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Exploring nutrient-sensitive landscape configurations for rural communities in southern Mexico

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HIGHLIGHTS

- Food production and ecosystem services can be improved by reconfiguring landscapes.
- Often neglected vitamins for human nutrition should be considered when designing landscapes.
- Exploration of trade-offs and synergies between indicators shows the room to maneuver in planning processes.
- Visualization of a large array of landscape redesign options informs to decision making and planning by communities.

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ABSTRACT

In Mexico, the traditional MILPA polycropping system is giving way to maize monocultures, impacting the nutritional diversity of smallholder farmers and diminishing ecosystem services. This study explores landscape alternatives to enhance nutritional self-sufficiency and environmental performance in rural communities, comparing scenarios without (S1) and with (S2) innovative cropping systems. The innovations, maize-squash and MIAF (a variation of MILPA with fruit trees), were evaluated using the LandscapeIMAGES modeling framework in two Oaxacan municipalities: Santa Catarina Tayata (SCT) and San Cristóbal Amoltepec (SCA). The assessment considered nutritional elements, ecosystem services proxies, labor requirements, and income associated with various land-use options. In scenario S1, nutritional self-sufficiency was achievable in SCT but not in SCA, even with a 17% expansion of agriculture into forest and grassland areas. Scenario S2, incorporating maize-squash and MIAF, facilitated nutritional self-sufficiency in both municipalities, while concurrently boosting incomes, carbon stocks, and reducing soil erosion. This research underscores the potential of reshaping landscapes in small communities to address widespread issues like nutritional gaps and inadequate natural resource conservation. By emphasizing innovative cropping systems, the study provides positive solutions to enhance the well-being of smallholder farmers and promote sustainable land use practices in the face of evolving agricultural trends.

1. Introduction

Agricultural production has managed to keep pace with population growth in the last decades (Willett et al., 2019). However, the number of food insecure people has seen an unprecedented rise since World War II (UN), according to the UN's recent secretary-general, Guterres (2022). The rise in food insecurity can be attributed to major events such as Brexit, the COVID-19 pandemic, the China-USA trade war, and the

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Ukraine-Russia war, which have disrupted global markets (Carriquiry, Dumortier, & Elobeid, 2022). The cascading effects of these major events have prompted nations to reconsider the role of self-sufficiency (Bisoffi et al., 2021; Mottaleb, Kruseman, & Snapp, 2022). Concurrently, food systems contribute to climate change by emitting one-third of greenhouse gases (GHG) (Geyik, Hadjikakou, & Bryan, 2022). The IPCC (2022) predicts a worsening negative impact of climate change on food security. The interconnectedness of agriculture with global issues such as persistent food insecurity, incremental CO_2 emissions, and degradation of natural services raises the question of how to produce more sustainable and diverse food for an ever-increasing population while restoring the environment (Ickowitz et al., 2022; Powell et al., 2015). Thus, landscape planning approaches that account for the socioeconomic and environmental complexity of food systems are essential.

In Latin America, two major types of food production systems coexist: intensified techno-centric monocropping systems and traditional diversified production systems (Parraguez-Vergara et al., 2018). The former, despite bringing increased yields through improved genetic material and intense input use, has proven ineffective against hunger and it is linked with unemployment, migration, and ecosystem degradation (Altieri & Nicholls, 2008; FAO, 2014; de Gordillo, 2004; Jokisch, 2002). Nevertheless, public incentives and labor shortages are compelling smallholder farmers to shift away from crop diversity towards simplified systems (Parraguez-Vergara et al., 2018), potentially having negative implications for food security in rural areas (Isakson, 2009). This oversimplification of agricultural systems is a global issue, as food systems worldwide are failing to produce enough crop variety to ensure a healthy and balanced diet, with only three crops (rice, maize, and wheat) providing 48% of the daily human calorie consumption (FAO, 2018).

The traditional Mexican cropping system MILPA centers around maize, which is combined with other species such as common beans (*Phaseolus vulgaris*), fava beans (*Vicia faba*), and squash (*Cucurbita* spp.). This cropping system holds high potential for contributing to nutritional self-sufficiency, defined as the relation between the availability of nutrients and vitamins from locally produced products and the mean recommended intake of these nutrients and vitamins (Sioen, Sekiyama, Terada, & Yokohari, 2017). Despite its many advantages, MILPA is being replaced by monocultures, leading to the freeing up of labor for off-farm activities at the expense of the production and consumption of vitamins A and C, as observed in southern Mexico (Novotny, Fuentes-Ponce, Tittonell, Lopez-Ridaura, & Rossing, 2021). The low nutritional self-sufficiency at the household level is also reflected at the national level, with the country increasing grain imports by 65% between 2007 and 2012 (Senado de la Republica, 2017).

The Nutrition-Sensitive Landscape (NSL) framework was proposed for analyzing landscape ecosystem services and nutritional performance (Bioversity International, 2014; Groot et al., 2017; Kennedy et al., 2017). Here we use the framework to explore landscape configurations prospectively and in a spatially explicit fashion. The application of the NSL framework is particularly relevant for Mexico, where food security and environmental conservation are often considered separately and at the national rather than at the local level (Galeana-Pizaña, Couturier, & Monsivais-Huertero, 2018).

Research in nutrition-sensitive agriculture and landscape planning has been gaining traction over the past years, exploring various topics such as the relationship between closing global nutrient gaps and greenhouse gas emissions (Geyik et al., 2022) and exploring farm-scale management options for improving agricultural production and nutrition (Timler et al., 2020). To our knowledge, however, there is currently no study that evaluates mid-scale landscape-level management options for improving food production and the provisioning of ecosystem services.

For that reason, this study focuses on two municipalities in southern Mexico. We chose the municipal level as an administrative unit where the local authorities and local population interact to manage the communal land. This decision-making process can have significant positive or negative impacts on the landscape, as shown by Novotny, Tittonell, Fuentes-Ponce, López-Ridaura, and Rossing (2021). We selected the state of Oaxaca for being one of the most marginalized states in Mexico (CONAPO, 2016) and for presenting large degrees of land degradation. Improving nutritional self-sufficiency through a landscape re-design can be beneficial to these marginalized communities where access to food from markets is restricted (Galeana-Pizaña et al., 2018). Food security depends not only on availability but also on access, stability, and utilization (FAO, 1996). Here, we focus on food availability from local production and food utilization, estimated through a combination of field surveys, land-use/land-cover (LULC) maps, and dietary reference intake of several nutrients and vitamins.

The two municipalities chosen for this study have contrasting socioeconomic contexts. The first municipality, San Cristobal Amoltepec, is characterized by low crop yields and high population density, resulting in pressure on the land. The second community, Santa Catarina Tayata, is marked by intense abandonment of agriculture and negative demographic growth. Together, these communities are representative of other municipalities in Mexico (Novotny et al., 2021). Our goal is to compare the current landscape performance of these two communities in terms of food production and nutritional diversity. Subsequently, we explored ways to improve the nutritional, socio-economic, and environmental landscape performances through (i) the expansion of current LULC and cropping systems, or (ii) the introduction of alternative and diversified cropping systems.

2. Materials and methods

2.1. Study area and production systems

This study was conducted in two neighboring municipalities, Santa Catarina Tayata (SCT) and San Cristobal Amoltepec (SCA), located in the state of Oaxaca, Mexico (Fig. 1). The two communities are similar in terms of climate conditions, cropping systems, and community landscape management (Novotny et al., 2021). They differ, however, in demography, crop performance, and LULC configuration. The three dominant cropping systems in the area are monocultures of maize and common bean and MILPA. MILPA systems in this region include maize in combination with one or more of the following crops: common bean, fava bean, and squash. Cropping may be followed by a fallow period, which usually lasts one year but may last up to five years. Sheep husbandry is the most common type of animal production. Sheep mostly forage on fallow fields and grasslands in communal areas.

Like in other municipalities of Mexico, the land in SCT and SCA is divided into common and private land (Fig. 1). Cropping activities are performed exclusively on private land, although this is not the rule in other municipalities. Common land is managed by *Bienes Comunales* (BC), a local institution that enforces local regulations decided on by municipal assemblies. Forest and grassland are the most frequent LULCs on common land. Settlement areas were left out of the analysis as they are not managed by the community.

Both communities are considered marginalized (CONAPO, 2016). SCT is self-sufficient for more nutrients and vitamins than SCA, but neither community is entirely self-sufficient (Novotny et al., 2021). Over the last three decades, SCT and SCA increased forest cover and reduced the surface with bare soil through a series of local regulations (Novotny et al., 2021).

2.2. Nutrition-sensitive landscapes and modeling framework

Kennedy et al. (2017) established the NSL framework, integrating UNICEF's conceptual framework for nutrition with ecosystem service functions. Derived from the UNICEF framework addressing malnutrition issues, including food insecurity, inadequate maternal and child care,

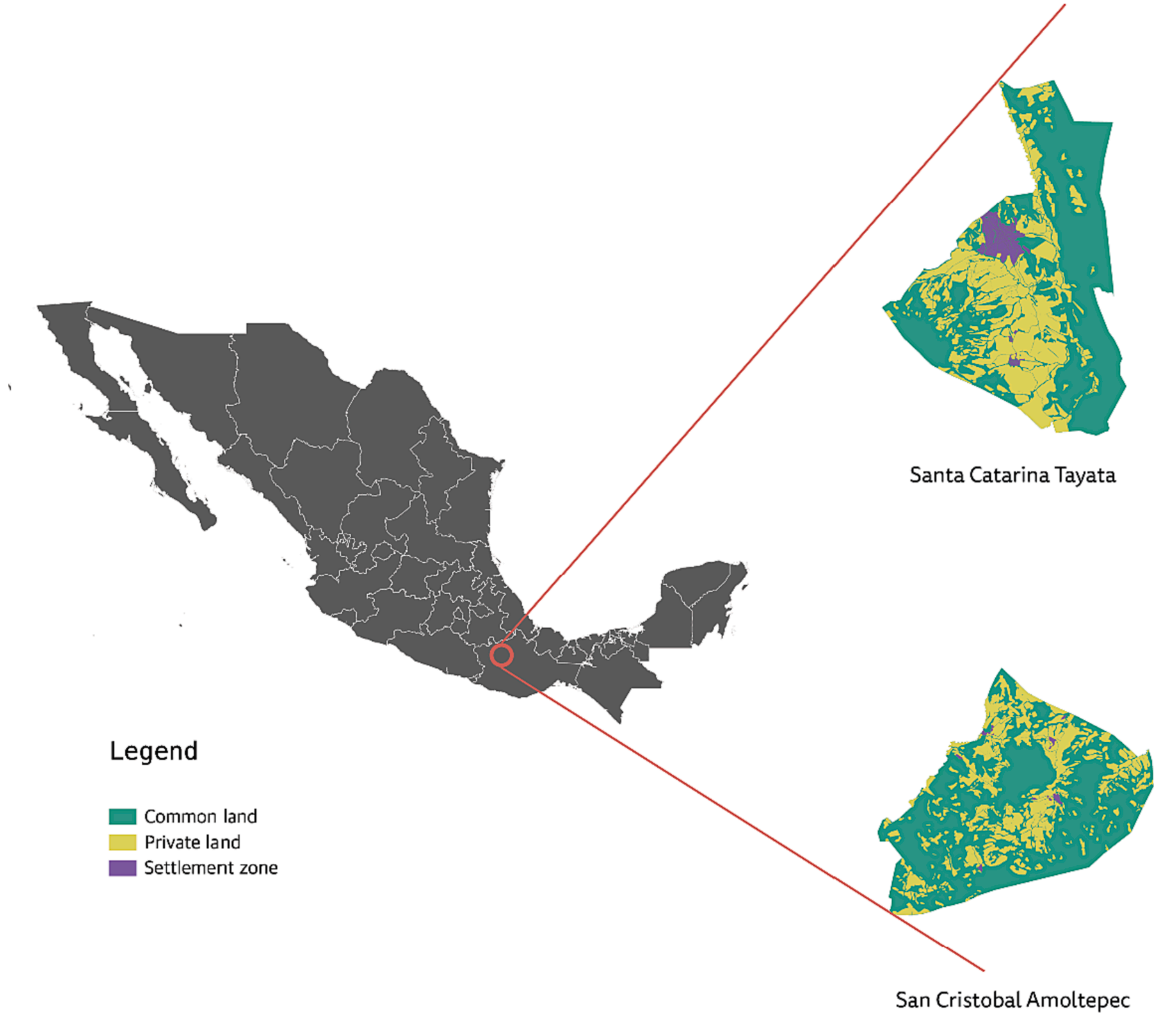

Fig. 1. Location of the case study municipalities Santa Catarina Tayata and San Cristóbal Amoltepec within the state of Oaxaca.

insufficient health services, and unhealthy environments (UNICEF, 1991), the NSL approach focuses on enhancing human nutrition and health. It particularly targets locations where natural resources are managed by stakeholders with diverse and often conflicting objectives (Kennedy et al., 2017).

In this study, The LandscapeIMAGES (Landscape Interactive Multi-Goal Agroecosystem Generation and Evaluation System – LI, Groot et al., 2007) was employed. This framework facilitates the evaluation of the current and alternative performance of landscapes using a Pareto-based multi-objective Differential Evolution (P-MODE) algorithm. The aim was to explore trade-offs and synergies among various landscape performance indicators, such as soil erosion, food provision, habitat connectivity, and carbon sequestration (Groot et al., 2007, 2009). For each map polygon, alternative LULCs are described by decision variables that are iteratively varied by the optimization algorithm. Pareto-optimality is achieved when the performance of a landscape in terms of a particular indicator cannot be improved without compromising performance in one or more other indicators (Groot, Yalew, & Rossing, 2018).

This study adopted a a five-step approach to apply the model (Fig. 2), detailed in the subsequent sub-sections. First, data was collected, and production, socioeconomic, and environmental indicators were calculated. Second, different LULCs were classified. Third, the combined LULC classification and indicators were employed to assess landscape performance. Fourth, stakeholders' objectives and potential alternative scenarios were identified. Lastly, stakeholders' objectives were translated into six indicators, and the Pareto-based differential evolution method was utilized to evaluate trade-offs and synergies across these indicators.

2.2.1. Data collection and quantification of indicators

To comprehensively assess nutrition, socio-economic factors, and environmental aspects, a diverse set of data sources and measurement techniques was employed (Table 1). The primary data collection methods included a household survey conducted in December 2017, encompassing 60 respondents (30 in SCT and 30 in SCA), yielding insights from 157 plots (Novotny et al., 2021). The survey, strategically selecting participants for geographic diversity, covered crucial aspects such as family structure, production systems, labor allocation, and economic performance.

Crop yields and sheep production estimates derived from the survey data revealed a consistent sheep stocking rate (3.5 sheep ha^{-1} of grassland) across both municipalities. Although average crop yields were similar, SCA consistently exhibited lower attainable yields (highest observed yields) (Table 3). To account for the polyculture nature of MILPA, the Land Equivalent Ratio (LER; Mead & Willey, 1980) was calculated, utilizing average and highest observed yields for both municipalities. Squash production, absent as a monocrop, was estimated using the average squash production in the state of Guerrero (10 Mg ha^{-1}; SIAP, 2017), the nearest state with relevant squash data.

The study used the Nutrient System Yield ($NSY_{j,p}$, persons ha^{-1} year^{-1}) to quantify nutrient and vitamin yield, considering various crops

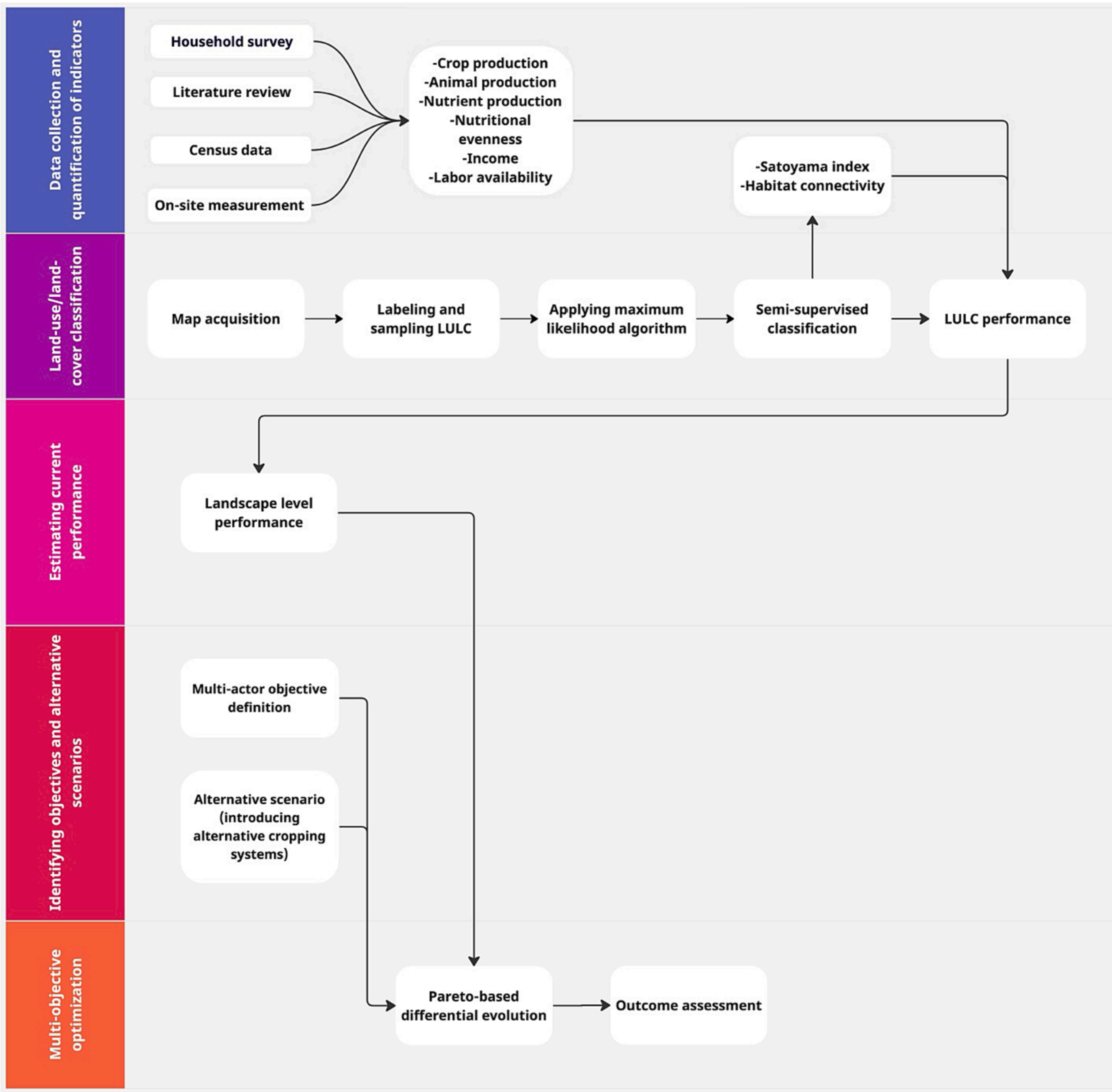

Fig. 2. Methodoological framework with steps in the data acquisition and modelling approach. Arrows show the connection between the different steps taken to collect and analyze the data. Colored rows represent the major phases of data collection and analysis.

and cropping systems. Nutritional self-sufficiency ($NSS_{j,p}$) for each nutrient or vitamin in a municipality was calculated by dividing $NSY_{j,p}$ by the population size. $NSY_{j,p}$ was calculated as:

$$NSY_{j,p} = \frac{\sum_{m=1}^{n} CY_{j,m} \times NC_{p,m}}{R_p}$$

where p is a nutrient or vitamin, CY is the yield of an individual crop m in Mg/ha year^{-1} in municipality j. $NC_{p,m}$ is the content of nutrient or vitamin p (unit dependent on the nutrient or vitamin) per Mg of crop m. R_p is the annual Dietary Reference Intake (DRI, National Academy of Sciences, 2011) per person for nutrient p (adapted from Timler et al., 2020).

The nutritional self-sufficiency ($NSS_{j,p}$) for individual nutrients and vitamins p in municipality j was calculated as:

$$NSS_{j,p} = \frac{NSY_{j,p}}{Pop_j}$$

where Pop_j is the population size of municipality j, which was 680 persons for SCT and 1005 persons for SCA (INEGI, 2015). The Dietary Reference Intake for the population between 31 and 50 years old was used as this range is representative of the population average of both communities. Deviating requirements of pregnant women and children were not considered here, as their special dietary requirements demand specific analyses.

Erosion was estimated based on a study conducted in the area (Naranjo et al., 2021), which collected the eroded soil after 39 precipitation events in plots with forest, maize, and fallow after 39 precipitation events.

Table 1
Nutritional, socio-economic, and environmental indicators and sources used as inputs for each LULC.

Indicator type	Indicator	Units	Used in LI as[1]	Source
Nutritional	Nutritional evenness	–	Indicator	Survey + literature[2]
	$NSY_{Dietary.\ energy}$	Persons fed yr^{-1} ha^{-1}	Indicator	Survey + literature[2]
	$NSY_{Protein}$	Persons fed yr^{-1} ha^{-1}	Indicator	Survey + literature[2]
	NSY_{Ca}	Persons fed yr^{-1} ha^{-1}	Indicator	Survey + literature[2]
	NSY_{P}	Persons fed yr^{-1} ha^{-1}	Indicator	Survey + literature[2]
	NSY_{Fe}	Persons fed yr^{-1} ha^{-1}	Indicator	Survey + literature[2]
	NSY_{Mg}	Persons fed yr^{-1} ha^{-1}	Indicator	Survey + literature[2]
	NSY_{Zn}	Persons fed yr^{-1} ha^{-1}	Indicator	Survey + literature[2]
	$NSY_{Vit.A}$	Persons fed yr^{-1} ha^{-1}	Objective (increase)	Survey + literature[2]
	$NSY_{Vit.B2}$	Persons fed yr^{-1} ha^{-1}	Indicator	Survey + literature[2]
	$NSY_{Vit.B3}$	Persons fed yr^{-1} ha^{-1}	Indicator	Survey + literature[2]
	$NSY_{Vit.B6}$	Persons fed yr^{-1} ha^{-1}	Indicator	Survey + literature[2]
	$NSY_{Vit.B9}$	Persons fed yr^{-1} ha^{-1}	Indicator	Survey + literature[2]
	$NSY_{Vit.B12}$	Persons fed yr^{-1} ha^{-1}	Objective (increase)	Survey + literature[2]
	$NSY_{Vit.C}$	Persons fed yr^{-1} ha^{-1}	Indicator	Survey + literature[2]
Socio-economic	Required labor	days ha^{-1}	Objective (decrease)	Reyna et al.,
	Locally available labor	days ha^{-1}	Indicator	Calculated (Inegi, 2010)
	Income	MXN yr^{-1} ha^{-1}	Objective (increase)	Survey + (Cadena-Iñiguez et al., 2018)
Environmental	Soil loss	Mg yr^{-1} ha^{-1}	Objective (decrease)	(Etchevers et al., 2004; Naranjo-Macias, 2019)
	Total carbon	t ha^{-1}	Objective (increase)	Calculated from soil samples + (Bos, 2020; Etchevers et al., 2004)
	Habitat connectivity	ha	Indicator	Calculated (Urban & Keitt, 2001)
	Satoyama index	–	Indicator	Calculated (Kadoya & Washitani, 2011)

[1] "Used in LI as" refers to whether an indicator was defined in LandscapeIMAGES as an "objective" for the multi-objective optimization. Indicators not used as objectives were termed "indicators."
[2] Literature used: Bressani (2015); Cadena-Iñiguez et al. (2018); Incap (2006); Jiménez, Gadámez, Aguilar, Hernández, and Solis (2019); USDA (2010).

Income generated from various activities (sheep-grazed grassland, maize, bean, and MILPA) was calculated by subtracting production costs (e.g., labor, inputs) from product prices.

Locally available labor was determined from INEGI (2010), considering the population between 15 and 60 years of age and an 8-hour working day. Only labor requirements for May and June were considered and compared with locally available labor. This time frame was preferred over the annual requirement because May and June are the most labor-demanding months during which locally available labor should be available.

To determine carbon stock for each LULC, the analysis considered soil organic matter (SOM) and above-ground biomass (AGB). SOM data were derived from 64 stratified random soil samples, accounting for bulk density. For AGB, focus was placed on pasture and forest classes, excluding bare soil devoid of vegetation and crop residues removed post-harvest.

Forest AGB calculation involved identifying trees with a diameter exceeding 7 cm at breast height (DBH) across 14 forest plots covering a 200 m^2 surface. Tree height information was incorporated into an allometric formula to quantify biomass (Návar, 2009). A distinct allometric model estimated below-ground biomass from tree AGB (Mokany, Raison, & Prokushkin, 2006). Additionally, understory biomass was assessed by collecting non-woody material in a 1 m^2 quadrant, dried for 48 h at 70 °C, and weighed (Bartholomée, Grigulis, Colace, Arnoldi, & Lavorel, 2018). Combining tree and understory biomass provided the total AGB. Pasture AGB estimation mirrored understory biomass, involving cutting and weighing vegetation in a 1 m^2 quadrant. Below-ground biomass (BGB) for pastures was derived by multiplying AGB by a factor of 1.6 (Eggleston, 2006).

Three additional landscape indicators—nutritional evenness, Satoyama index, and habitat connectivity—were computed based on LULC spatial distribution (Fig. 3). Nutritional evenness, assessed via the Shannon index, gauged food richness and evenness in each municipality (Remans et al., 2011). A higher nutritional evenness signifies potential for a more balanced and diverse diet, crucial in mitigating issues related to hidden hunger (Bamji, Murty, & Sudhir, 2021). The Satoyama index was calculated following the methodology by Kadoya and Washitani (2011), incorporating Simpson's diversity index and the Compound Index, its value ranges from 0 (homogeneous monoculture landscape) to 1 (highly diverse landscape). The habitat connectivity, indicating the spatial contiguity of forests and biodiversity potential (Groot et al., 2018), was calculated using the method by Urban and Keitt (2001).

2.2.2. LULC classification

GIS polygons serve as a powerful tool to illustrate the structural components of an agricultural landscape, encompassing fields, borders, roads, rivers, and more. Linear features such as field borders and hedgerows are represented using GIS line elements. Information specific to each landscape element is integrated into the GIS file as an internal attribute table. Additional details regarding alternative properties, such as vegetation type and land use, as well as the management of landscape elements, are stored in database tables using MS Access/SQLite.

LI captures information about each landscape element in the GIS file's attribute table (Groot et al., 2018). In this study, the key landscape elements encompass various LULC classes, including forest, agricultural fields, and pasture. To categorize these elements, a LULC classification was performed using a Landsat 8 image taken in October 2017 with a spatial resolution of 30 m (https://earthexplorer.usgs.gov), carefully chosen for minimal cloud cover and high contrast between LULCs.

Applying the Dark Object Subtraction atmospheric correction method (Ellis & Porter-Bolland, 2008), the semi-supervised classification method was utilized. It combines elements of both supervised and unsupervised classification, leveraging a small amount of labeled data (supervised learning) sampled from Google Earth's high-resolution map (WorldView-2, 0.5 m resolution), and applying a maximum likelihood algorithm to classify the remaining, unsampled data (unsupervised,

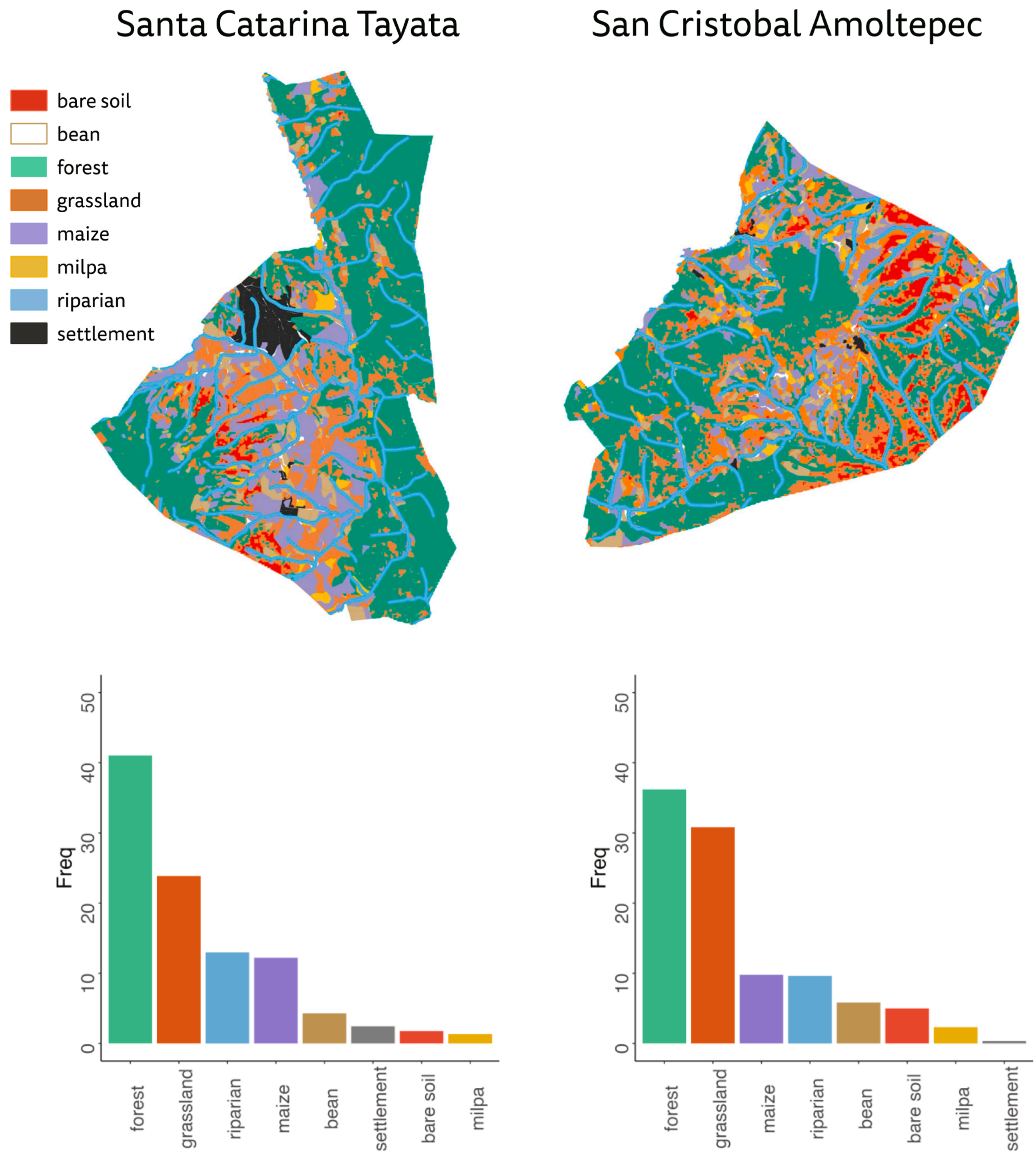

Fig. 3. Current landscape configuration in Santa Catarina Tayata and San Cristobal Amoltepec. LULCs such as bean, fallow, maize, and MILPA were randomly allocated to the LULC class cropland based on the current proportion of each LULC.

Mekasha, Gerard, Tesfaye, Nigatu, & Duncan, 2014; Tolessa, Senbeta, & Kidane, 2017). The three LULC labels utilized were forest, cropland/grassland, and bare soil, achieving an overall classification accuracy of 88% (Appendix D).

Cropland and grassland were merged under the same label for the semi-supervised classification as these produced very similar spectral signatures. Considering that grassland is important for animal production and cropland for growing crops, they had to be further differentiated. This was done by first using a shapefile containing the land ownership information of SCT and SCA, which are divided into three types of land ownership: private plots, common land, and settlement (RAN, 2019). To distinguish cropland from grassland, we overlaid the shapefile containing the land ownership with our LULC classification map. Our differentiation criteria were: if a classified cropland/grassland pixel overlayed with a private plot, then it was classified as cropland, if it overlayed with a common area, then it was classified as grassland. Based on a survey performed before this study (described below), cropland was used for growing maize, beans, MILPA, or fallow. Results from this survey showed that 20% of the cropland area in SCT was occupied by maize, 7% by bean, 33% by MILPA, and 40% by fallow. For SCA 26% of the cropland areas was occupied by maize, 4% by bean, 50% by milpa, and 20% by fallow. These proportions were used to randomly distribute these crops across all the classified cropland plots.

The Semi-Automatic Classification Plugin (version 6.4.2) for QGIS (version 3.4) facilitated the LULC classification process, contributing to the robustness of the study's GIS-based landscape characterization.

2.2.3. *Estimating current performance*

Most indicators, except for the Satoyama index, habitat connectivity, and nutritional evenness, were calculated per area of each LULC class.

These indicators were stored in a GIS file used in LI. The performance of these indicators can therefore be calculated by:

$$P_{i,j} = \sum_{l=1}^{n} P_{i,l} \times A_{j,l}$$

where $P_{i,j}$ is the value of indicator i (unit dependent on the indicator) in municipality j (e.g. SCT or SCA). $P_{i,l}$ is the value of indicator i per ha of LULC l. $A_{j,l}$ is the area of LULC l in community j (ha).

2.2.4. Identifying stakeholders' objectives and alternative scenarios

Various indicators may be used as objectives to guide the exploration of alternative landscape configurations (Table 1). To define locally relevant objectives three major stakeholder categories in the municipalities were asked for their opinions: farmers, local officials, and ENLACE (a local NGO). ENLACE seeks to promote sustainable agricultural practices and improve rural infrastructure. ENLACE's and local officials' objectives were defined in workshops held in 2015 and 2017. The workshops consisted of identifying the stakeholders' perceptions of major problems in the case study area and objectives in their policy agendas. ENLACE's representatives stated that their priority goals are to improve food security, minimize soil losses, and increase forest cover. In addition to ENLACE's goals, the local officials also wanted to protect rivers and streams from soil sediments. Farmers were asked about their objectives during the same household survey described before. The most frequently expressed goals by farmers were improving crop performance, minimizing labor, and improving income. Objectives for the two communities were similar.

We translated the crop performance and food security goals into the objectives maximization produced vitamins A and B12. Vitamin A was selected because reaching its nutritional self-sufficiency also guarantees that minimum requirements for other nutrients and vitamins would be met, except for vitamin B12 (Novotny et al., 2021). Vitamin B12 is derived from free-range sheep production. Sheep production is associated with grassland. Maximizing carbon stocks was used as an objective, as this indicator is directly related to ENLACE's and local officials' objective of increasing carbon sequestration.

Community regulations issued by the *Bienes Communales* were implemented as restrictions in LI: 1) no forest clearing in common areas; 2) each river and stream should be protected by at least 15 m forest buffer on each side; and 3) cropped land was allowed to be turned into fallow.

Two scenarios were considered for this study. The first scenario (S1) was used to explore ways to improve the stakeholders' goals by redesigning landscapes using current LULCs and cropping systems. This scenario is particularly relevant for highly marginalized places such as SCT and SCA, where innovations in cropping systems are less likely to occur. Forest, fallow, grassland, maize, bean, and MILPA were defined as LULC options in LI, and multi-objective optimizations were performed to assess this scenario.

The second scenario (S2) aimed at investigating opportunities to improve nutritional self-sufficiency while offering new economic opportunities. As such, two novel cropping systems developed elsewhere in Mexico were selected. The selected innovations were maize intercropped with squash (henceforth referred to as maize-squash) and an agroforestry-based MILPA system (locally also known as MIAF). The maize-squash system was selected because of farmers' familiarity with both species, reduced labor requirements compared to the traditional MILPA, and its potential for improving the production of vitamins A and C (the most limiting vitamins in the region;). The MIAF system was developed to reduce poverty and environmental damage in hillside areas such as the highlands of Oaxaca (Cadena-Iñiguez, Camas-Gómez, López-Báez, López-Gómez, & González-Cifuentes, 2018). The MIAF considered for this study consisted of maize intercropped with bean and peach. The composition was chosen based on experiences with the system in an agroecologically similar area in Mexico (Cadena-Iñiguez et al., 2018).

2.2.5. Multi-objective optimization

The evolutionary algorithm Differential Evolution (Storn & Price, 1997) was used for Pareto-based multi-objective optimization. The complete mathematical explanation with the corresponding formulae, used in LI is described by Groot et al. (2018). Here we briefly summarize the optimization process. The DE algorithm generates two populations of solutions which represent the decision variables that indicate allocated LULC on map polygons. 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 a 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, Oomen, & Rossing, 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. 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 the 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.

3. Results

3.1. Current landscape performance

The total areas of SCT and SCA were 4220 and 3490 ha, respectively. Forest and grassland were the most common LULC types in both municipalities, occupying around 50 and 30% of the total territory in SCT, and 40 and 35% in SCA, respectively (Fig. 3). Crops occupied 20% of the total territory in each municipality. Maize was grown on around 70 and 55% of the cropland in SCT and SCA, respectively. Bean took around 25 and 30% and MILPA 5 and 15% of the cropland in SCT and SCA, respectively.

In SCT nutrients and vitamins were enough to feed a population of 679 people, except for vitamins A and C (Table 2). Vitamins A and C are found in high concentrations in squash, which is produced in MILPA. Apart from vitamin A and C deficiencies, SCA fell short of the population's requirements for vitamin B9, dietary energy, calcium, iron, and zinc (Table 2). The lower nutrient and vitamin systems yields in SCA were attributable to lower crop yields and less cropland area compared to SCT.

The amount of locally available labor in SCA (41,280 days) in May and June was double that of SCT (Table 2). Neither community could meet the required labor with locally available labor for these months. Therefore, both communities hire external labor to address this deficit.

The distribution of plots across the municipalities affected habitat connectivity. The concentration of agricultural plots in the mid-section of SCT (Fig. 3) decreased forest habitat connectivity by physically separating the forests on the west and east sides of the community. In SCA, forest cover was found interspersed among agricultural plots, which resulted in greater habitat connectivity. SCT performed better than SCA in terms of carbon stock due to its larger forest area. The Satoyama index values in each municipality were similar (0.9 for SCT and 0.91 for SCA), meaning that both municipal landscapes had a high diversity of LULCs and showed patchy patterns.

Table 2
Current nutritional, socio-economic, and environmental performance for Santa Catarina Tayata and San Cristobal Amoltepec.

Indicator type	Indicator	Units	Municipality	
			Santa Catarina Tayata[1]	San Cristobal Amoltepec[1]
Nutritional	Nutritional evenness	–	3.53	4.07
	$NSY_{Dietary.\ energy}$	Persons fed yr^{-1}	1,992 (293%)	860 (85%)
	$NSY_{Protein}$	Persons fed yr^{-1}	2,734 (402%)	1,508 (150%)
	NSY_{Ca}	Persons fed yr^{-1}	1,523 (224%)	595 (59%)
	NSY_{P}	Persons fed yr^{-1}	2,851 (419%)	1,488 (148%)
	NSY_{Fe}	Persons fed yr^{-1}	1,601 (235%)	826 (82%)
	NSY_{Mg}	Persons fed yr^{-1}	3,398 (500%)	1,350 (134%)
	NSY_{Zn}	Persons fed yr^{-1}	1,054 (155%)	827 (82%)
	$NSY_{Vit.A}$	Persons fed yr^{-1}	102 (15%)	73 (7%)
	$NSY_{Vit.B2}$	Persons fed yr^{-1}	1,992 (293%)	1,058 (105%)
	$NSY_{Vit.B3}$	Persons fed yr^{-1}	2,421 (356%)	1,290 (128%)
	$NSY_{Vit.B6}$	Persons fed yr^{-1}	3,124 (459%)	1,356 (135%)
	$NSY_{Vit.B9}$	Persons fed yr^{-1}	898 (132%)	860 (86%)
	$NSY_{Vit.B12}$	Persons fed yr^{-1}	1,367 (201%)	1,488 (148%)
	$NSY_{Vit.C}$	Persons fed yr^{-1}	117 (17%)	86 (8%)
Socio-economic	Required labor	Days	55,855	49,268
	Locally available labor	Days	20,520	41,280
	Income	MXN yr^{-1} (USD yr^{-1})	5,709,818 (285,490)	5,717,113 (285,855)
Environmental	Soil loss	Mg yr^{-1}	13,005	11,143
	Total carbon	T	283,929	239,398
	Habitat connectivity	Ha	834	1411
	Satoyama index	–	0.90	0.91

[1] Values outside the parentheses are the nutrient system yield while percentual values between parentheses represent the nutritional self-sufficiency of a given nutrient or vitamin.

Table 3
Average and highest maize, common bean, and squash yields in different cropping systems and calculated land equivalent ratios (LERs) of MILPA.

	Santa Catarina Tayata		San Cristobal Amoltepec	
	Average (Mg/ha)	Highest observed yield (Mg/ha)	Average (Mg/ha)	Highest observed yield (Mg/ha)
Maize	0.84	2.00	0.34	1.62
Maize in MILPA	0.04	1.62	0.04	1.56
Common bean	0.15	0.45	0.12	0.25
Common bean in MILPA	0.05	0.22	0.04	0.04
Squash in MILPA	0.45	1.00	0.22	1.00
Land Equivalent Ratio MILPA	0.42	1.40	0.47	1.22

3.2. *Exploring landscape configuration alternatives*

3.2.1. *Scenario S1 - Reallocation of existing LULC options*

Around 40% and 30% of the alternative landscapes generated by multi-objective optimization for SCT and SCA satisfied the population's demand for vitamin A (points above red line Fig. 4). Across the alternative landscape configurations generated by LI, vitamin A supply was positively connected with income, soil erosion, and labor requirements (Fig. 4 and Appendix B). Greater carbon stocks were generally associated with greater vitamin B12 yields. A trade-off existed between vitamin B12 and vitamin A. A reduction in vitamin B12 yield and an increase in vitamin A production was accompanied by a reduction in grassland and an increase in MILPA (Appendix B).

Nutritional self-sufficiency of vitamin A could be achieved with different landscape configurations in SCT (red line in Fig. 4). Reaching vitamin A self-sufficiency in SCT would require 10% of the land to be occupied with MILPA (red lines in Fig. 5). For SCA, the most productive landscape alternative for vitamin A would be able to feed 968 out of its 1005 persons. To reach this level, the cropping area would have to be expanded by 17% (horizontal black lines in Fig. 5).

In scenario S1, increasing vitamin A self-sufficiency through MILPA would come at the cost of reduced forest and grassland surface (Fig. 5). Since forest and grassland are the LULCs that resulted in less soil erosion, their reduction would increase soil losses throughout the landscape.

3.2.2. *Scenario S2: Reallocations including new LULC options*

The introduction of maize-squash and MIAF systems in scenario S2 considerably changed the solution spaces compared to the first scenario (Fig. 4). Notably, both communities had a much larger window of opportunity for improving vitamin A production and generating income. Nevertheless, the attainable levels for carbon stock and vitamin B12 were lower compared to the S1 scenario without maize-squash and MIAF. Similarly, in scenario S2 erosion could not be reduced below 2.7 Mg ha^{-1} $year^{-1}$, which was reachable for scenario S1. This is explained by a larger share of the land being allocated to crops, reducing the share of forest and grassland in scenario S2 when compared to S1.

In scenario S2, any Pareto-optimal landscape would allow both communities to increase their vitamin A production, and consequently, nutritional self-sufficiency of vitamin A could be reached for all alternative landscape configurations in the result-set. Reaching vitamin A self-sufficiency would require a minimum cropland area of 19 and 20% of the total territory for SCT and SCA, respectively. This is particularly relevant for SCA, which had no alternative landscape that would reach self-sufficiency without cropping systems innovations. Despite the potential benefits offered by introducing maize-squash and MIAF systems, these systems would increase labor requirements and reduce the production of vitamin B12.

Fig. 6 shows four landscape configuration options for each municipality. They provide insights into how landscape configuration changes according to stakeholder's goals. When maximizing vitamin A production, there was an emphasis on maize-squash production. Landscapes that generated more income had increased MIAF production.

4. Discussion

4.1. *Achieving nutrition-sensitive landscapes*

Our study showed how the landscape performance can improved through reorganizing the different LULCs to optimize nutritional self-sufficiency while increasing carbon stocks. Among current cropping systems, the diversified MILPA plays a clear role in sustaining and improving nutritional self-sufficiency (Novotny et al., 2021). Introducing cropping systems such as maize-squash and MIAF could increase vitamin A production and generate greater incomes for farmers. However, expanding maize-squash and MIAF onto grasslands and forest lands could lead to increased soil erosion rates and smaller carbon stocks

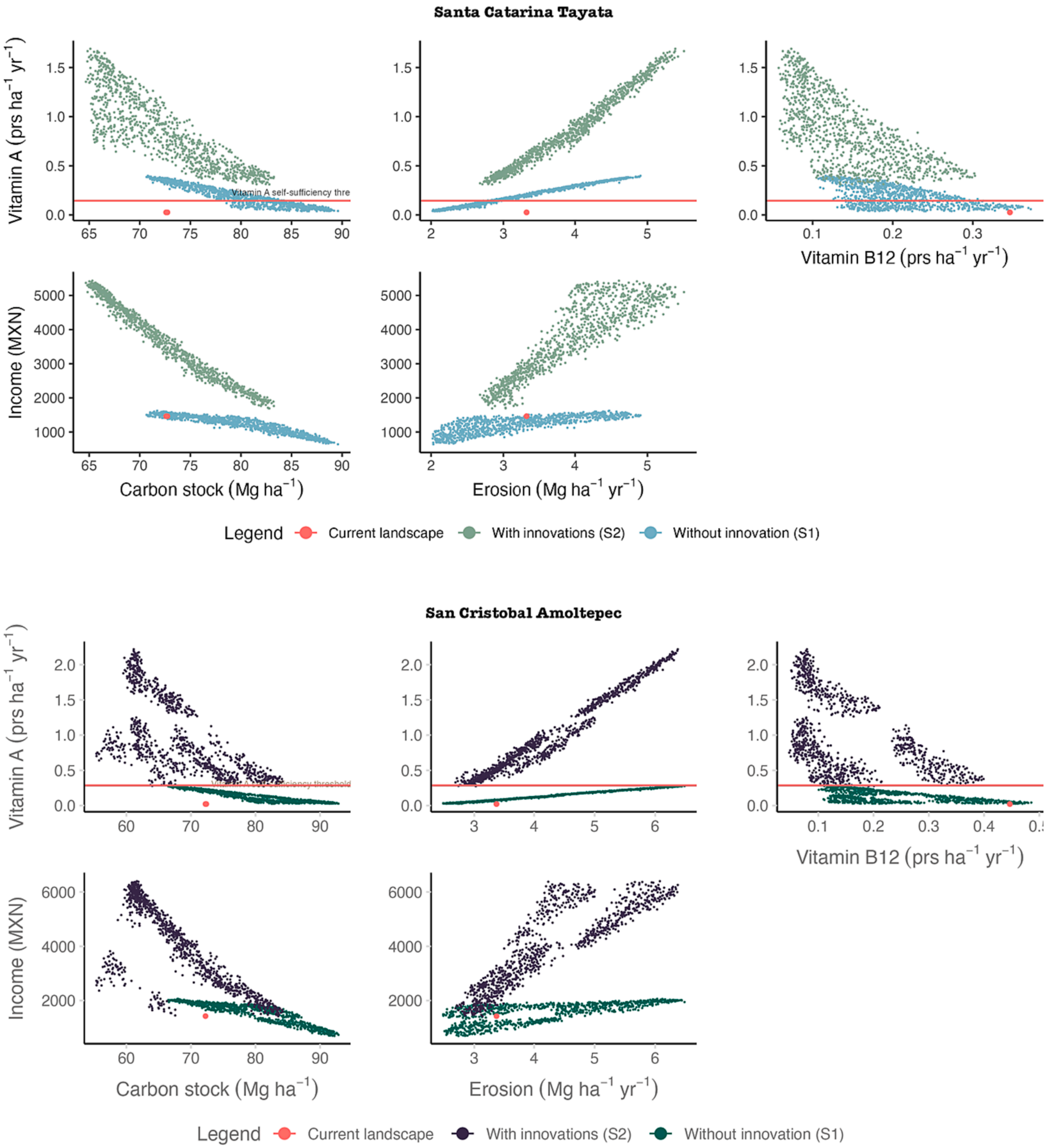

Fig. 4. Performance of alternative Pareto-optimal landscapes generated by multi-objective optimization for Scenarios S1 and S2, expressed in five objectives: vitamin A, vitamin B12, income, carbon stock, and erosion. Red dots represent current landscape performance. Red lines indicate the nutritional self-sufficiency threshold for vitamin A. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

at the landscape level.

Our study aimed to answer the question raised by Ickowitz et al. (2022) and Powell et al. (2015) regarding how landscapes can sustain healthy food production while maintaining or even improving, ecosystem services. Moreover, international organizations call for nutrition-sensitive landscape solutions that aim at improving both food and nutritional security while promoting sustainable use of natural resources and conservation (Bioversity International, 2014; IFPRI, 2014). Broegaard et al. (2017) followed an NSL approach to study a wide array of systems from forests, fallow, and agricultural fields to demonstrate wild foods' relevance in decreasing protein gaps. Similar to the study from Broegaard et al. (2017), our study assessed food production according to different LULCs. However, our study is the first to include a set of nutritional components in the analysis and relate nutritional self-sufficiency with ecosystem services.

As a result of favoring maize monoculture instead of MILPA, vitamins

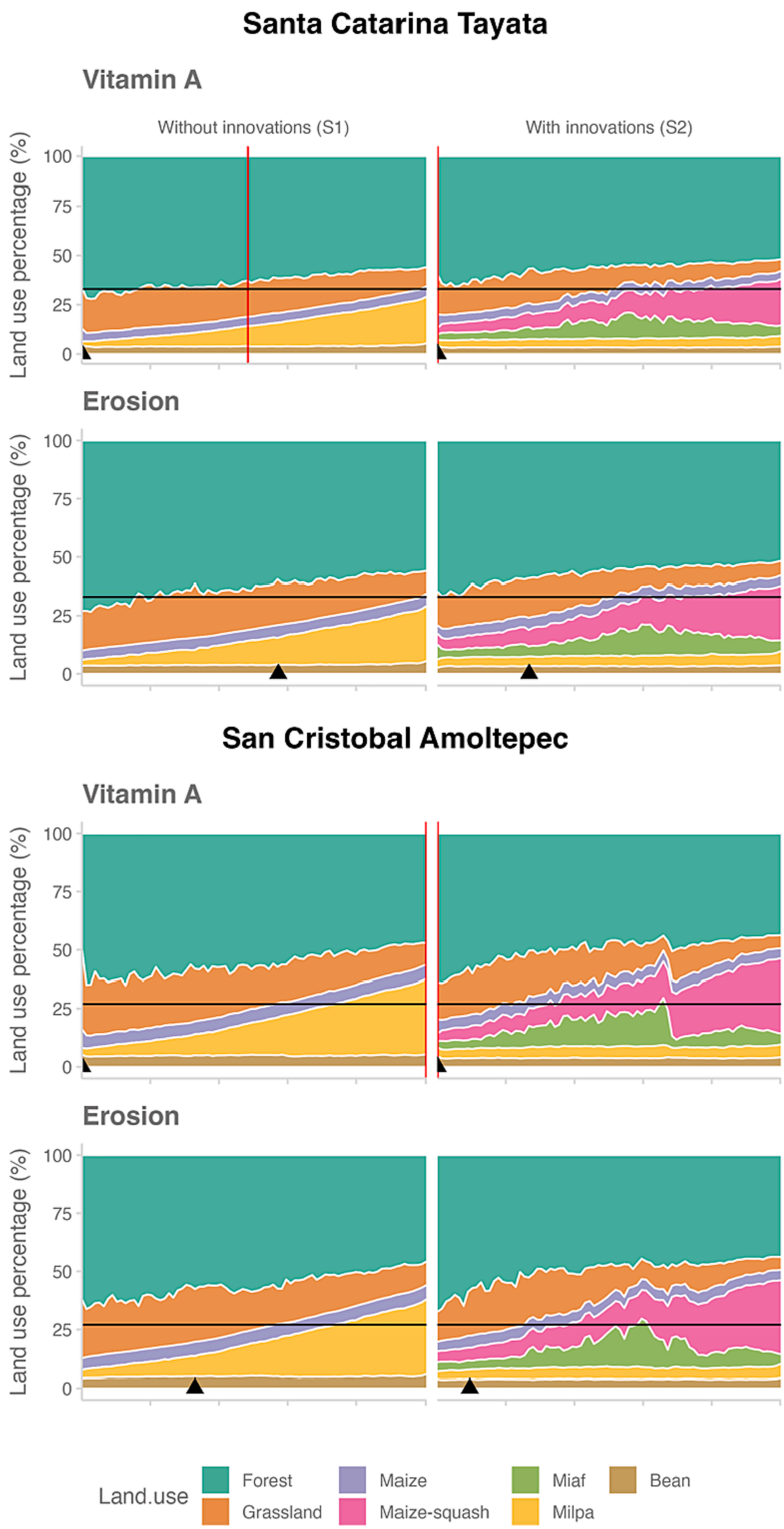

Fig. 5. Thousand landscape configurations (percentage of different LULCs indicated on the y-axis) ranked by the performance of vitamin A and soil erosion (low–high, x-axis) for Santa Catarina Tayata (SCT) and San Cristobal Amoltepec (SCA) without (scenario S1) and with (scenario S2) the introduction of maize-squash and MIAF. Horizontal black lines indicate the legal limit of land allowed for agricultural exploitation. Vertical red lines represent the nutritional self-sufficiency threshold. Black arrows represent the current LULC proportions. The lines of percentages of LULCs were smoothed using the LOESS method for better interpretation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 6. Landscape configuration for maximizing vitamin A production, income, and carbon stock and minimizing soil erosio.

A and C were produced in low quantities in each case study municipality. Vitamin A deficiency is a common problem in Mexico (Leatherman, Goodman, & Stillman, 2020; Mora, Gueri, & Mora, 1998), with alarming cases of severe deficiency in children (Brito et al., 2015). Also for other regions of Latin America (Brito et al., 2015; Mora et al., 1998) and the world (Laillou et al., 2012; Timler et al., 2020), vitamin A deficiency has been reported as a concern for human nutrition. Reaching self-sufficiency for vitamin A proved to be particularly difficult at the San Cristobal Amoltepec municipality. Given the current LULCs and productivity levels (scenario S1), SCA would require an expansion of its cropland to come close to achieving the local demand for vitamin A, consequently reducing LULCs that can improve carbon stocks and reduce erosion (e.g., forest and grassland).

By diversifying cropping systems options (scenario S2), MILPA could provide sufficient amounts of nutrients and vitamins for adequate human nutrition (Novotny et al., 2021). Despite the nutritional benefits of MILPA, these polycultures exhibited relatively low productivity (Table 3) and high labor demands in the region of study. Together with an increasing engagement in off-farm activities (Novotny, 2020), farmers might be less inclined to grow MILPA, which requires also more manual labor than maize monocultures. Other places in Mexico exhibit similar preferences for monocropping systems (Birol, Villalba, & Smale, 2009; Gutiérrez-Carbajal & Magaña-Magaña, 2017; Kontoleon, Pascual, Smale, 2009; Otero-Prevost, Gurri-García, Mariaca-Méndez, & Guízar-Vázquez, 2018; Richard, 2008; Rodríguez & Arias, 2014).

Improving MILPA to bring the average yield closer to the attainable yield could provide greater amounts of food and generate more income, making this system more attractive to farmers. Technical interventions should aim at bridging this gap. In experimental conditions in Texcoco, Mexico, MILPA polycultures yielded 4.5, 0.9, and 6.2 Mg ha^{-1} of maize, bean, and squash respectively (Ebel, Pozas, Soria, & Cruz, 2017); this represents 110-, 6-, and 10-fold the average yields measured in our region of study. Another option is to increase squash density in MILPA to favor the production of vitamins A and C, although experimental trials should be performed for better recommendations on plant density. At the policy level, efforts should be made to stimulate MILPA production instead of steering farmers away from it towards monocultures, as has been the case in the last decade (Sánchez & Hernández, 2014).

Considering the challenges of expanding MILPA to provide better nutrition, alternative production management or cropping systems, such as the ones proposed in this study, should be also considered. Results showed that maize-squash and MIAF systems could change the landscape performance for the indicators assessed. Maize-squash could increase vitamin A, while MIAF could offer better economic performance, as seen in other studies (Cadena-Iñiguez et al., 2018; Cortés et al., 2007; Etchevers et al., 2004). Our modeling study revealed several landscape configurations with maize-squash and MIAF that could reach vitamin A self-sufficiency while also increasing ecosystem services like carbon stocks and soil erosion reduction. In contrast, reaching vitamin A self-sufficiency with current cropping systems would not be possible without greatly compromising these ecosystem services.

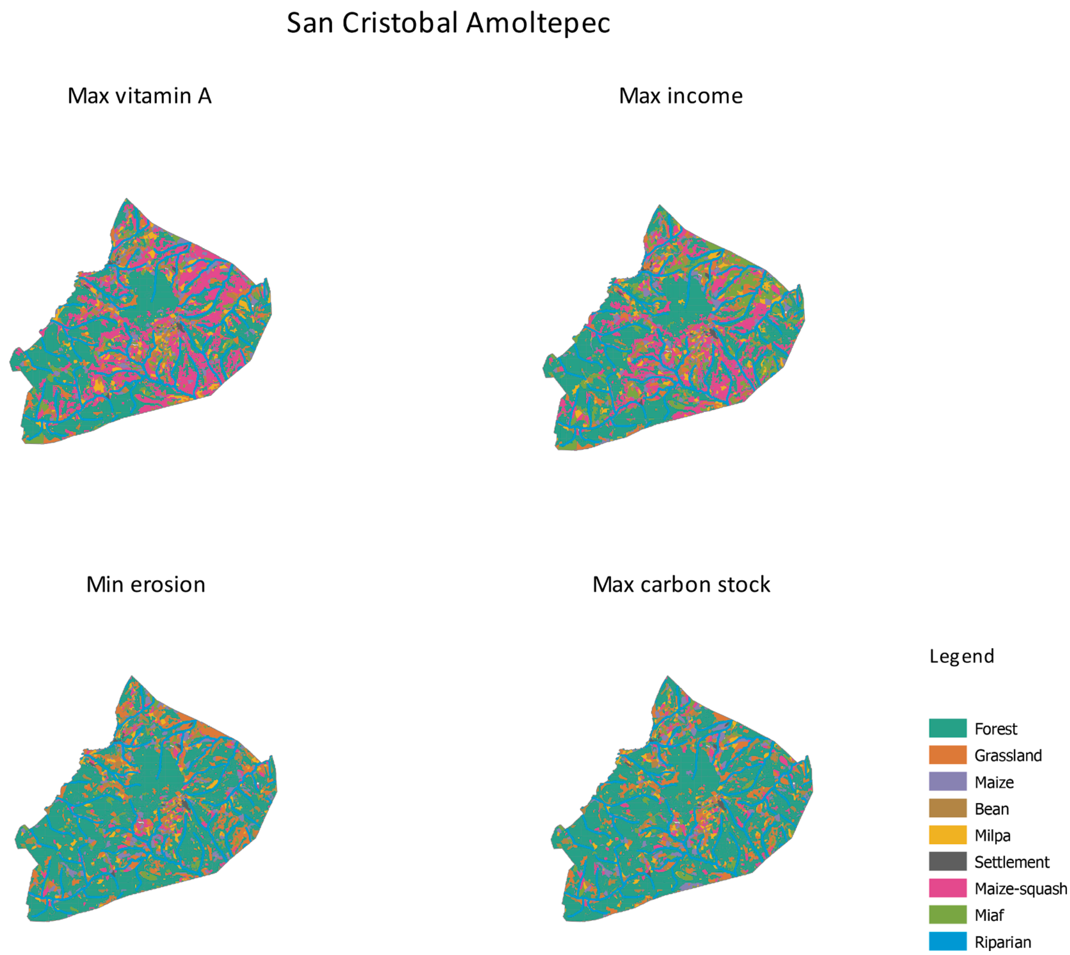

Fig. 6. (*continued*).

4.2. Socio-ecological landscapes

The assessment of scenarios that considered only current LULCs and cropping systems revealed the limited potential to improve the socio-economic, nutritional, and environmental performance of landscapes in contexts where no changes in cropping systems are likely to happen. This is particularly relevant to highly marginalized places such as the state of Oaxaca (CONAPO, 2016). Results from this study showed landscape alternatives that could improve carbon stocks, and vitamin A production, and reduce soil erosion (Fig. 4). Combining this potential with the fact that communities in Mexico have the autonomy to govern their land (Novotny et al., 2021), offers prospects for improved landscapes. Despite this study being realized in an unproductive and marginalized area, the robustness of our approach can be replicated in different contexts. Landscape-level management often involves wicked problems that arise from a socio-economic and ecological complexity fueled by social actors with conflicting interests. Incorporating these actors' goals and aspirations into the analysis and exploring potential landscape alternatives and their associated synergies and trade-offs can offer a transparent and inclusive platform for discussing these alternatives.

Reaching food regional self-sufficiency has several implications for food markets. A more localized food production boosts the rural economy, mitigates the influence of price fluctuations, and reduces travel costs (Clapp, 2017; Puma, Bose, Chon, & Cook, 2015; Suweis, Carr, Maritan, Rinaldo, & D'Odorico, 2015). In contrast, a few negative points should also be considered. Achieving higher food self-sufficiency might not be possible depending on whether the environment's agricultural aptitude can sustain a sufficient supply of food for its population (Fader, Gerten, Krause, Lucht, & Cramer, 2013). Furthermore, reducing the dependency on external markets might remove the assurance of obtaining extra food in the face of crop failure, pest outbreaks, or extreme weather events.

4.3. Limitations and future research

This study had some limitations. First, it focused on nutritional self-sufficiency, which assesses food availability from agriculture and food utilization. Although both are important for a food security assessment, data on access to food and food production stability are required for a fuller panorama of food security. This study explored alternative landscapes for two municipalities, and the question remains of how to scale up and incorporate these findings at the regional landscape planning level. However, landscape performance can be improved, even for regions where high marginalization, nutritional gaps, and land degradation exist. As such, learnings from this study could be carried out in similar socio-economic contexts. Third, the addition of two cropping systems did not aim to be exhaustive in terms of available possibilities. Instead, it was used as an example of how alternative systems can alter landscape performance and create new opportunities for productive and sustainable landscapes. Other cropping systems and management can and should be considered for reaching improved landscape performances. While this study assessed the current performance of indicators whose performance depended on the spatial configuration of land uses (Satoyama index and habitat connectivity), they were not considered by stakeholders as key variables for optimization. Nevertheless, we suggest future studies to not only consider the amount of areas per land use but also how distribute and connect with one another in the landscape.

Lastly, this study offers a way to inspire further collaboration between stakeholders by discussing the advantages and disadvantages of alternative landscape configurations.

The potential for improving landscape performance through diversification and intensification, with or without innovations in cropping systems exists. Nevertheless, with the current yield levels and labor demands, traditional MILPA systems are losing interest from farmers. Therefore, an agronomic rejuvenation of the agroecological concept behind this iconic mixed cropping system is needed to fit both the economic and socio-cultural contexts.

5. Conclusions

Through a nutrition-sensitive landscape approach, we generated and illustrated several landscape configurations for improving landscape performance in terms of income, nutritional self-sufficiency, carbon stocks, and soil erosion reduction. This study demonstrated it is possible to improve the nutritional, economic, and environmental performance solely by re-arranging current LULCs. Yet, introducing new cropping systems may contribute to breaking deadlocks and improving landscape performance even further. The inclusion of a maize-squash intercropping system would vastly improve the provision of vitamin A, while the MIAF agroforestry system would provide farmers with an opportunity to increase their income. These benefits, however, come at the cost of higher labor demands and more soil erosion risks as cropping systems activities start to replace forests and grasslands. The multi-objective model used here was based on stakeholders' objectives, offering a robust way to assess landscape configurations in a risk-free environment. This increases the chance for every party involved to have their voice expressed in the design process and to foresee how changing aspects of the landscape affect its performance. The use of this framework in participatory exercises of landscape redesign with local communities and other stakeholders has the potential to inform discussion in the quest for more equitable, sustainable, and nutritionally sensitive landscapes.

CRediT authorship contribution statement

Ivan P. Novotny: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Visualization, Writing – original draft, Writing – review & editing. **Walter A.H. Rossing:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Pablo Tittonell:** Funding acquisition, Supervision, Writing – review & editing. **Mariela Fuentes-Ponce:** Conceptualization, Supervision, Writing – review & editing. **Jeroen C.J. Groot:** Methodology, Software, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix

Appendix A. Production per LULC in Santa Catarina Tayata and San Cristobal Amoltepec

		LULC in Santa Catarina Tayata						
Indicator	Unit	Forest	Grassland	Maize	Bean	MILPA	Maize-squash	MIAF
Dietary energy	persons fed ha^{-1}	0	0.19	3.14	0.64	3.75	8.63	4.91
Protein	persons fed ha^{-1}	0	0.48	3.60	1.85	5	10.31	6.27
Calcium	persons fed ha^{-1}	0	0.02	2.61	0.56	3.11	7.25	4.08
Phosphorus	persons fed ha^{-1}	0	0.33	3.73	2.47	6.37	13.73	6.40
Iron	persons fed ha^{-1}	0	0.13	2.15	1.64	3.51	7.37	3.99
Magnesium	persons fed ha^{-1}	0	0.08	5.84	0.62	8.03	19.75	8.22
Zinc	persons fed ha^{-1}	0	0.49	0.64	1.06	2.07	4.62	1.99
Vitamin A	persons fed ha^{-1}	0	0	0	0	1.96	7.83	0.63
Vitamin B2	persons fed ha^{-1}	0	0.27	2.68	1.63	3.84	8.28	5.38
Vitamin B3	persons fed ha^{-1}	0	0.59	3.22	0.58	4.11	9.89	6.19
Vitamin B6	persons fed ha^{-1}	0	0.14	4.96	1.69	6.26	14.23	8.00
Vitamin B9	persons fed ha^{-1}	0	0	0	4.82	1.99	1.97	3.37
Vitamin B12	persons fed ha^{-1}	0	1.45	0	0	0	0	0
Vitamin C	persons fed ha^{-1}	0	0	0	0	2.01	8.25	5.55
Required labor	days ha^{-1}	0	60	69	90	125	90	170
Income	MXN ha^{-1}	0	4615	3050	−1900	5245	18,881	18,450
Soil loss	Mg/ha	1	1	15	15	15	15	5
Total carbon	t ha^{-1}	121.1	78.7	23	23	23.8	23	26.8
		LULC in San Cristobal Amoltepec						
Indicator	Unit	Forest	Grassland	Maize	Bean	MILPA	Maize-squash	MIAF
Dietary energy	persons fed ha^{-1}	0	0.19	1.29	0.52	2.17	8.63	4.91
Protein	persons fed ha^{-1}	0	0.48	1.46	1.50	2.99	10.31	6.27
Calcium	persons fed ha^{-1}	0	0.02	1.06	0.45	1.79	7.25	4.08
Phosphorus	persons fed ha^{-1}	0	0.33	1.51	2.00	3.76	13.73	6.40

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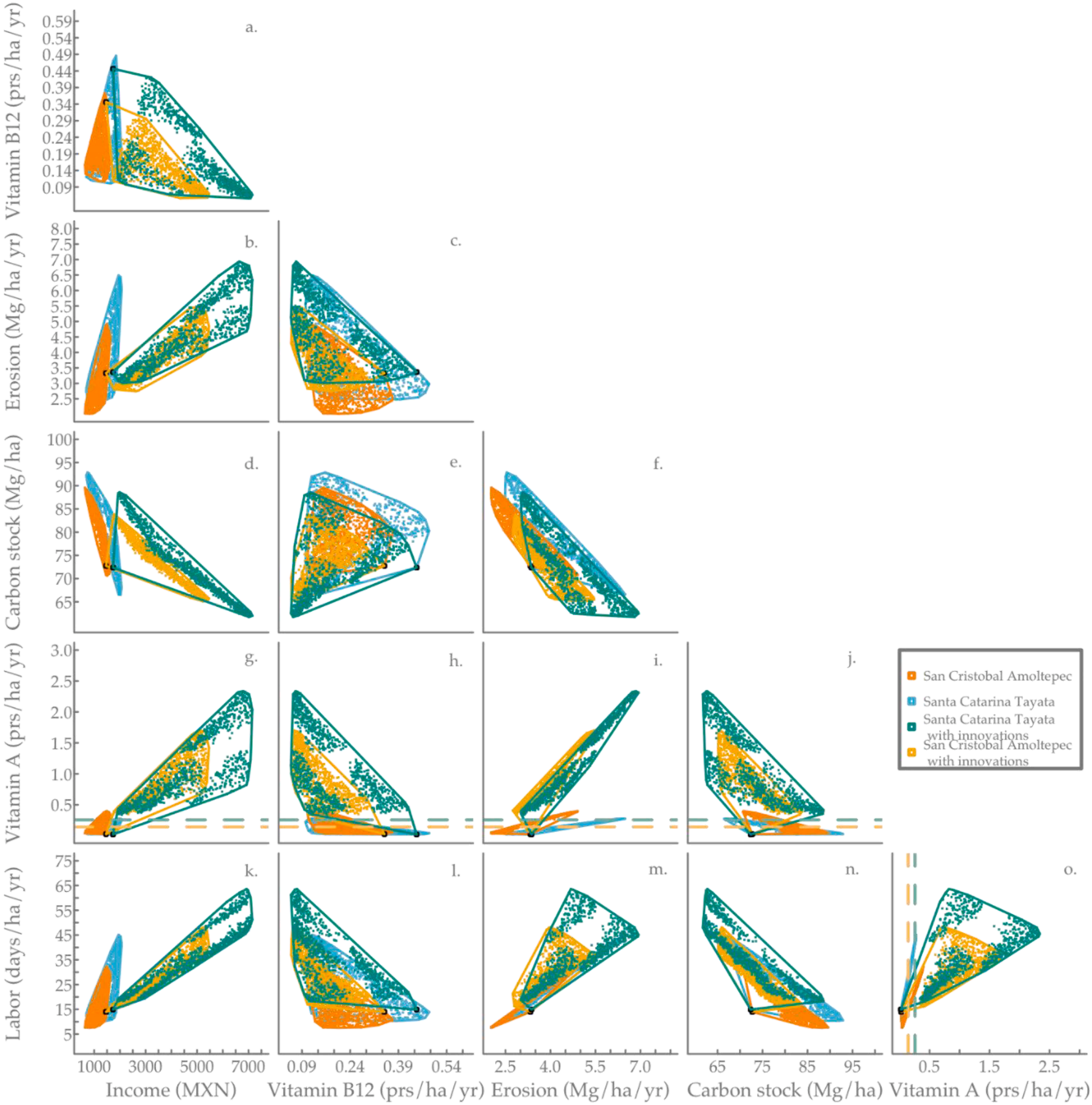
Indicator	Unit	LULC in Santa Catarina Tayata						
		Forest	Grassland	Maize	Bean	MILPA	Maize-squash	MIAF
Iron	persons fed ha^{-1}	0	0.13	0.87	1.33	2.11	7.37	3.99
Magnesium	persons fed ha^{-1}	0	0.08	2.36	0.51	4.54	19.75	8.22
Zinc	persons fed ha^{-1}	0	0.49	0.26	0.85	1.22	4.62	1.99
Vitamin A	persons fed ha^{-1}	0	0	0	0	0.95	7.83	0.63
Vitamin B2	persons fed ha^{-1}	0	0.27	1.09	1.31	1.02	8.28	5.38
Vitamin B3	persons fed ha^{-1}	0	0.59	1.30	0.47	2.29	9.89	6.19
Vitamin B6	persons fed ha^{-1}	0	0.14	2.01	1.37	2.35	14.23	8.00
Vitamin B9	persons fed ha^{-1}	0	0	0	3.9	3.65	1.97	3.37
Vitamin B12	persons fed ha^{-1}	0	1.45	0	0	1.44	0	0
Vitamin C	persons fed ha^{-1}	0	0	0	0.04	1.02	8.25	5.55
Required labor	days	0	60	69	90	125	90	170
Income	MXN	0	4615	−700	−645	5000	18,881	18,450
Soil loss	Mg/ha	1	1	15	15	15	15	5
Total carbon	t	121.1	78.7	23	23	23.8	23	26.8


Vitamin B12 (prs/ha/yr)
Erosion (Mg/ha/yr)
Carbon stock (Mg/ha)
Vitamin A (prs/ha/yr)
Labor (days/ha/yr)
Income (MXN)
San Cristobal Amoltepec
Santa Catarina Tayata
Santa Catarina Tayata with innovations
San Cristobal Amoltepec with innovations
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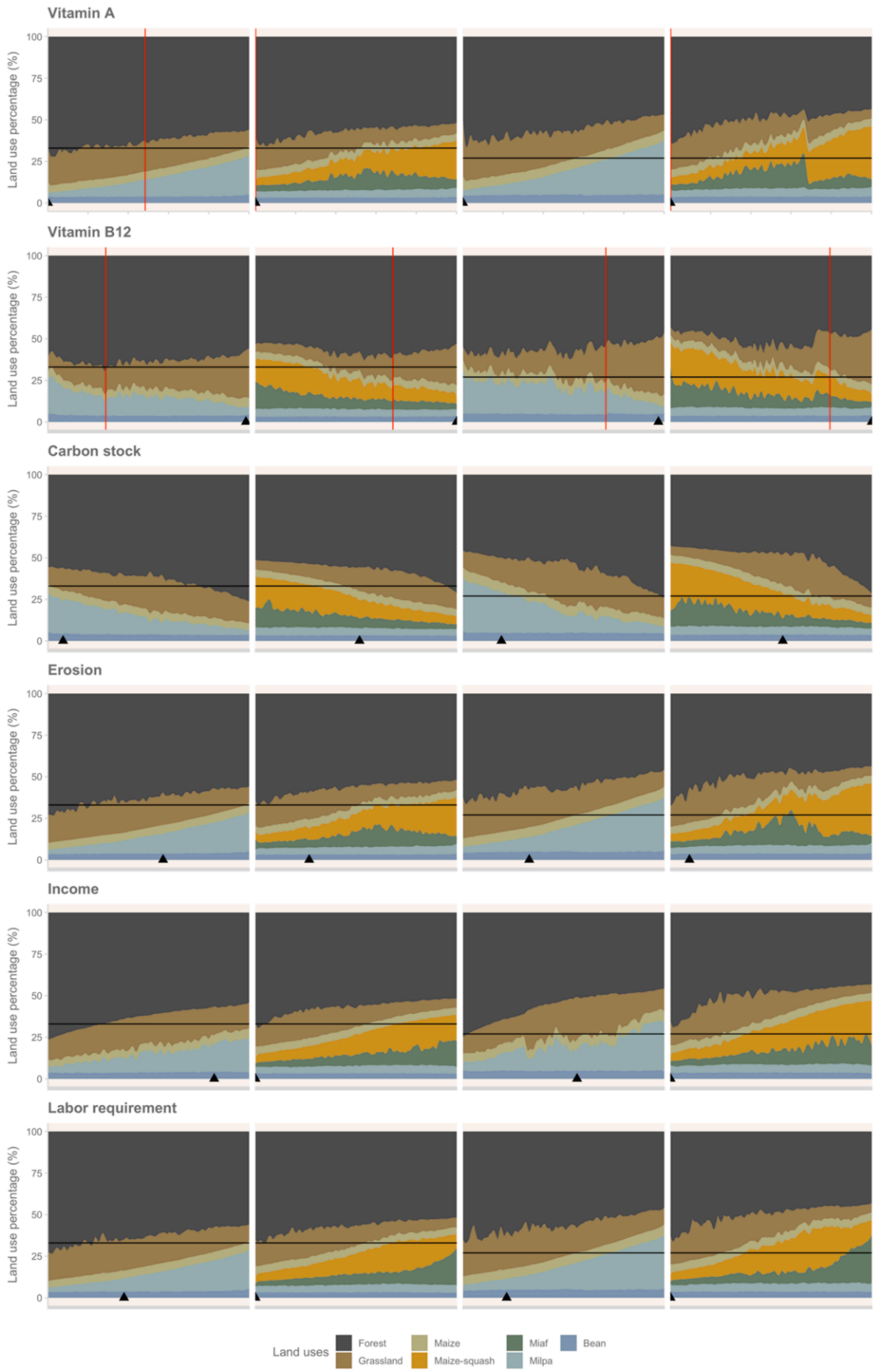
Appendix B. Performance of alternative Pareto-optimal landscapes expressed in six objectives: income, vitamin B12, erosion, carbon stock, vitamin A, and labor. Black squares represent current landscape performance. Dashed lines indicate the vitamin self-sufficiency threshold. Blue: San Cristobal Amoltepec, red: Santa Catarina de Tayata. Hulls around the solution clouds were added for ease of comparison between municipalities



Appendix C. Thousand landscape configurations (y-axis) ranked by the performance of 6 objectives (low–high, x-axis) for Santa Catarina Tayata (SCT) and San Cristobal Amoltepec (SCA) with and without the introduction of maize-squash and MIAF. Horizontal black lines indicate the current maximum surface allowed for private agricultural exploitation. Vertical red lines represent the nutritional self-sufficiency threshold. Black arrows represent the current LULC proportions. The figures' lines were smoothed using the LOESS method for better interpretation

Appendix D. Area-based error matrix

	Reference			
Classified	Forest	Agriculture	Bare soil	Area
Forest	0.6028	0.0009	0	1,265,400
Agriculture	0.0906	0.1765	0.0013	562,500
Bare soil	0	0.024	0.1039	268,200
Total	0.6934	0.2014	0.1052	2,096,100
Estimated area	1,453,500	422,100	220,500	2,096,100
Standard error	0.0051	0.0059	0.003	
Standard error area	10724.32	12359.2	6275.52	
95% CI area	21019.67	24224.04	12300.03	
Producer accuracy [%]	86.935	87.6333	98.7755	
User accuracy [%]	99.8578	65.76	81.2081	
Overall accuracy [%] = 88.3212				

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