, its high reliance on external inputs such as fossil fuels and agrochemicals led to decreased environmental health, and more variable farm productivity and incomes (Ramankutty et al., 2018).

Sustainable intensification has been proposed by science and policy to address the challenge of feeding a growing global population from the same area of land while reducing environmental impacts (Godfray et al., 2010). However, despite the concept being endorsed and employed by various organizations including United States Agency for International Development (USAID) and the United Nations, sustainable intensification has remained poorly defined and understood. Concerns include the vague understanding of what 'sustainable' means, and whether it is a significant departure from business as usual (Peterson and Snapp, 2015). System redesign is considered to be essential to deliver optimum economic and ecological outcomes, going beyond increased efficiency and substitution (Pretty et al., 2018). Sustainable agricultural intensification aims to mitigate trade-offs between environmental protection and profitability (Peterson and Snapp, 2015; Tilman et al., 2011). The integration of crops and livestock is often seen as one ingredient for sustainable intensification as it offers multiple management and sustainability benefits including provision of nutrients for crop production through manure, provision of draft power and crop residues and forage that serve as animal feed (Herrero et al., 2007). Commercialization, specialization and industrialization of agriculture has often led to a separation of crop and livestock sub-systems thus recoupling is seen as an important step to sustainable management in agriculture (Ramankutty et al., 2018). The potential impact of crop-livestock integration practices like feeding of crop residues, cultivation of improved forages and the increased use of animal manure for crop fertilization have been assessed. However, little explicit exploration into environmental impacts in the Greater Mekong has been conducted to date (Birnholz et al., 2017; Castella, 2012; Castella et al., 2018; Epper et al., 2020; Stür et al., 2013). It is important to note that there is no one-size fits all solution, and both the nature and the magnitude of impacts of crop-livestock integration practices varies by farming system (e.g. Douxchamps et al., 2016; Giller et al., 2011). Agricultural diversity has been identified as a key driver of variation in the Greater Mekong (Epper et al., 2020; Ritzema et al., 2019), but is also an important adaptation strategy for food under continued population increase, dietary shifts and climate change. Indeed, agricultural diversity spreads risk among different crop and livestock types, ensures varied income sources, and balances between market orientation and self-sufficiency (Waha et al., 2018).

The range of profitable management options that a farmer can choose from without compromising future productivity and environment protection can be called a solution space (Martin et al., 2013). The delimitation of these solution spaces for smallholder farming systems is therefore critical for the sustainable agricultural intensification of the Greater Mekong, and is the first step of a system redesign process (Prost et al., 2018). A multitude of agro-environmental indicators exist that are helpful instruments to assess farming systems, their sustainability and trade-offs (Langeveld et al., 2007; Smith et al., 2017). Performance can be compared considering various objectives and resource balances (Groot et al., 2012). Whole-farm bio-economic models, especially with multi-objective optimization functions, have been highlighted by the agricultural systems research community to be particularly helpful to explore trade-offs and solution spaces, and their differential interplay in various farming systems and agro-ecosystems (Jones et al., 2017; Kanter et al., 2018; Klapwijk et al., 2014; Paul et al., 2020a). In multi-objective optimization, the model can generate alternative farm configurations that represent the solution space that the farming system can navigate and that visualizes potential trade-offs and synergies between different agricultural production, environmental and economic objectives (Groot and Rossing, 2011; Groot et al., 2012). Such detailed modeling offers insights into dynamics and allows for participatory feedback cycles, but often relies on selecting few, representative farming systems which risks omitting within-type variability. Multi-disciplinary studies remain necessary to explore impacts and trade-offs of crop-livestock intensification and other sustainable intensification practises to inform policies and technology dissemination in South-East Asia (Burra et al., 2021).

This study aims to explore the potential of crop-livestock integration to mitigate trade-offs between economic and environmental impacts of transitioning smallholder farming systems across the Greater Mekong Subregion. More specifically, we i) analyze economic and environmental performance and trade-offs of smallholder farming systems at different stages of agricultural transition and degrees of agricultural diversity; ii) and explore solution spaces to mitigate these economic-environmental trade-offs through crop-livestock integration practices. We hypothesize that a) stage of agricultural transition and degree of agricultural diversity impact environmental performance, and that b) crop-livestock integration can improve immediate profits while reducing negative environmental impacts in smallholder farming systems, with high diversity systems having a wider range of applicable options.

2. Materials and methods

2.1. Study sites

Three sites were selected to represent different stages of agricultural transition from subsistence orientation to commercial production, following previous characterization in Ritzema et al. (2019) and Burra et al. (2021). Ratanakiri province in Cambodia, Xieng Khouang province in Laos, and the Central Highlands in Vietnam are characterized by specific farming practices, climatic and topographic conditions (Table 1).

Table 1
Main topographic, climatic and agricultural practices characteristics of the three study regions Xieng Khouang, Ratanakiri and Central Highlands.

		Cambodia	Laos	Vietnam
Province	Unit	Ratanakiri	Xieng Khouang	Dak Lak and Dak Nong[i]
Capital city of province		Banlung	Phonsavan	Buôn Ma Thuột and Gia Nghĩa
Latitude/ longitude of provincial capital city		13° 44′ 48″ N, 107° 0′ 16″ E	19° 27′ 36″ N, 103° 10′ 48″ E	Dak Lak 12° 40′ 0″ N, 108° 3′ 0″ E Dak Nong 11° 59′ 0″ N, 107° 42′ 0″ E
Topography[ii]		Mostly flat	Upland	Flat plateau
Elevation[ii]	m.a.s.l	200-400	1200	400–900
Average precipitation rate[ii]	mm y^{-iii}	2,318[iii]	1590	Dak Lak: 1,630[iv] Dak Nong: 2019
Average temperature	°C	26.2	19.6	Dak Lak: 24.2[iv] Dak Nong: 23.4
Common soil type		Acrisols	Acrisols[v]	Basaltic soil[iv]
Main agricultural system		Low-inputs, mixed subsistence and markets	Mostly subsistence	Mostly market-oriented, high inputs
Main crops produced[ii]		Rice, cassava, cashew, soybeans, rubber	Rice (paddy and upland), maize for feed, cassava, chili, banana, vegetables for household, tea, forages	Paddy rice, coffee, pepper, cashew, maize, cassava, forages
Main livestock kept[ii]		Poultry	Cattle, pigs and poultry	Cattle, pigs and poultry
Population density[ii]	Persons/ km^2	19[vi]	16	94–143

[i] The study farms in the Central Highlands of Vietnam span across two provinces, Dak Lak and Dak Nong. Farms were located close to the border with Dak Lak.

[ii] Information retrieved from Ritzema et al., 2019 if not indicated otherwise.

[iii] The rainy season in the Cambodian study region accounts for about 99% of the total yearly precipitation.

[iv] Dak Lak Statistics Office (2019); Dak Nong Statistics Office (2019).

[v] Information retrieved from Epper et al., 2020

[vi] NIS, 2019

Smallholder farming was dominant in all three sites, although production orientation and management practices differed. In Xieng Khouang province, smallholder crop-livestock farms were mainly subsistence-oriented, based on rice (*Oryza sativa* L.) and vegetables (different varieties in home gardens), with few cash crops (tea, maize, banana and chili). Slash-and-burn practices remained common, while mineral or organic fertilizers were not widely used. Poultry and pigs were left free during the day and additionally fed with maize grains bought at the local market. Cattle were mainly left grazing on the own pasture land and additionally fed with local or improved forages (*Brachiaria ruziziensis*, *Pennisetum purpureum*). Although cattle fattening was starting to emerge, livestock was generally kept for household consumption or as asset in case of sudden cash need. In Ratanakiri, smallholder farmers have started to cultivate more cash crops, due to improved road infrastructure with Vietnam, increasing attraction of external investors, and conversion of forest and pasture into rubber, cashew and cassava plantations. Similar to Laos, poultry and pigs were raised for home consumption, and few ruminants were kept as asset. The situation in the Central Highlands was much more intensive, with high use of chemical inputs and focus on coffee, pepper, cashew and sugarcane for sale. The region has undergone a clear transition from subsistence to market orientation in the last three decades, particularly after the prohibition of the shifting cultivation practice in 1981 (Salemink, 2003). Rice and vegetables were mostly produced for household consumption. The local government has supported meat production and most farmers have intensified from extensive grazing to specialized, crossbred cattle species fattening practices and the production of improved cut-and-carry forage.

2.2. Household survey and selection

Two broad approaches to whole farm modeling and trade-off analysis can be distinguished: detailed modeling of few farming systems, types or classes that are considered representative, or quick calculations across a population of households. In this study, we decided for ‘middle ground’, aiming to combine the strengths of both approaches through not omitting variability within types while at the same time being able to gain insights into detailed dynamics. We therefore relied on a large survey dataset of more than 1300 households from where we derived a farming systems classification based on agricultural diversity. Then, we proceeded to in-depth understanding of the farming system types by modeling a larger-than-usual set of 24 households to have replicates per farming system. The procedure and methods are described in the following.

A baseline survey dataset was used for classification and farm selection, which was carried out among 632 households selected randomly in Ratanakiri, 366 in Xieng Khouang, and 310 in the Central Highlands between December 2015 and March 2016 (Ritzema et al., 2019), using the Rural Household Multi-Indicator Survey (RHoMIS) tool (Hammond et al., 2017). Focus group meetings and discussions with local experts, conducted in February and March 2017, allowed identifying agricultural diversity as one of the main factors behind the observed variation between the sites.

Agricultural diversity is defined in this study as the sum of crop and livestock diversity, with one count per one crop or one livestock species. Home gardens are also counted as one, although we acknowledge that those can harbour various different crops that are important for nutritional diversity. The diversity score was calculated for each household, and households were then categorized into two distinct farm types: Low diversity (LD) and high diversity (HD). The threshold between low and high diversity was site-specific, based on frequencies of each diversity score across the entire RHoMIS dataset (see Supplementary Material SM1), and validated by local experts. Low diversity was defined as <6 for Xieng Khouang, and <5 for Ratanakiri and Central Highlands, while high diversity was set to be >7 for Xieng Khouang and >6 for both Ratanakiri and Central Highlands. Farms falling into the middle range values, or “buffer zone”, were excluded. RHoMIS survey villages with important representation of each type were selected for visits in each site, during which farms were randomly selected, subject to accessibility and availability of the farmers, for a total of four farms per type and site, or 24 farms. Fig. 1 indicates the locations (Fig. 1a) and the diversity scores of the modeling farms (red lines) against the entire household dataset (Fig. 1b).

The same data collection process described in Epper et al. (2020) was used to interview the 24 case study farms. In brief, all farmers were interviewed between March – June 2017 using the IMPACTlite survey (Rufino et al., 2009) to collect quantitative data on assets, farm production and management. Additional data on environmental characteristics and nutrient contents was found in literature (see Supplementary Material SM2 for complete list of parameters used for the study).

2.3. Agro-environmental indicators

The 24 case study farms were simulated using the whole-farm bio-economic optimization model FarmDESIGN (Groot et al., 2012), which calculates the impacts of various farm configurations on a large set of agro-environmental and socio-economic performance indicators. Applications globally have suggested the model is robust enough to accommodate various agro-environments and farming systems, and its functionality has been illustrated in South-East Asia in various recent studies (Birnholz et al., 2017; Epper et al., 2020; Ditzler et al., 2019; Estrada-Carmona et al., 2020; Timler et al., 2020). FarmDESIGN has been evaluated in terms of design-, output- and end-user validity. However, uncertainty lies in the quality of input data, as well as parameterization of degradation, nutrient losses and organic matter (OM) breakdown (Groot et al., 2012). The inputs required for the model can be grouped into: (i) biophysical environment (e.g. soils, climate); (ii) socio-economics (e.g. input costs, labour price); (iii) crops and crop products yield, composition and use; (iv) livestock and livestock products yield, composition and use; (v) manure types and degradation, and mineral fertilizer use; (vi) household members and labour availability.

In this study, farm performance was evaluated in terms of farm nitrogen (N) balance, greenhouse gas (GHG) emissions and operating profit using the same system boundaries as in Epper et al. (2020). The indicators for the 24 farms were calculated as follows:

$$\text{Nitrogen balance}\ \left(\text{kg N ha}^{-1}\ \text{y}^{-1}\right)\ (\text{input–output})$$
$$= (f1+f2+f3+f4+f5) - (f6+f7+f8+f9+f10+f11+f12+f13) \tag{1}$$

where f1: Feed import; f2: Import manure; f3: Biological N fixation; f4: N-deposition; f5: Import mineral or organic fertilizers; f6: Animal products for household; f7: Export animal products; f8: Export animal manure; f9: Manure volatilization; f10: Crop products for household; f11: Export crop products; f12: Export crop residues; f13: N volatilization of crop residues burned.

$$\text{Operating profit}\ \left(\text{USD y}^{-1}\right)$$
$$= \textit{Gross margin crops} + \textit{gross margin livestock} - \textit{fixed costs} - \textit{variable costs} \tag{2}$$

where gross margin crops and gross margin livestock: the products that the farmers produce on their farm and that could potentially be sold; fixed costs: land rent, equipment and building costs – on our study assumed to be zero in this study as farmers mainly cultivate on their own land and use minimal equipment; variable costs: refer to expenses for fertilizer, crop protecion, green manure, feed and hired casual labour. Exchange rates of 4085 Cambodian Riel (KHR), 8692 Lao kip (LAK), 23,208 Vietnamese Dong (VDN) to the US Dollar were applied (exchange rates from October 2019).

The GHG emission module of FarmDESIGN is described in detail in Paul et al. (2019), relying on a combination of IPCC Tier 1 and 2 methods. In brief, it includes the following GHG sources: (i) methane (CH_4) from livestock enteric fermentation, (ii) CH_4 and direct and indirect nitrous oxide (N_2O) from manure storage and application, (iii) N_2O from mineral fertilizer application; (iv) direct and indirect N_2O from soils through N input from crop residue retention, N fixation and atmospheric deposition, (v) CO, CO_2, N_2O, NOx and CH_4 from burning of organic material. Input data on livestock numbers, manure production, crop residue use, and fertilizer and manure application were multiplied with IPCC Tier 1 emission factors. N manure excretion rate was calculated by the model taking into account protein intake by livestock and protein digestibility of the feed basket, so that manure related N_2O emissions can be considered an IPCC Tier 2 method. Calculated N_2O and CH_4 emissions were converted into CO_2 equivalents (CO_2e) by multiplying by their respective global warming potentials – 21 for CH_4 and 310 for N_2O. Off-farm GHG emissions, for example for fertilizer or feed production, are not taken into account.

Farm characteristics and agro-environmental indicators were compared using a combination of farm type (LD referring to Low Diversity and HD referring to High Diversity) and study region (Ratanakiri, Xieng Khouang and Central Highlands). Since the sample size within each farm type and region was low (i.e. $n = 4$), and the residuals of the response variables, i.e. agro-environmental and economic characteristics (Nitrogen Balance, GHG emissions/ha and Operating profit) did not exhibit normal distribution, we employed non-parametric tests to test for significant differences in agro-environmental and economic variables, between regions, between farm types and between farm types within each region. Therefore, we first performed an analysis that

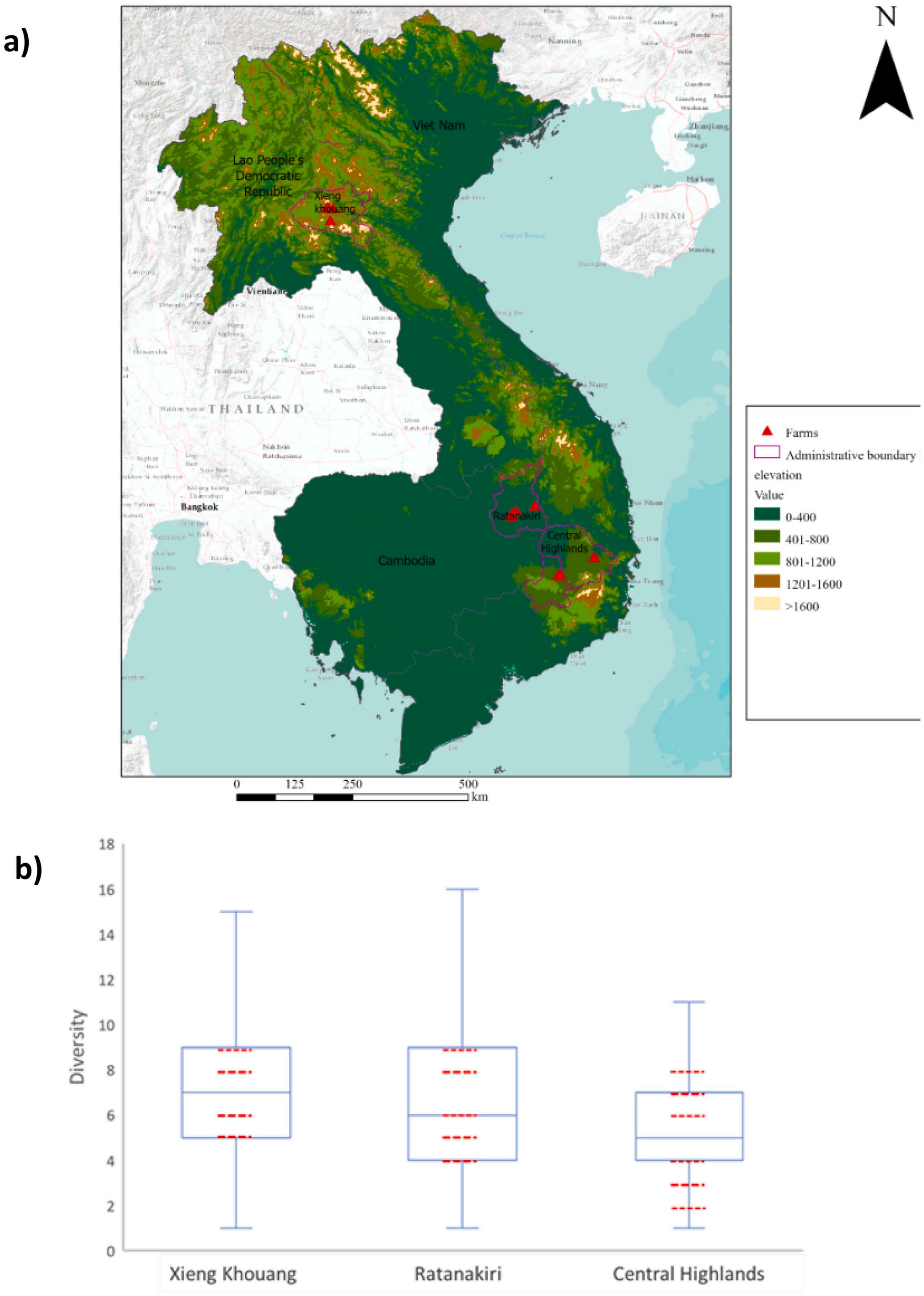

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Fig. 1. Location of case study farms for bio-economic modeling in Xieng Khouang, Ratanakiri and Central Highlands, mapped on elevation in meters above sea level (from https://www.worldclim.org/), administrative boundaries (from https://gadm.org) and the world terrain reference map from ESRI (a) and box plot of case study farms in Xieng Khouang, Ratanakiri and Central Highlands (red lines – thicker lines indicating two farms at the same level) scored against all approximately 1300 RHoMIS households (b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

assessed, if there were significant differences in agro-environmental and economic characteristics between the three study regions independent of farm types, using a Kruskal-Wallis Chi Squared test. We further followed this analysis, by investigating if there were significant differences in agro-environmental and economic characteristics between LD and HD farm types, independent of regions, using a Wilcoxon rank sum test procedure. Additionally, we used the Wilcoxon rank sum test procedure, to further investigate differences between LD and HD farms within each region separately. In the case of Kruskal-Wallis Chi-squared test, the obtained p-values were adjusted using the Benjamini-Hochberg approach. Both the Kruskal-Wallis Chi Squared test and Wilcoxon rank sum test procedure were performed using using BaseR functions (R Core Team, 2020).

2.4. Multi-objective optimization

FarmDESIGN contains a multi-objective Pareto-based optimization algorithm that can evaluate and minimize trade-offs between several production objectives. The model generates clouds of alternative farm configurations, based on available resources and provided with a limited room and decision variables to reallocate these (Groot et al., 2012).

Two optimization runs were applied to the 24 farms (Table 2). The aim of both multi-objective optimizations in this study was set to maximize the operating profit, minimize GHG emissions, maximize organic matter balance, and minimize (Central Highlands) and maximize (Ratanakiri, Xieng Khouang) farm N balance. In the first optimization (business as usual), the model was provided with various decision variables to select the best outcomes. The farms could only produce the same crops and livestock they had before, but could increase area used for the production of the cash crop and could increase their livestock holdings. Farms could also increase their inputs, refering to fertilizer application and feed imports. For the second optimization (crop-livestock integration), we gave the model the option to increase diversity of crops by introducing new cash and forage crops including legumes. The model also had the option to change crop management practices such as residue retention and burning, and manure recycling for crop fertilization. Livestock production could be intensified through increasing feed import and increased livestock numbers and body weight. In both optimizations, land area could not be increased more than 5% than the currently managed area, and the livestock feed at maintenance must be guaranteed. The crop-livestock intensification scenario represents an alternative development pathway that has been encouraged by policies and programs throughout the region. In Cambodia, one of the strategic focuses of the government is to push the investment in research development of high value-added crops, livestock and aquaculture to improve agricultural productivity, quality and diversification (Royal Government of Cambodia, 2018). The Agricultural Development Strategic Plan 2019–2023 aims to modernize farming practices and to build more infrastructure to become more competitive and resilient to climate change, thus enhancing productivity, diversifying potential crops and commercialization (MAFF, 2019). In the Central Highlands of Vietnam, local government advocates for development of the beef value chains to meet the high domestic demand and create economic opportunities for smallholder farmers (Stür et al., 2013). Dak Lak and Dak Nong's Provincial People Committee explicitly encourages crop diversification in its provincial restructuring agricultural plans, and envisions the development of the livestock sector towards incentive systems by 2020 (MARD, 2009; Dak Lak PPC, 2016; Dak Nong PPC, 2018).

Table 2
Objectives, decision variables and main constraints for two optimization runs for 24 farms in FarmDESIGN: business as usual vs. crop-livestock integration.

Optimizations	Business as usual	Crop-livestock integration
Objectives	• Minimize GHG emissions • Maximize operating profit • Maximize organic matter balance • Minimize (Central Highlands) or maximize (Ratanakiri, Xieng Khouang) the farm N balance	
Decision variables	• Increase the production of the crop that is most profitable on the current market (commercial cash crop)	• Increase the diversity of crops produced on the farm by addition of cash crops and legumes as well as *Stylosanthes guianensis* and *Pennisetum purpureum* as improved forages for feeding additional cattle
	• No changes in crop and livestock management practices (e.g. crop residues burning, manure recycling)	• Decrease the crop management practices that have a negative environmental impact (e.g. crop residue burning)
	• Increase the production of the livestock holdings and body weight production, if the farm is already managing livestock	• Increase the production of the livestock holdings and body weight production, and add cattle where farmers are not keeping any
	• Increase the feed import amount	• Increase the feed import and production amount
	• Add mineral fertilizers as possible external input	• Increase the recycling of livestock manure and add mineral fertilizer as possible external input
		• Increase the amount of crop residues that are either fed to own livestock or used as green manure
Main constraints	Total cropped area cannot be increased by more than 5% of current managed area. Livestock maintenance must be guaranteed in respect to feeding dry matter, energy and protein intake.	

3. Results

3.1. Characterization of low and high diversity farming systems across an agricultural transition gradient

Household size was similar for all sites though slightly higher for HD farms (Table 3). The cropping area in Ratanakiri was higher than in the Central Highlands for both LD and HD. In all sites, HD farms had larger cropping areas than LD farms with the difference being least pronounced in Central Highlands (1.6 ha HD, 1.1 ha LD) and more pronounced in Ratanakiri (6.7 ha HD, 3.9 ha LD) and Xieng Khouang (3.5 ha HD, 1.1 ha LD). Farmers in Xieng Khouang used about half of their production for household consumption (45% LD, 53% HD), while in the Central Highlands (24% LD, 20% HD) and Ratanakiri (20% LD, 7.5% HD) this percentage was much lower. Median Tropical Livestock Units (TLU) tended to be higher in HD than LD farms across all sites, with the largest differences in Central Highlands (0.3 LD, 2.0 HD) and Xieng Khouang (0.2 LD, 4.5 HD) and smallest livestock holdings in Ratanakiri (0.2 LD, 0.3 HD) (Table 3).

In Ratanakiri, farmers could exploit larger farm sizes (3.5–10.5 ha) for rubber, cashew, and cassava for markets in Vietnam and China (Fig. 2a). The Central Highlands had intensified production systems on relatively small farms (0.5–3 ha), focusing on major cash crops such as cassava, cashew, coffee, and pepper (Fig. 2a) under external mineral fertilizer inputs of more than 100 kg N ha-1 in six out of eight farms

Table 3
Median, minimum and maximum values of key characteristics of the 24 study farms (four per type and site) in the three study regions Ratanakiri (Cambodia), Xieng Khouang (Laos) and Central Highlands (Vietnam).

			Ratanakiri			Xieng Khouang			Central Highlands		
Farm type		Unit	median	min	max	median	min	max	median	min	max
LD	Diversity score	–	4.5	4	5	5	5	6	3	2	4
	Household members	#	5	4	6	4.5	4	5	4	3	6
	Cropping area	ha	3.9	3.3	10	1.1	0.2	4.8	1.1	0.5	2.8
	Share of production for home consumption	%	20	9	87	45.5	2	107	24	2	79
	Livestock units	TLU	0.2	0	1.2	0.2	0.2	2.7	0.3	0	1.5
	Share of ruminants in TLU	%	0	0	0	0	0	78	0	0	87
HD	Diversity score	–	8	6	9	8	6	9	7	6	8
	Household members	#	6.5	5	9	5.5	4	7	4.5	4	5
	Cropping area	ha	6.7	4.2	10.5	3.5	1.2	7	1.6	1.3	1.9
	Share of production for home consumption	%	7.5	1	40	53.5	20	73	20	5	92
	Livestock units	TLU	0.3	0.2	4.3	4.5	1.9	9.8	2.0	1.2	2.5
	Share of ruminants in TLU	%	0	0	98	72	38	88	67.5	0	92

(Fig. 4a). Xieng Khouang farms on the contrary produced more crops for home consumption than in the other two sites. While tea production has been a source of income for many decades, maize has started to be produced on the hillsides. Extensive grazing on pasture was also common practice for Xieng Khouang, and the production of forages as feed for cattle fattening practice was increasing as well (Fig. 2a).

The TLU distribution reflected the livestock systems of the three study regions (Fig. 2b). LD farms tended to keep a smaller number of livestock, particularly poultry, in all three provinces (Table 3). Usually farmers produced feed from their own farms, and only imported small quantities. Farms in Ratanakiri kept fewest livestock of which mostly poultry for household consumption, and only one farm held ruminants as asset and for ceremonies. Xieng Khouang farmers owned the largest TLU and ruminant numbers which were mostly local breeds (calves and cows), while some kept improved breeds that were fattened and sold on the international market (three out of eight farms). HD farms in Xieng Khouang all kept at least one cow, and sometimes also a small herd which stays on the own pasture or grazes freely during the day. Farms in Central Highland had the most intensified livestock keeping systems, relying on cattle fattening and improved breeds fed under cut-and-carry, often with improved varieties of Napier grass (*P. purpureum*) and then sold to the market. Pigs were common in both Xieng Khouang and Central highland farms and sold to the market as regular source of income.

3.2. Economic and environmental performance of farming systems

Mean nitrogen (N) balances across both HD and LD farms were negative for Ratanakiri (average − 20.5 kg N ha^{-1} y^{-1}) and Xieng Khouang farmers (−36.5 kg N ha^{-1} y^{-1}), and significantly differed from those of Central Highlands (73 kg N ha^{-1} y^{-1}; Kruskal-Wallis chi-squared = 10.573, df = 2, BH adjusted p-value <0.05 between Ratanakiri and Central Highlands, BH adjusted p-value <0.05 between Xieng Khouang and Central Highlands). Highest N balance was found in the Central Highlands (192 kg N ha^{-1} y^{-1}), and lowest in Xieng Khouang (−96 ha^{-1} y^{-1}) (Fig. 3a). Total GHG emissions ranged from 0.52–8.12 t CO_2e/ha. No significant differences in GHG emissions were observed, either between regions, or between farm types, and even between farm types within each region (Fig. 3b). However, in the case of operational profits, HD farm types obtained higher (10,379 USD y^{-1}), and marginally significant operating profits in comparison to LD farm types (4584 USD y^{-1}; Wilcoxon rank sum test, p-value <0.05; Fig. 3C). However, the same was not observed when comparing between LD and HD farm types within each region. Neither did operating profits differ significantly between the three regions (Fig. 3c).

In Ratanakiri the high N outputs caused by the export of cash crops were not compensated by adequate nutrient provision, resulting in nutrient mining (Fig. 4a). External N inputs were only provided through biological fixation due to substantial soybean cultivation, balancing some of the nutrient export through cash crops. HD farms in Ratanakiri produced rubber and cashew nuts which need less nutrient supply than other annual cash crops. In the Central Highlands, farmers tended to over-compensate the export of N with high input quantities of mineral fertilizer particularly for coffee production, resulting in strongly positive N balances for almost all farms. Significant nutrient export through cash crops in Xieng Khouang was only found in two farms producing maize for the international market. Main N imports in this site were feed (maize grain for poultry) and in one case manure from neighbors. In Xieng Khouang, both LD and HD managed wild tea or tea plantations, which provided the opportunity to earn income, but did not influence the final N-balance as much as maize monoculture (Fig. 4a).

The main source of GHG emissions in Ratanakiri and Xieng Khouang was burning of organic material, dominated by cassava residues (Ratanakiri) and maize stalks (Ratanakiri and Xieng Khouang) (Fig. 4b). Paddy rice production resulted in considerable GHG emissions from most farms. GHG emissions from ruminants reflected the higher livestock holdings in Xieng Khouang and Central Highlands. Central Highlands farms were the only ones applying mineral fertilizers at high rates, but compared to other GHG sources these GHG emissions were considerably smaller (Fig. 4b).

3.3. Exploring solution spaces for crop-livestock integration vs. business as usual

The size of the 'solution space' or performance of alternative farm configurations that the model generates provides indication for the number of options these farms have to navigate agro-environmental trade-offs (Fig. 5). In both scenarios, business as usual (5b) and crop-livestock integration (5d), a trade-off was apparent between profitability and GHG emissions, though higher profitability could be achieved with crop-livestock intensification under similar GHG emission increases. The relationship between profitability and N balance was more diverse (Fig. 5a and c). In general, HD farms had larger solution spaces than LD farms. Slopes, incremental changes per unit profit, were lower for HD farms than for LD farms, almost everywhere, showing that the negative effects (increased GHG emissions or disbalanced N) were less dramatic in HD farms for each increase in profit. Farms in Central Highlands had smaller solution spaces (often rather linear than scattered spaces) than the farms in Ratanakiri and Xieng Khouang related to the small available cropping areas in the Central Highlands which limits their opportunities. In the 'crop-livestock integration' optimization (Fig. 5c, d), the solution spaces and thus options to mitigate trade-offs for all farms for both N balance and GHG emissions increased when compared to 'business as usual'. Farms in Ratanakiri had more options to reduce agro-environmental trade-offs than farmers in the other sites (Fig. 5).

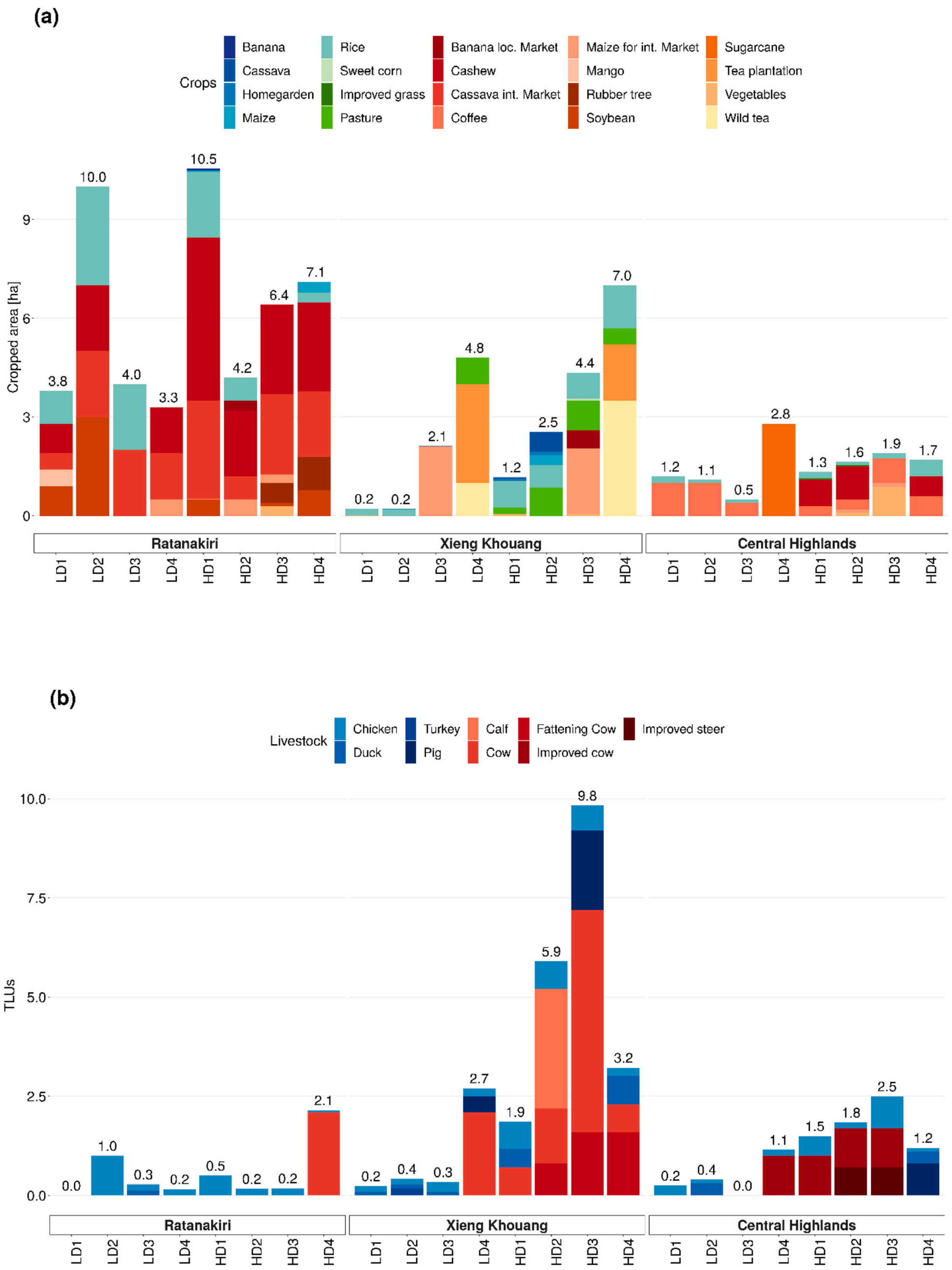

Fig. 2. Cropping areas (a) and total livestock units (TLUs) (b) for 24 study farms in Ratanakiri (Cambodia), Xieng Khouang (Laos) and Central Highlands (Vietnam). Crops and livestock in blue are mainly produced and kept for household consumption, while red colors indicate produce for the local or international market. Maize, bananas and cassava are represented twice as they are often either used for home consumption or sold to the markets. The numbers above the stacked barplots indicate total cropping area (ha) (a) and total TLUs (b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

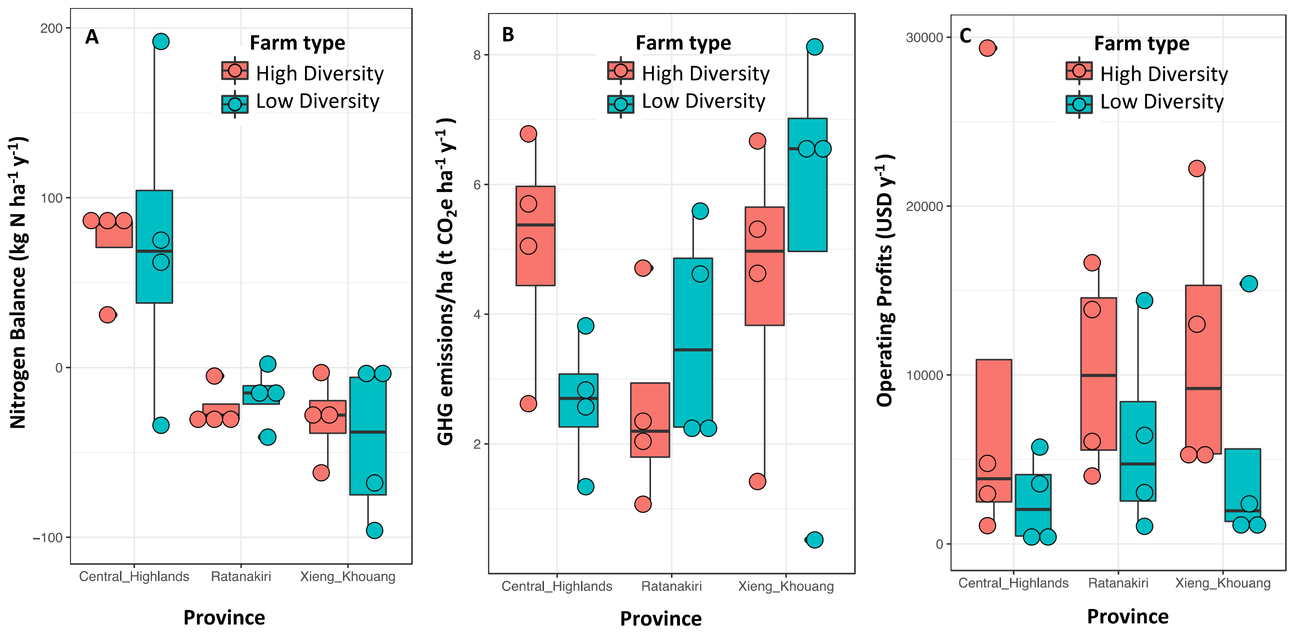

Fig. 3. Boxplots representing differences in (a) Nitrogen balance (b) GHG emissions and (c) operating profits between High Diversity (HD) and Low Diversity (LD) farms located in Ratanakiri (Cambodia), Xieng Khouang (Laos) and Central Highlands (Vietnam).

4. Discussion

4.1. Environmental performance under current agricultural practices

Agricultural systems in Ratanakiri, Xieng Khouang and Central Highlands differed in their production orientation and practices, representing various stages of agricultural transition. In the Central Highlands, farms have developed towards market-oriented systems, with large input use and livestock produced for sale. Xieng Khouang in Laos and Ratanakiri in Cambodia display more convergent traits of transition, having access to larger cropping areas and producing cash crops to a varying degree, with dominance of home consumption in Xieng Khouang. Ratanakiri had hardly any livestock holdings except poultry while livestock keeping in Xieng Khouang was mainly extensive and for home consumption. Environmental impacts of agricultural production per unit area could only be partly related to the stage of agricultural transition. Farmers in the Central Highlands had significantly higher N balances than in the other two regions. This is linked to processes of commercialization and small landholdings, and farmers have intensified using large amounts of available and affordable mineral fertilizers. Positive nutrient balances between 80 and 100 kg N ha^{-1} have been found in other studies from Vietnam as well (Phong et al., 2010). Although target values for N management and balances depend on specific contexts, Quemada et al. (2020) suggest 80 kg N ha^{-1} as an upper boundary beyond which environmental contamination is expected. N balances were mostly negative for Ratanakiri and Xieng Khouang farmers, pointing to ongoing nutrient mining due to low input use despite sale of cash crop products. In Ratanakiri, cropping land was increased by relatively recent forest clearing so that nutrient replenishment has not yet become urgent. Legacy soil fertility, relatively large cropping land sizes and wide-spread soybean cultivation still provide sufficient nutrients to sustain productivity in the meantime. Findings for Xieng Khouang farmers are in line with Epper et al. (2020), who have reported that the traditional soil fertility management technique, fallows of 5–10 years, are not possible anymore but that the new, more intensified cropping systems without nutrient replenishment is unsustainable. GHG emissions did not differ significantly between regions, though the GHG sources varied. Main source in the Central Highlands was fertilizer use, and in Ratanakiri and Xieng Khouang the common practice of cassava and maize residue burning. The prohibition of slash-and-burn practices in the Central Highlands showed its effects, while the practice is still common in Ratanakiri and Xieng Khouang (Burra et al., 2021). Total GHG emissions from the studied farms ranged from 0.52–8.12 t CO_2e/ha, and were lower than for example in smallholder crop-livestock systems in Central Kenya where average emissions ranged from 4.5 to 12.5 t CO_2e/ha with highest emissions from farms with high livestock density and high input use (Ortiz-Gonzalo et al., 2017). Seebauer (2014) found whole-farm emissions from Western Kenya ranging from 5.9–10.1 t CO_2e/ha, while Paul et al. (2018) calculated annual GHG emissions of 0.4–1.5 t CO_2e per household in Rwanda (Paul et al., 2018) and 2.9–16.2 t CO_2e per household in Northern Tanzania (Paul et al., 2019). Agricultural diversity did not consistently impact environmental outcomes. This trend parallels with Ritzema et al. (2019) who found dietary diversity not being determined by single consistent factors across all sites, but influenced by different determinants in each site. Burra et al. (2021) also found various, context-specific drivers for complex land-use change in the Greater Mekong region. Impacts of transition on dietary diversity, land use change and environmental impact appear site-specific and therefore require contextualized policies and approaches.

4.2. Potential of crop-livestock integration to mitigate economic-environmental trade-offs

Crop-livestock integration referred to a package of options to the farms including more productive livestock herds, higher crop diversity including forage legumes and grasses, decrease of crop residue burning, more manure application to crops and residue feeding to livestock. This was contrasted with a business as usual scenario that focused on increasing cash crop production (Table 2). Crop-livestock integration resulted in larger ‘solution spaces’, thus providing farmers with more options to mitigate economic-environmental trade-offs. HD farms tended to have larger solution spaces than LD farms, and farms in Ratanakiri had more options available while farmers in the Central Highlands the least. These solution spaces can also be seen as wiggle room, giving farms the space to maneuver and making them more resilient. The more diverse a system, the more integrated it has the potential to be, the greater the resilience through complementarity

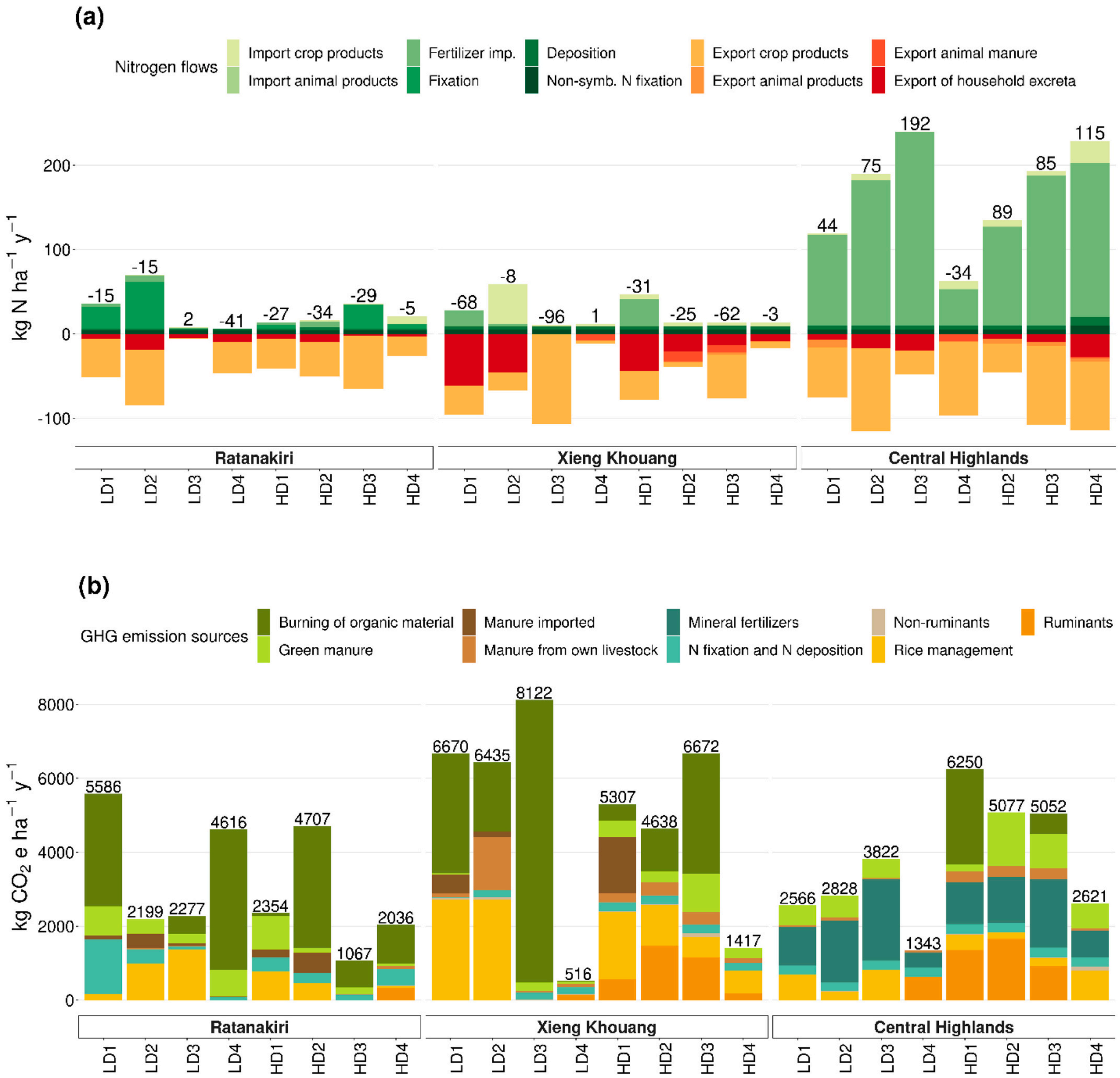

Fig. 4. (a) N balance (kg N ha^{-1} y^{-1}) across farm types and study sites in Ratanakiri (Cambodia), Xieng Khouang (Laos) and Central Highlands Vietnam. The numbers above the stacked barplots represent the total N balance per farm. Fertilizer imp. refers to both animal manure and mineral fertilizers (a). GHG emissions (kg CO$_2$e ha^{-1} y^{-1}) per year across farm types and study sites. The numbers above the stacked barplots represent the total GHG emission per farm and hectare (b).

mechanisms (Gil et al., 2017). Livestock, when well-managed and closely integrated with crop production, could potentially play an important role to mitigate economic-environmental trade-offs by converting residues into animal-source food and manure for fertilization while reducing the polluting practice of residue burning. A previous study demonstrated that forage-based livestock fattening can increase operating profits by 35%, while maintaining soil organic matter and decreasing GHG intensities (Birnholz et al., 2017). Timler et al. (2020) demonstrated the potential for crop diversification options to satisfy household dietary needs and generate income gains in Vietnam, while Estrada-Carmona et al. (2020) also point to trade-offs between achieving both nutritional and economic objectives. This study underlined that realizing the potential of livestock's positive contribution to sustainable intensification will require a shift of perception towards a more nuanced discussion and investment (Paul et al., 2020b). However, despite the technical potential of such solutions that this and other modeling studies can illustrate, adoption at farm level is determined by additional, practical factors. In the case of improved livestock feeding and forages, such factors include lack of awareness and knowledge, low support, and lack of available and accessible inputs, labor and market linkages. More systemic issues around land tenure, challenging transitions of entire production systems and differences in production objectives can also inhibit adoption of closer crop-livestock integration (Paul et al., 2020a).

4.3. Methodological reflections on whole farm modeling and optimization

In terms of methods, this study aimed to take the middle way between two basic contrasting approaches to whole-farm modeling of

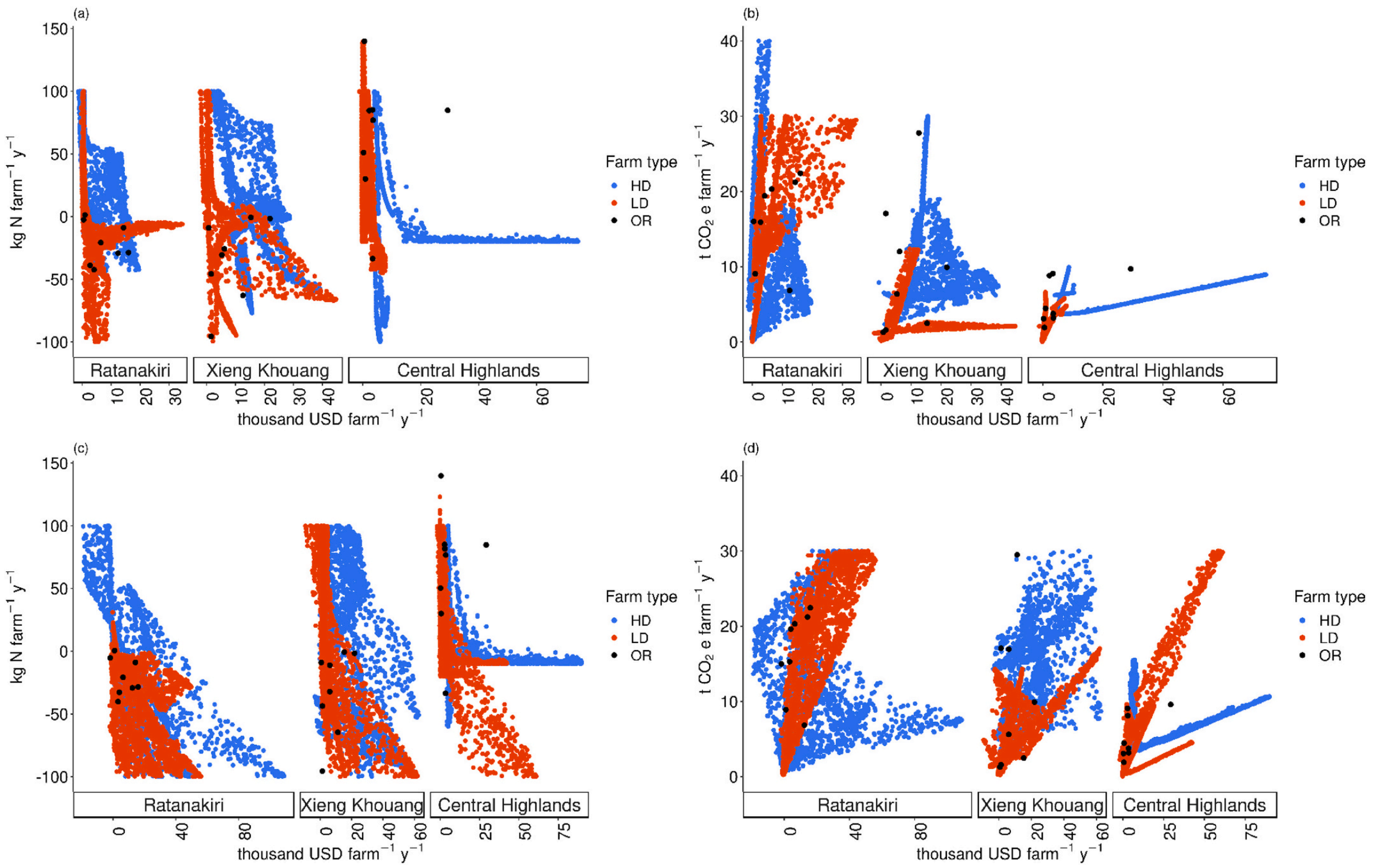

Fig. 5. 'Solution spaces' or performance of alternative farm configurations for 24 farms to achieve higher farm profitability, balanced N balance and lower GHG emissions 'business as usual' (a and b) and 'crop-livestock integration' (c, d) across the three study sites Ratanakiri (Cambodia), Xieng Khouang (Laos) and Central Highlands (Vietnam). For optimization settings and assumptions, see Table 2. The original farm configurations are given in black (OR), the possible solutions for low diversity (LD) and high diversity (HD) farms are indicated in red and blue respectively.

smallholder systems: i) Detailed modeling of few farming system types or classes that are considered representative (typically <10), or ii) quick calculations and modeling of a population of households (typically 30 - >10,000). We relied on a large survey dataset of more than 1300 households from where we derived a farming systems classification based on agricultural diversity. Then, we proceeded to in-depth understanding of the farming systems types by modeling a larger-than-usual set of 24 households to have replicates per farming system. Table 5 illustrates the two contrasting approaches with selected studies and their geographic scope and number of farming systems/households modeled. Methods for selecting farms can be classified as 'real' versus 'constructed'. By 'real', we refer to an actually existing farm that is considered representative for the farming system type, which can be identified in various ways. It can be selected from a household dataset through multivariate statistics (e.g. Alary et al., 2016; Cortez-Arriola et al., 2014; Paul et al., 2019; Rigolot et al., 2017; Waithaka et al., 2006), or through participatory Focus Group Discussions (Michalscheck et al., 2018). A farm can also be purposively selected to test and illustrate functionalities of a new model or modules (Ditzler et al., 2019; Parsons et al., 2011). Generic or constructed farming systems, thus not corresponding to existing households, have been defined for large geographic areas using various data sources including literature, policy documents, census data and expert knowledge (Mayberry et al., 2017, 2018) or from mean values of household survey data for each particular type (Descheemaker et al., 2018). The second approach is modeling entire household populations. Relatively simple indicators, such as land productivity, food availability and self-sufficiency, greenhouse gas emissions (IPCC Tier 1), household income, or dietary diversity score can be calculated for all households of a household survey. Although not necessary in this approach, results are often presented in strata following the particular research question. Strata could be based on research questions (Shikuku et al., 2017), classes identified in the outcome variables such as food availability or greenhouse gas emissions (e.g. Frelat et al., 2016; Paul et al., 2018; Ritzema et al., 2017), or types identified through multivariate statistics (Douxchamps et al., 2016; Falconnier et al., 2015; Lopez-Ridaura et al., 2018).

The selection of our mixed methods aimed to combine the strengths of both approaches. Modeling of real and existing households allowed for the modeling to be conducted in a participatory manner, fostering the dialogue with farmers between 'actual' and 'desirable' systems (Prost et al., 2018). We could also verify and validate data used for model parameterization and calibration, and obtain a more in-depth understanding of dynamics and complexities. Having replicates for each farming system type enabled us to not omit variability within types, and we could perform statistical analysis on results that is often not possible when modeling of single households per type.

This study aimed to explore the potential of crop-livestock integration to mitigate trade-offs between economic and environmental performance. Farming systems research is mainly seen here as a problem-solving process, where emphasis is placed on the computational exploration of solution spaces (Martin et al., 2013). Drawing the boundaries of these spaces is essential but we acknowledge that it is just the first step in a necessary further process to identify which practical solutions within these spaces are most appropriate and practically feasible. This step will have to be embedded in a participatory process, involving stakeholder with different backgrounds and skills, and working at different scales, to offer a more balanced view of issues and potential solutions. Far from linear, this is an iterative process of co-learning and

Table 5
Selected studies illustrating two contrasting approaches to whole-farm modeling of smallholder systems, including geographic scope and number of farms/ households modeled.

		Geographic scope	Number of farming systems/ households	Reference
i) Modeling of farming system types	Constructed	India, Ethiopia	4	Mayberry et al., 2018
		India, Ethiopia	5	Mayberry et al., 2017
		Mexico: Yucatan	1	Parsons et al., 2011
		Zimbabwe: Nkayi	6	Descheemaker et al., 2018
	Real	Tanzania: Babati	4	Paul et al., 2019
		Burkina Faso: Yatenga	2	Rigolot et al., 2017
		China: Gansu	3	Komarek et al., 2012
		Kenya: Vihiga	9	Waithaka et al., 2006
		Mexico: Michoacan	6	Cortez-Arriola et al., 2014
		Ghana: three regions	9	Michalscheck et al., 2018
		Vietnam: Son La	2	Ditzler et al., 2019
		Brazil: Cerrados	6	Alary et al., 2016
ii) Modeling of household population		Mali: Koutiala	30	Falconnier et al., 2015
		India: Uttarakhand	42	Ditzler et al. 2018
		Tanzania: Lushoto district	164	Shikuku et al., 2017
		India: Bihar	269	Lopez-Ridaura et al., 2018
		Burkina Faso, Ghana, Senegal	600	Douxchamps et al., 2016
		Rwanda: different districts	884	Paul et al., 2018
		Kenya, Tanzania, Uganda, Ethiopia, Senegal, Burkina Faso	1019	Henderson et al. 2016
		East and West Africa: 7 countries	1800	Ritzema et al., 2017
		Sub-Saharan Africa	13,000	Frelat et al., 2016

negotiation (Klerkx et al., 2010; Martin et al., 2013). These changes will need to be supported by private and public investments, as well as appropriate policies, to develop and scale context-specific crop-livestock integration practices.

5. Conclusions

This study aimed to explore the potential of crop-livestock integration to mitigate trade-offs between economic and environmental impacts of transitioning smallholder farming systems across the Greater Mekong Subregion. Agricultural systems in Ratanakiri, Xieng Khouang and Central Highlands differed in their production orientation and practices, representing different stages of agricultural transition. Environmental impacts in terms of N balances and GHG emissions were only partly determined by agricultural transition, while agricultural diversity did not affect environmental impacts. Crop-livestock integration resulted in larger 'solution spaces', thus providing farmers with more options to mitigate agro-environmental trade-offs.

The results of this study illustrate the potential of crop-livestock integration to support much-needed sustainable intensification pathways in the Greater Mekong, where rapid commercialization is leading to environmental trade-offs. Livestock, when well-managed and closely integrated with crop production, can convert residues and roughages into animal-source food and manure for fertilization while reducing the polluting practice of residue burning. However, the global public discussion has long focused on livestock's negative health and environmental impacts, resulting in under-investment in research and development programs on livestock in low- and middle-income countries. Realizing the potential of livestock's positive contribution to sustainable intensification will require a shift of perception towards a more nuanced global discussion (Paul et al., 2020b). This study therefore underlines the need for public and private investments in research and extension to develop and scale context-specific crop-livestock integration practices in support of sustainable intensification pathways in the Greater Mekong.

Declaration of competing interest

The authors have no conflict of interest to report.

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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.2021.103285.

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