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Ecological Modelling

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https://doi.org/10.1016/j.ecolmodel.2023.110435

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Ecological Modelling 483 (2023) 110435

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

In highly-biodiverse tropical landscapes, multiple-objective optimization reveals opportunities for increasing both conservation and agricultural production

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ARTICLE INFO

Keywords:
Agronomy landscapes
Simulation models
Multifunctional landscapes
Agriculture-driven deforestation

ABSTRACT

In humid tropics, small and medium farming systems are important for producing food but also because they retain rainforest patches with high conservation value. Forest conservation and agricultural production strongly compete for land in Tropical Farming Systems (TFS). Finding solutions that synergize increasing conservation areas and agricultural production is an issue that has yet to be resolved in human-modified tropical landscapes. Achieving this objective requires analyzing how farms could be reorganized to relieve the pressure for production on the land. Pareto-based genetic algorithms that produce a set of solutions that satisfy apparently opposed objectives may tackle multi-objective problems. We explored trade-offs and synergies to increase the profits by sustainable intensification and maintain or increase rainforest areas in five TFS. There was a strong trade-off between conservation and economic profits in all TFS. However, depending on the total farming area, initial configurations and the amount of external inputs used, TFS showed low (two out of five) or high (three out of five) potential to increase forest conservation and profits. In low potential areas, the expansion of conservation areas and profits was only possible by increasing external inputs, primarily due to the limiting farming area and intensification status in those areas. In contrast, in high potential areas it was possible to increase conservation areas and profits through sustainable intensification practices, such as increasing maize silage, changing high for low use-pesticides crops but also reducing variable costs by minimizing cost-supply uses or external feeds. Alternative management and resource allocation options were specific for each TFS. The multi-objective simulation yielded novel results showing that it is possible to overcome the conservation-production antagonism (a regional-global scale issue) by adjusting management at farm (local) scale.

1. Introduction

Small and medium farming systems (<15 ha size) sustain more than 380 million farming households worldwide, they produce more than 70% of the food calories in the regions where they are present and are responsible for more than 50% of the food calories produced globally (Samberg et al., 2016). This group of farmers may be incentivized to change their land-use under the influence of cash commodities crops and the pressure of large-scale stakeholders, and land tenure insecurity (Meyfroidt et al., 2014). Moreover, small family farmers face vulnerabilities due to climate change with less resources to achieve innovation and actions for adaptation (Bouroncle et al., 2017; Donatti et al., 2019; Liu et al., 2023).

Tropical farming systems (TFS) have been developed in the regions with most biodiversity in the world (Laurance et al., 2014). Currently, in these regions there is a fast spread of simplified large-scale cropping systems (rice, soybean, palm oil and pastures for cattle) that threaten not only tropical rainforest (Pendrill et al., 2022) but also the diverse and multifunctional land-uses that are typical of peasants' and indigenous traditional systems (Toledo et al., 2003). Monoculture expansion has put pressure to remove the remaining natural tropical patches inside the systems that still host species diversity and provide regulation and support ecosystem services (Alamgir et al., 2016; Riva and Fahrig, 2022).

To address these issues, landscape ecology and agronomy have developed different approaches, which could be integrated. From the

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https://doi.org/10.1016/j.ecolmodel.2023.110435
Received 2 May 2023; Received in revised form 26 May 2023; Accepted 4 June 2023

perspective of landscape ecology, outside the protected areas there is a widely spread landscape structure, recently defined as “Human Modified Landscapes” (Melo et al., 2013). In these landscapes, small, medium and more recently big-sized farming systems co-occur with old-growth forest fragments, and patches of second-growth forests (Gardner et al., 2009). In this context, the amount of forest areas inside TFS is the best driver for forest management conservation (Ochoa-Quintero et al., 2015; Rocha-Santos et al., 2017; Wies et al., 2021).

According to the agronomic approach, one important challenge in TFS is to develop alternative land-uses and management practices, which increase farm productivity and economic profits in the local context of economy of subsistence (Donatti et al., 2019). Thus, the agronomic strategy should guarantee economic development while not involving large expenses that farmers cannot afford (Kanter et al., 2018). The sustainable intensification approach may consider agroecological practices such as diversification of cropping systems, nature mimicry, and some forms of conservational agriculture (Altieri, 2002; Tittonell, 2014). Major and widely applicable managements implemented in the context of sustainable intensification includes decreasing external inputs (pesticides, fertilizers and external feeds) and increasing crops diversification and farm self-resilience (Cortez-Arriola et al., 2016; Flores-Sánchez et al., 2015).

In systems that involve productive and environmental objectives while meeting farm and conservation constraints, interactions between objectives may behave as trade-offs or synergies. The use of tools that enable farm re-configuration and provide insight into the interactions between these objectives would be important to inform farmers and stakeholders about potential adjustments to be implemented. Simulation models have been developed to tackle this issue at the farm, landscape, and regional levels (Chopin et al., 2015; Groot et al., 2012; Todman et al., 2019). Some of these models are based on multi-objective optimization algorithms that generate a large set of Pareto-optimal alternative farm configurations characterized by adjusted management and resource allocation that satisfy the required initial conditions. Such models depart from the original system configuration and generate a set of alternative solutions that satisfy the initially established constraints. The Pareto ranking procedure selects the better performing solutions compared to the initial situation by mimicking the principles of the natural selection. This process is repeated until all solutions are assigned to an optimized Pareto rank (detailed procedures can be found in Groot et al., 2012). Multi-objective models have been applied in natural resource and production management systems (Groot et al., 2010, 2007; Todman et al., 2019). In Mexico, they have been applied to dairy and maize-livestock systems to improve initial agronomic and environmental situations (Castelán-Ortega et al., 2003; Cortez-Arriola et al., 2016; Flores-Sánchez et al., 2015).

The most common analysis to identify agronomic performance in agricultural systems, across scales is the yield gap analysis (Affholder et al., 2013; Neumann et al., 2010; Van Ittersum et al., 2013) which detects the causes of limitations in different agricultural systems (Affholder et al., 2013; González-Quintero et al., 2022; Mayberry et al., 2017). Often, agricultural activities report wide yield gaps in TFS. However, sometimes a wide yield gap obtained from considering a high attainable crop yield (most suitable genotype) does not reflect the reality of the local context, where, for example, a low yield landrace is chosen because it has other preferred traits like pest resistance or high post-harvest durability (Abakemal et al., 2013; Ndoli et al., 2019). Moreover, yield gap analysis does not include the relationships of all the activities within the TFS, much less analyzes resulting synergies, nor does it provide improvement alternatives. Our study extends beyond yield gap analysis by considering the local context and the complex realities of TFS through multi-objective modeling. Our approach involves examining different TFS to explore practical alternative management solutions that have the potential to enhance agricultural production while concurrently preserving or expanding forest areas inside TFS. This approach not only offers potential reconciliations of goals, but also provide an alternative perspective and valuable insights for the land-sharing versus land-sparing framework (Baudron et al., 2021).

The objectives of this study were i) to explore trade-offs and synergies aiming to increase the profits by sustainable intensification and at the same time maintain or increase tropical rainforest areas inside TFS, ii) to investigate the management and land-use configurations that provide alternative solutions in the simulation outcomes, and iii) to analyze pathways for the TFS to satisfy the demands of increasing agricultural production while maintaining or increasing forest areas.

2. Materials and methods

2.1. *Case study region*

The Marqués de Comillas region (MDC) (16°54′N, 92°05′W), Southeast Mexico (Fig. 1) covers an area of ~2008 km^2. Average annual precipitation is about 3000 mm with a three-month dry season (February-April less than 60 mm month^{-1}) and with an average monthly temperature of 22 °C (Martínez-Ramos et al., 2009). Before 1970, MDC was completely covered by old-growth forest. Later, MDC was part of the Mexican federal government’s land distribution program (Tarrío García and Concheiro Bórquez, 2006). The region experienced immigration from different states of Mexico. Many groups of peasants and indigenous people from different states and also from Guatemala (de Vos and Marion, 2015) arrived to start or continue their farming activities. They were grouped into “*ejidos*”, communities with a relative degree of institutional organization (Alcorn and Toledo, 1995).

Federal incentives during the 1970s-80 s promoted cattle pastures and staple crops and more recently palm oil production (Carabias et al., 2015). Currently, ~70% of the region is covered livestock pastures, crop fields (such as maize, bean, chili), palm oil plantations, and patches of secondary and old growth forest (Zermeño-Hernández et al., 2016). However, given that the *ejidos* are mostly constituted by people with the same place of origin and are therefore rather homogeneous, the differences between *ejidos* are large and are reflected in the different agricultural production characteristics associated with the customs of the inhabitants (Berget et al., 2021; Lohbeck et al., 2022; Wies et al., 2022).

2.2. *Interviews and farming systems characterization*

Sixty-two interviews were conducted in the MDC in five *ejidos* with different origin groups. At least eleven interviews were conducted in each *ejido* representing more than 9% of the total number of farmers in the sample and 9.5% of the total area of the *ejidos*. To characterize the TFS we designed a semi-structured interview aiming to describe the whole farm land-uses and the main drivers and farm functioning incurred. The most frequent land-uses on the farms were maize cropping, cattle ranching and remaining forest areas followed by bean, palm oil and maize cropping for silage (Fig. S1 and Table S1). For each crop, we asked about the main drivers behind inputs and outputs. When we visited the farmers and carried out interviews, we toured the countryside together with the farmer while asking the questions. This tour served us to visually check the information they provided and to georeference the vertices of the farm to check the extents they indicated.

2.2.1. *Model-based farm construction*

For each community we modelled a typical farm. First, we counted current activities in farms grouped into *ejido*. We considered activities practiced by five or more farmers (Supplementary Material, Fig S1). Land-uses for each typical farm are shown in Table S1. Inputs, outputs and management decisions for land-uses are detailed in Figure S2. For cattle production, we collected data pertaining to herd structure, meat production, body weight, dry matter intake (DMI), labor input, and sanitary and reproductive management. For the cropping activity, we collected inputs (seeds, fertilizers, herbicides and insecticides) and outputs (grain or fruit yields and estimated manure). Also, we registered

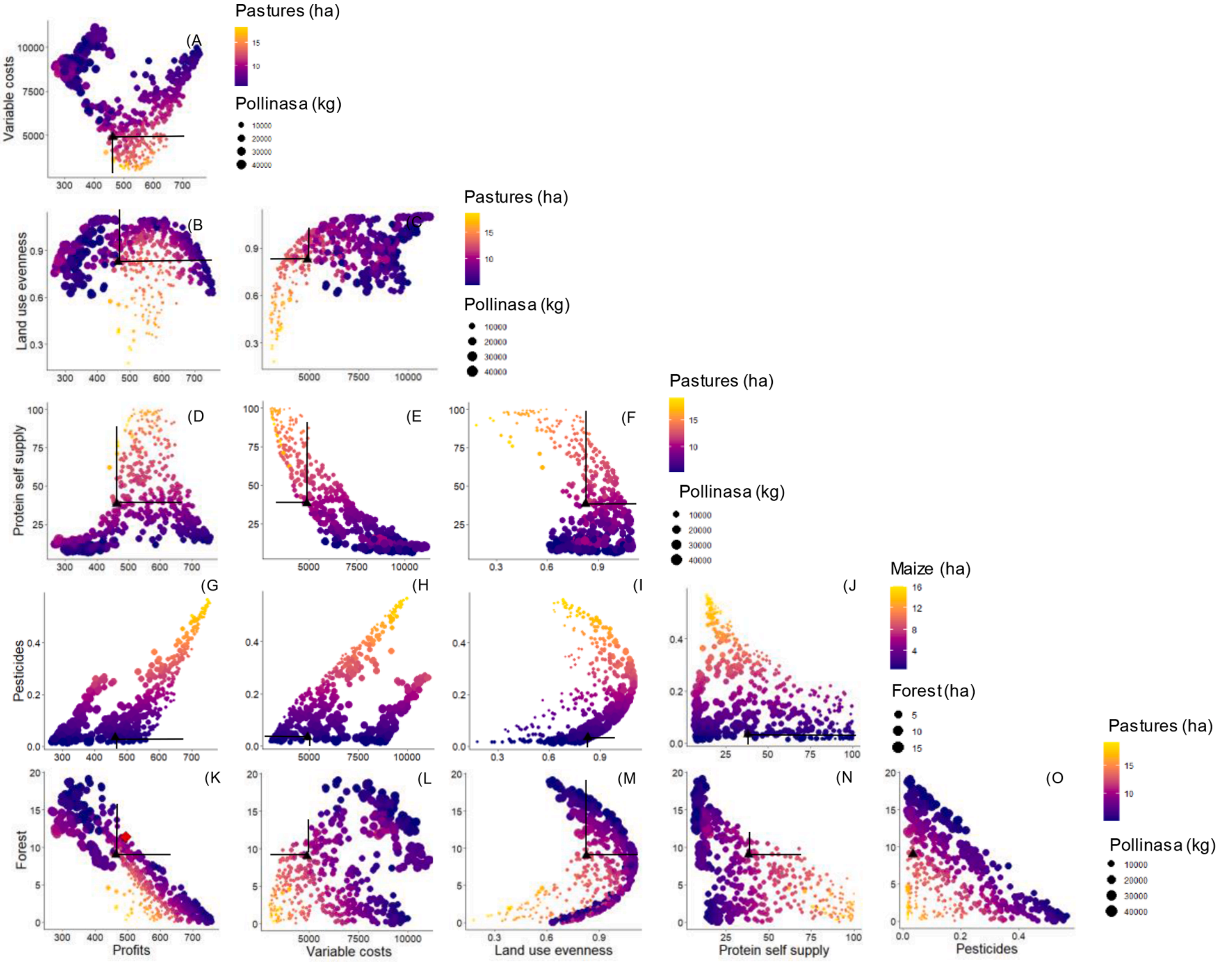

Fig. 1. Relations between optimization objectives for San Jose farm (SJ). Each dot represents one alternative solution resulting from optimization. Triangles denote the farm initial situation. The black lines represent synergic improvement relative to the original situation. For Y-axes the two most correlated farm drivers (variables) are detailed with colors (first correlated) and dot size (second correlated).

forage species and utilization (to estimate grass productivity) and labor, costs, subsidies and allocation. For cattle production, parameters to estimate DMI capacity, metabolizable energy (ME) and crude protein (CP) requirements per animal type in the herd were obtained from NRC standards (NRC, 2001). Nutrient requirements for maintenance, growth and meat production were obtained from NRC (2001) as well.

2.3. Data analysis

2.3.1. Description of the model

We used the FarmDESIGN model to explore trade-offs or synergies between optimization objectives as influenced by management choices about areas of agricultural land-uses and conservation areas and amounts of inputs like agrochemicals and external feed for livestock. FarmDESIGN algorithm uses a Pareto-based version of the evolutionary algorithm of “Differential Evolution” (DE, Storn and Price, 1997). The DE algorithm generates two populations of solutions which represent the decision variables that indicate the management choices. The opportunity space created by these populations is diverse; the variety in the decision variables (genotypes) creates diversity in landscape performance that is measured by the indicators (phenotypes). The first population of ‘parents’ serves as the result-set that is iteratively improved, while the second population consists of ‘competitors’ that are generated by uniform cross-over of three selected ‘parent’ solutions in each iteration. The parameters of the DE algorithm are the probability of cross-over (CR=0.85) and the amplitude of mutation ($F = 0.15$). Each population consisted of 1000 solutions.

The solutions in both populations are ranked using the principle of Pareto-optimality (Groot et al., 2012) and the Euclidean distance between the solutions in the opportunity space is calculated from the normalized indicator values, which serves to quantify a crowding metric. The Pareto-principle allows to evaluate all objectives simultaneously without weighing (Groot and Rossing, 2011). After the ranking, the selection process is conducted by pairwise comparison: solutions in the result-set population are replaced by individuals from the competitor population if the latter has a better Pareto rank or is positioned in a less crowded part of the opportunity space. The rank-based selection results in movement of the ‘parent’ population in the direction of the trade-off frontier (or surface), while the crowd-based selection ensures spread along the frontier (or surface). This process was conducted for 1000 iterations.

The model requires information to describe the biophysical environment, socioeconomics (production costs of activities and labor), type and crop products (agronomic inputs and outputs), herd composition and products (production costs and outputs), manure types and degradation rates, external sources of mineral nutrients (through animal food or fertilizers) and physical assets. A static farm balance model calculates a large range of indicators pertaining to nutrient and organic matter flows and balances, herd feed consumption and energy and protein balance, manure balance, labor balance and economic results. The model can be downloaded freely from https://fse.models.gitlab.io/COMPASS/FarmDESIGN/.

We considered the amount of inputs and the agricultural and conservation areas as “decision variables” for exploration. Decision variables must be set within coherent ranges. Also, land use area constraints must be set for farm functioning (i.e., land use areas cannot exceed the farm size). Model outcomes can serve as objectives that can be either minimized or maximized.

2.3.2. *Decision variables*

We considered decision variables for crops (including pastures for cattle) and forest areas and agrochemicals amounts (fertilizers and pesticides). Moreover, we added decision variables to modify the destination of products, such as maize grain from crop to animal feed or self-consumption (Table 1).

2.3.3. *Constraints and objectives*

Adjustments in decision variables lead to changes in model outcomes. Outcomes can be selected as constraints that should be within a given range, or as objectives that can be minimized or maximized. Important constraints relate to the feed balance: the deviation between demand and supply of energy and protein should be within narrow ranges to allow the production levels to be defined by animal numbers and corresponding productivity. Moreover, the dry matter (DM) supply to the animals cannot exceed the intake capacity. Another important constraint was the maximum conservation area which could not exceed the total farming area. Minimum area for maize and beans required for self-consumption was also specified. An overview of selected constraints and their allowed ranges for the farm in La Victoria is presented in Table 1 (see variables and constraints information of completing farms in Table S3).

Finally, we selected six common objectives for the five farms. Following the research question of the study, the main objectives were to maximize economic profits (considered as an integrator of total agricultural production) and conservation forest areas. Then, agricultural production had to include sustainable intensification practices as alternative managements that would allow for an easier transition to improved smallholders farming systems. The common objectives for all TFS were:

- Maximizing economic profits
- Maximizing forest conservation areas
- Maximizing feed protein self-supply
- Maximizing land-use evenness
- Minimizing agrochemical use (herbicides, insecticides)
- Minimizing variable costs.

For analyzing the initial farm situations and those optimized in the conservation-production trade-off frontier, we categorized farms according to their potential to improve their initial situations. In the solutions plot of the maximization of forest areas and economic profits (Figs. 1K, 2K, S3K, S4K, S5K), we considered the visual Euclidean distance between the coordinates position of the initial status (black triangle) and one situation which improved both conservation and production, chosen from the improved solution frontier (red diamond). We tagged farms with “low potential” to those with short distances (SJ and LV) and farms with “high potential” to those with large distance (QU, ZPO and RA).

Table 1
Decision variables and constraints set for the multi-objective optimization for the typical farm in *ejido* “La Victoria”.

		Decision variable	Initial	Minimum	Maximum
Variables	Land-use areas	Rainforest area (ha)	16.19	0	63
		Maize (ha)	1	0.5	10
		Beans (ha)	1	0.5	3
		Palm oil (ha)	24.5	0	63
		Lemon (ha)	2	0	5
		Permanent pastures (ha)	16	5	63
		Fruit trees (ha)	1	0	2
	Fertilizers	Triple 17 (kg)	8282.5	0	20,000
		Urea (kg)	354	0	1000
	Pesticides	Cypermethrin (l ha^{-1})	0.75	0	4
		Paraquat (l ha-1)	65.55	0	1000
		Chlorpyrifos (l ha-1)	4.591	0	10
		Glyphosate (l ha-1)	73.3	0	1000
	Feed for cattle	Maize grain (kg)		0	25,000
		Pollinasa (kg)		0	25,000
Constraints	Land-use areas	Farm area (ha)	61.5	60	62
		Cropping area (ha)	29.5	1	61
		Cattle production area (ha)	16	1	61
		Conservation area (ha)	16	0	61
	Feed balance	Saturation (%)	-22.9	-999	0
		Energy (%)	-3.6	-5	5
		Protein (%)	39.5	0	45

2.4. *Statistical analyses and software*

We used R software (http://www.R-project.org/) and RStudio (http://www.rstudio.com/) interface for data analysis. In particular, we performed principal component analysis with FactoMiner package (Lê et al., 2008) to identify associations between optimization objectives and decision variables. Then, we plotted correlation graphs with ggplot2 package (Wickham et al., 2019).

3. Results

3.1. *Trade-offs and synergies objectives exploration and farm-configuration associated drivers*

Figs. 1 and 2 show the relations between the six objectives for the San Jose (SJ, low-income) and La Victoria (LV, high-income) farms. The principal component analyses (Fig. 3) indicate the relations between decision variables and objectives. In SJ, solutions yielded a trade-off between forest conservation and economic profits (Figs. 1K and 3A). The latter was driven by larger maize areas associated to higher pesticides use (Figs. 1G and 3A). Moreover, there was a synergetic relation between minimizing variable costs (driven by the *pollinasa* external feed, Figs. 1A and 3A) and maximizing protein self-supply which was associated to an increase in pasture area (Figs. 1D-F and 3A). Solutions with larger pasture areas therefore had lower variable costs (Fig. 1A) and consequently higher profits.

Increasing land-use evenness would require a reduction in pasture area and an increase in *pollinasa* imports leading to higher variable costs and lower feed self-supply (Fig. 1B-C). The original situation for pesticides appeared in the optimized frontier (Fig. 1G-J), positively driven by maize areas (increasing pesticides pressure) and negatively by forest areas. Synergetic improvements relative to the original situation that reduced variable costs, and increased land-use evenness, protein self-supply and forests areas were found with intermediate pasture areas (~15 ha) and low *pollinasa* use (Fig. 1, solutions between black lines).

In La Victoria farm (LV), there was a trade-off between economic profits and forest areas too (Fig. 2K). Increasing palm oil areas determined higher economic profits but with higher variable costs associated to higher pesticide use (Figs. 2A, 2G and 3B). On the other hand, higher land-use evenness, forest areas and protein self-supply could be reached by decreasing palm oil and increasing pastures areas (Figs. 2B–F,K and

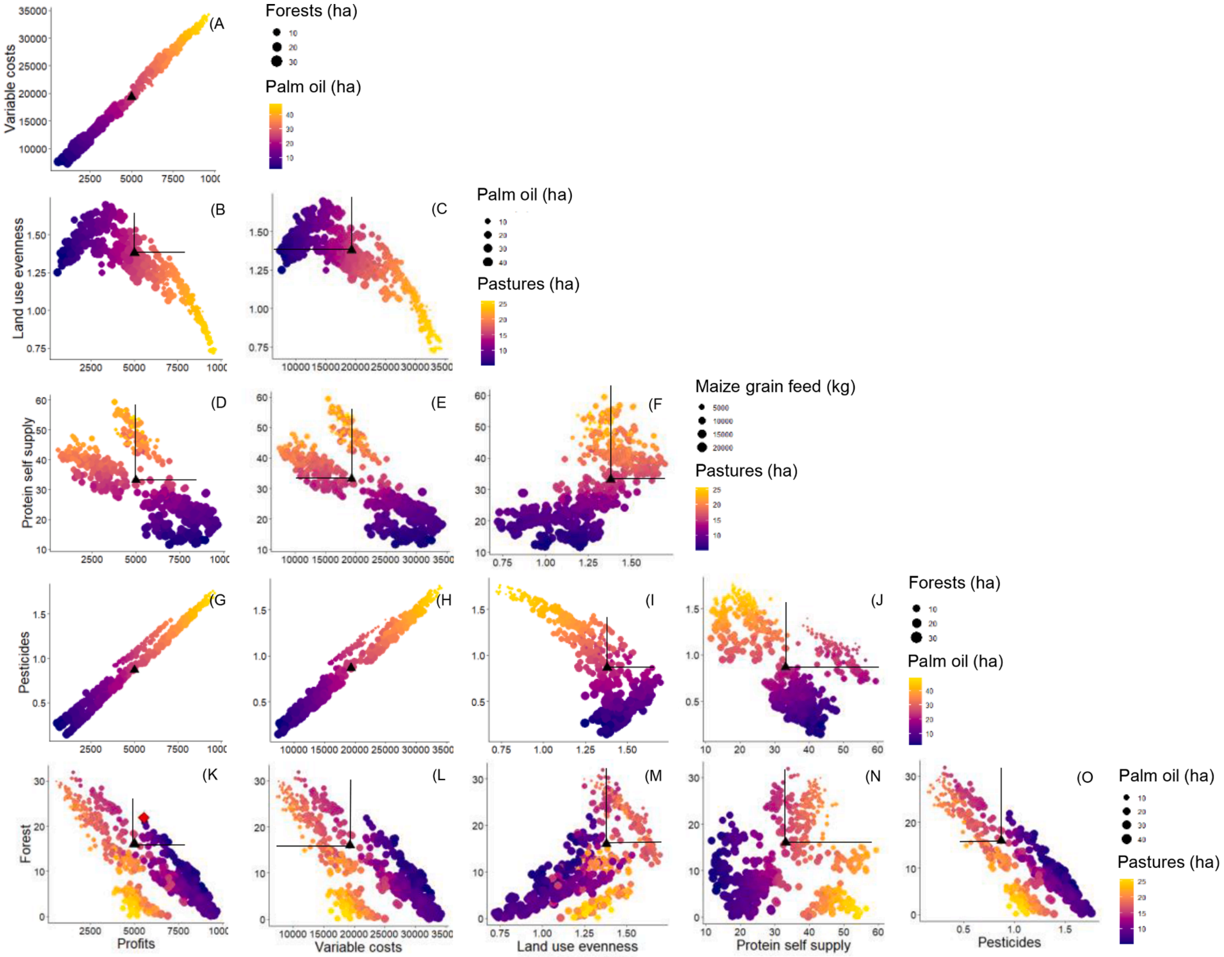

Fig. 2. Relations between optimization objectives for La Victoria farm (LV). Each dot represents one alternative solution resulting from optimization. Triangles denote the farm initial situation. Points inside the 90° black lines represent synergic improvement relative to the original situation. For Y-axes the two most correlated farm drivers (variables) are detailed with colors (first correlated) and dot size (second correlated).

3B).

In Quiringuicharo farm (QU), economic profits positively correlated with greater maize and beans areas, but negatively with forest, pastures and land-use evenness. In this farm, no pesticides were used and all protein in animal feeds were produced on-farm, therefore pesticides use was equal to zero and protein self-supply was fully covered (Fig. 3C). Simulation solutions, compared to the original farm configuration showed a great potential for maximizing economic profits and increasing forest areas for conservation (presumably due to its large total extension, Figs 3C and S2). For Reforma Agraria (RA) farm, economic profits correlated positively with greater beans areas and land-use evenness, and negatively with forest areas (Figs 3D and S3). Higher variable costs correlated with higher pesticides use in the maize crops and negatively with increasing pastures (Figs 3D and S3). Though the protein self-supply was satisfied (100%) in this farm, by increasing maize silage areas, it would be possible to decrease variable costs increasing economic profits (Fig. S3D and S3K). This farm showed a great potential to increase forest areas by decreasing beans and increasing maize silage areas (Fig. S3K).

In Zamora Pico de Oro farm (ZPO) the trade-off between pastures and *pollinasa* (Figs S4A-F) drove variable costs, land-use evenness and protein self-supply. Increasing pastures areas increased the protein self-supply. Increasing the *pollinasa* feed increased land-use evenness but also variable costs. Palm oil and maize areas were positively correlated with pesticides (Figs S4G-J and 3E). Finally, there was a trade-off between forest areas and economic profits. Profits were positively correlated with increasing mahogany and palm oil areas and higher pesticides use (Figs S4K-G and 3E).

3.2. *Analyzing the initial situations and those optimized in the conservation-production trade-off frontier*

TFS differed from each other when considering the pathways from their initial farm situations to those states that simultaneously improve forest conservation and profitability. Both low and high income TFS showed low and high potential to increase conservation areas and/or increase economic profits (see the distances between black triangles with red diamonds in Figs. 1K, 2K, S3K, S4K, S5K and Table 2). For TFS with low potential, improving the conservation-production antagonism meant a penalization in sustainable intensification objectives such as decreasing protein self-supply (19% and 51.5% for SJ and LV) and increasing variable costs (~15% for both, Table 2). It is necessary to highlight that in SJ, a low-income farm, the total volume of pesticides used is only ~10% of the application in LV due to the smaller land size (24.0 vs 61.5 ha). Moreover, SJ is characterized by the livestock-traditional maize system, unlike LV that mainly produces livestock-palm oil with high input rates.

TFS with high potential for conservation and production i.e., QU, RA (similar to QU and therefore not included in Table 2) and ZPO showed that increasing conservation areas and increasing economic profits simultaneously could be achieved through maintaining or improving the sustainable intensification objectives. For QU (low income), increasing maize for grains, maize for silage (2.4 to 13 ha, Table 2) and beans areas could increase crop diversity (land-use evenness) and economic profits

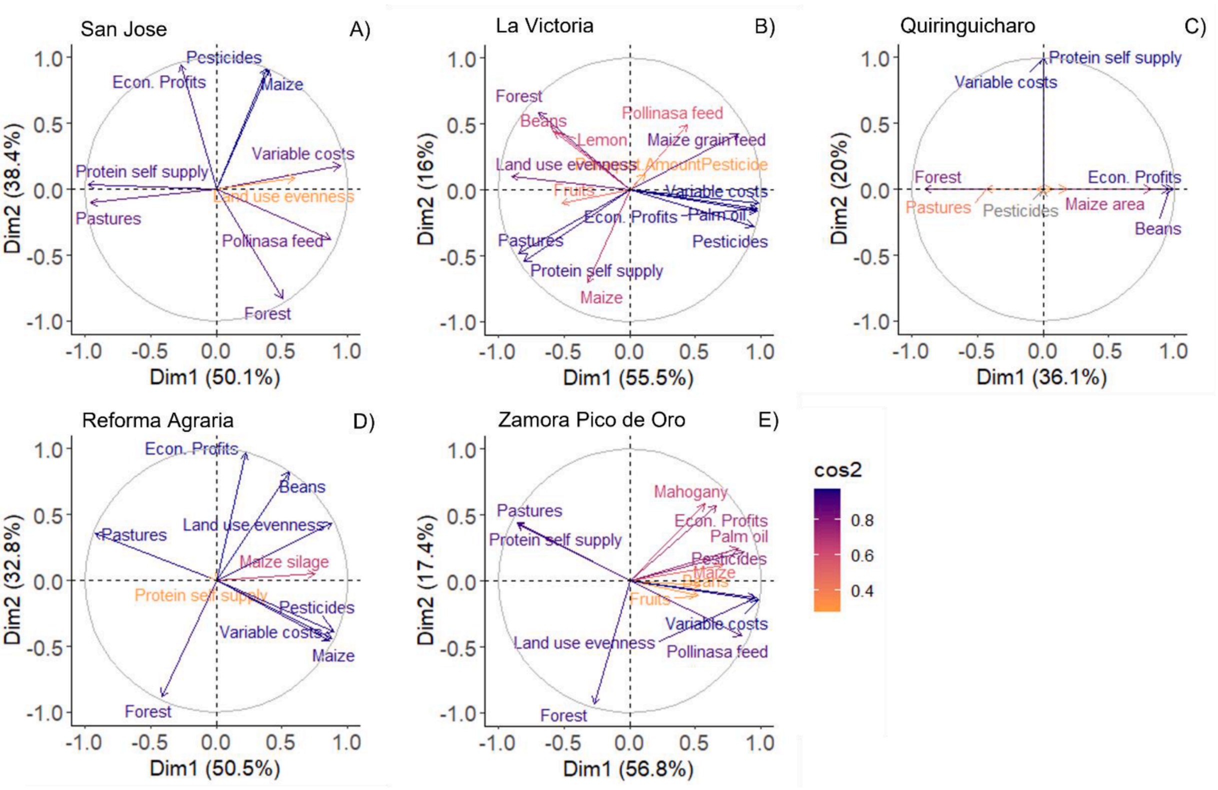

Fig. 3. PCA analysis for five TFS. Arrows represent objectives (economic profits, forest areas, pesticides, protein self-supply, land-use evenness and variable costs) and management variables (crops areas, maize, palm oil, beans, pastures, mahogany and feeds, maize grain, *pollinasa* and maize silage). The more violet variable the better represented by dimension 1.

(from 113 to 281 US$ yr $^{-1}$ ~ 159%) while pastures areas could be released for conservation (53 to ~2 ha, Table 2). A larger amount of maize silage for feed could compensate the reduction in pasture area resulting in maintaining protein self-supply (Table 2). In high income TFS of ZPO, decreasing the palm oil area (11 to 1.5 ha ~ 86%) and increasing the mahogany area ~ 4 times (a high value afforestation) may enable an increase of ~56% in conservation areas (from 14.5 to 22.6 ha) and economic profits (from 3083 to 5226 US$ yr $^{-1}$ ~70%). Moreover, reducing palm oil production would decrease pesticide use and variable costs (Table 2).

4. Discussion

4.1. Strategies associated to relieve the trade-off between conservation and agricultural production

We explored potential alternative farm configurations and management strategies in TFS that could contribute to maximize conservation areas and sustainable intensification production. The trade-offs between obtaining higher profits versus conserving forest were clear across all TFS (Figs. 1K, 2K, S-6). However, farm modeling using Pareto-based multi-objective optimization yielded alternative solutions that could overcome this trend increasing conservation areas and incomes, decreasing the local pressure of agricultural expansion on the remaining tropical rainforest patches.

Regarding objectives and decision variables, for all farms, the objective of increasing forest areas was not mainly determined by some land-use area or management (except for LV where forest areas correlated with beans and lemon crop areas, Fig. 3B). On the other hand, increasing economic profits was associated with particular crops/managements, depending on each TFS configuration (Fig. 3). Hence, conservation and production objectives seem to be reachable through different strategies that increase the unit of agricultural product per area i.e., intensifying the production areas. In that regard, initial farm configurations determined particular pathways for intensifying through increasing external inputs (e.g., in SJ) or through sustainable practices (e.g., in QU).

4.2. Multi-objective optimization for conservation-production issues

For natural resource management and production, Groot et al. (2010, 2007) applied the Landscape IMAGES model to spatial planning to reconcile crop yields, nutrient losses and natural hedgerows structure. One highlight was that to improve hedgerow cohesion it would be necessary to replace longitudinal to transversal hedgerow positions incurring new costs of implementation. In our case, for those farms which had more potential to increase forest areas (QU, RA and ZPO), fragments could be established strategically in the systems to, for example, reduce erosion in plots with high slopes or leave streams covered to prevent them from drying out (Grimaldi et al., 2014). Strategic allocation of forest regeneration patches does not require financial investment and could increase long-term returns by taking advantage of the regulation in ecosystem services that natural fragments could provide (Decocq et al., 2016).

Todman et al. (2019) evaluated agricultural landscapes with different crop managements and their potential negative impacts on the environment (greenhouse gas emissions) with a multi-objective optimization algorithm. They found that in the best soils (expected to produce high yields) management strategies still have a great potential to improve environmental and economical outcomes although these results were counterintuitive and good for discussion amongst stakeholders. Similarly, we found alternative configurations to maintain forest patches despite the strong trade-off between forest areas and economic profits. Also, multi-objective simulation highlighted different land use practices for each farm that could increase economic profits per hectare releasing areas for forest.

Table 2

Areas (ha), management variables and sustainable intensification objectives for TFS that have low (SJ and LV) and high (QU and ZPO) potential to improve conservation areas and economic profits. SJ and QU farms represent low-income farms and LV and ZPO represent high-income farms.

			Low income			High income		
			San Jose (SJ)			La Victoria (LV)		
			Current	Improved		Current	Improved	
Low potential to improve	Areas	Fruits				1.0	0.5	↓
		Beans				1.0	0.7	↓
		Palm oil				24.5	26.3	↑
		Lemon				2.0	2.9	↑
		Pastures	13.0	9.3	↓	16.0	6.9	↓
		Forests	9.0	11.4	↑	16.0	21.9	↑
		Maize	1.0	3.8	↑	1.0	0.9	↓
	Variables	Maize grain feed				9500.0	19,755.3	↑
		Pollinasa	14,908.9	14,641.5	≅	14,000.0	12,724.5	↓
		Triple 17	150.0	31.1	↓	8282.5	7312.1	↓
		Urea	200.0	275.2	↑	354.0	402.6	↑
	Sustainable intensification objectives	Pesticides	0.0	0.1	≅	0.9	1.0	≅
		Proteins self-supply	38.2	31.1	↓	33.2	17.1	↓
		Evenness	0.8	1.0	≅	1.4	1.3	≅
		Variable costs	4902.2	5647.7	↑	19,310.7	22,038.4	↑
			Low income			High income		
			Quiringuicharo (QU)			Zamora Pico de Oro (ZPO)		
			Current	Improved		Current	Improved	
High potential to improve	Areas	Fruits				1.5	0.9	↓
		Beans	0.8	15.5	↑	1.0	1.0	=
		Palm oil				11.0	1.5	↓
		Lemon						
		Pastures	53.0	1.8	↓	48.5	44.6	↓
		Forests	13.0	25.7	↑	14.5	22.6	↑
		Maize	0.6	12.7	↑	3.0	1.5	↓
		Maize silage	2.4	13.0	↑			
		Mahogany				2.0	7.7	↑
	Variables	Maize silage feed	9957.2	14,818.0	↑			
		Pollinasa				30,675.9	31,049.6	≅
		Triple 17				1423.0	1276.0	↓
		Urea				336.0	907.2	↑
	Sustainable intensification objectives	Pesticides	0.0	0.0	=	0.2	0.1	≅
		Proteins self-supply	100.0	100.0	=	62.7	60.4	≅
		Evenness	0.7	1.4	↑	1.2	1.2	=
		Variable costs	2140.0	2140.0	=	7590.4	5902.6	↓

4.3. Contributions to the land sharing vs. land sparing debate

Various studies have provided theoretical and practical support to the idea that increasing yields per hectare is an effective tool to release land for conservation (*Land sparing* approach, Folberth et al., 2020; Phalan et al., 2016). On the other hand, there are studies that show that simplified-high yield crop systems are the main causes of tropical deforestation (Byerlee et al., 2014; Meyfroidt et al., 2014; Richards et al., 2012).

For a land-sparing strategy to be successful, in our case, TFS with higher input, production and economic benefit should allow a larger proportion of forest areas. However, in contrast, TFS with the highest income and pesticides use (Table S4, LV and ZPO) showed low percentage of forest cover (the lowest for the case of ZPO) compared to those TFS with the smallest areas (SJ and RA with 24 and 43.5 ha, respectively) and intermediate economic profits per ha (Table S4). These relatively small TFS with low pesticides use showed the largest proportions of forest areas. Hence, *land sparing* in human modified tropical landscapes with high yielding activities (using high external inputs) may produce high economic incomes but may not guarantee the forest conservation. Moreover, these activities lead to dominance of monocultures and increased pesticides use and associated negative externalities for the environment.

4.4. Multi-objective optimizations in Mexican farming systems

Few studies in Mexico have been performed with multi-objective models to evaluate alternative solutions in farming systems. Flores-Sánchez et al. (2015) evaluated alternative solutions with FarmDESIGN in smaller farms (1 to ~4 ha) in the state of Guerrero. Unlike our study, the authors simulated new alternatives (fertilization and soil endowments and animal husbandry) to evaluate *ex-ante* improvements in farms economy, soil conditions and labor. Cortez-Arriola et al. (2016) using FarmDESIGN applied comparable principles of sustainable intensification to dairy farms. They found synergies between increasing economic incomes and decreasing feed costs. Similarly, LV and ZPO farms showed negative correlations between external feeds (maize or *pollinasa*) and economic profits (Fig. 3). In the former studies of Flores-Sanchez et al. (2015) and Cortez-Arriola et al. (2016), an important additional objective was to improve organic matter balance, which we did not consider although it could have improved the insights on long-term sustainability of alternative managements.

4.5. Practical implications and recommendations

Producing food in areas of great importance for biodiversity conservation is an issue that has recently gained much attention from world society. However, many inhabitants of these places face economic pressures and lack of support to be able to produce without falling into simplified extensive crops (Meyfroidt et al., 2014). As our study shows, there are no general land-use configurations nor managements to be implemented in all TFS since each farm characteristics determine the multi-objective optimization and outcomes. Our results support the ideas proposed by Cunningham et al. (2013) in their position paper that highlights that intensification and conservation of systems is possible as long as site-specific conditions are considered. Therefore, the analysis of particular cases, at least at *ejido* level (as done in this study), is necessary to improve the agricultural production and forest conservation through sustainable practices.

It is worth noticing that due to the way FarmDESIGN is structured, forests and agricultural activities were only considered as independent areas without considering the ecological processes which could be interacting with each other (nutrients and water cycling, soil degradation/conservation and the dynamics of flora and fauna population). These interactions could modify the expected/estimated modeling results (Alamgir et al., 2016; Duflot et al., 2022).

The multi-objective optimization model proved to be a great tool to better represent the local land use and management complexities in TFS. We demonstrate that there is potential in TFS to conserve the forest and increase agricultural production simultaneously through sustainable intensification practices for some of the farms depending on their initial configurations. Since there were no general alternative solutions for all farms, the analysis of individual farms or at least typical farms from typological groups emerges as a fundamental aspect. In a context where public policies tend to be general and with top-down applications, our results provide evidence that highlights the importance of considering farm singularities when designing and applying policies for integrating strategies to increase both conservation areas and agricultural production.

Authors' contributions

G. Wies, M. Martinez-Ramos and J. Groot conceived the ideas and conceptualization; G. Wies cured the data, developed the formal analisys, developed the data visualization and wrote the original draft. J. Groot developed the software and supervised and validated the modelling analysis. G. Wies and J. Groot developed the methodology. M. Martinez-Ramos adquired the research founds and administrated the project. G. Wies, M. Martinez-Ramos and J. Groot reviewed and edited the final version of the paper.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Acknowledgments

We are grateful to E, Salinas-Arroyo, E, R. de la Laserna, Hurán Drouet and Jesús Córdoba, who generously supported fieldwork. We thank the financial support from PAPIIT- DGAPA-UNAM (IN212617, IN201020) and FOREFRONT (INREF, Wageningen University). We thank to BIOPAIS (SEP-Conacyt grant CB-2016-01-285940) and the Farming systems ecology group, Wageningen University and Research, for the grateful academic internship (2019). Finally, we thank farmers for their kind predisposition to provide information.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ecolmodel.2023.110435.

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