UNIVERSIDAD NACIONAL AUTÓNOMA DE MÉXICO

POSGRADO EN CIENCIAS BIOLÓGICAS
INSTITUTO DE ECOLOGÍA
MANEJO INTEGRAL DE ECOSISTEMAS

CARACTERIZACIÓN DE LA HETEROGENEIDAD ESPACIAL EN DISTINTAS ESCALAS DE UN PAISAJE AGRÍCOLA DE OAXACA

TESIS

(**POR ARTÍCULO CIENTÍFICO**)

LANDSCAPE HETEROGENEITY IN A PEASANT-MANAGED AGRICULTURAL MATRIX IN OAXACA, MEXICO

QUE PARA OPTAR POR EL GRADO DE:

MAESTRA EN CIENCIAS BIOLÓGICAS

PRESENTA:

ANA LAURA URRUTIA CÁRDENAS

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DR. LUIS E. GARCÍA BARRIOS
COLEGIO DE LA FRONTERA SUR

MÉXICO, CD. MX. Septiembre, 2019

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M en C. Ivonne Ramírez Wence
Directora General de Administración Escolar, UNAM
Presente

Me permito informar a usted, que el Subcomité de Biología Experimental y Biomedicina, en su sesión ordinaria del día 27 de mayo de 2019, aprobó el jurado para la presentación del examen para obtener el grado de **MAESTRA EN CIENCIAS BIOLÓGICAS**, del Posgrado en Ciencias Biológicas a la alumna **URRUTIA CÁRDENAS ANA LAURA** con número de cuenta **412060089,** por la modalidad de graduación de **tesis por artículo científico,** en el campo de conocimiento de **Manejo Integral de Ecosistemas,** con la tesis titulada: "**Landscape heterogeneity of peasant-managed agricultural matrices",** producto del proyecto realizado en la maestría que lleva por título: **"CARACTERIZACIÓN DE LA HETEROGENEIDAD ESPACIAL EN DISTINTAS ESCALAS DE UN PAISAJE AGRÍCOLA DE OAXACA.",** bajo la dirección de la **DRA. MARIANA BENÍTEZ KEINRAD:**

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Cd. Universitaria, Cd. Mx., a, 20 de agosto

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Resumen

Los paisajes están en constante cambio y uno de los cambios más frecuentes es el cambio de uso de suelo es de vegetación primaria a uso agrícola, con el que las prácticas de manejo y otros factores ambientales y sociales dan forma a matrices agroecológicas complejas. A su vez, la estructura de dichas matrices afecta tanto a las actividades agrícolas como a la conservación de la biodiversidad, por ejemplo, al mediar la migración de la vida silvestre entre los parches agrícolas y de hábitat. Una forma de estudiar una matriz, junto con su posible papel en la conservación de la biodiversidad y hacer el estudio comparable con otros estudios realizados en distintas escalas es por medio de la caracterización de las llamadas métricas de los paisajes y la exploración de los cambios de los valores descriptivos de dicho paisaje en diferentes escalas. Las métricas del paisaje y el análisis sistemático del cambio de dichas métricas con el tamaño de grano y la extensión del paisaje permiten describir la heterogeneidad espacial de estos paisajes y permiten compararla con otros paisajes con historias y manejos diferentes. Sin embargo, estos métodos rara vez se han aplicado a paisajes agrícolas y en los trópicos a pesar de que este tipo de paisaje suele estar en o cerca de puntos críticos de biodiversidad. Nos enfocamos en el municipio de la Villa de Zaachila un paisaje agrícola en Oaxaca, México, para el cual mapeamos y cuantificamos las clases de uso de suelo y evaluamos las métricas de heterogeneidad espacial. También examinamos la respuesta de las métricas a los cambios en las escalas de grano y extensión e identificamos escala clave para entender estas métricas. Con base en nuestros resultados discutimos el papel potencial de esta matriz en la conservación de la biodiversidad, así como la pertinencia de estrategias conjuntas de conservación y producción.

Abstract

Landscapes are continually changing and one of the most frequent changes of land use is from primary vegetation towards agricultural use, in which management practices and other environmental and social factors shape complex agroecological matrices. In turn, the structure of such matrices impacts both agricultural activities and biodiversity conservation, for instance, by mediating wildlife migration between agricultural and habitat patches. One way of studying a matrix, together with its possible role in maintaining biodiversity and making the study comparable with other studies carried out at different scales is by characterizing landscapes with the so called landscape metrics and exploring changes in the descriptive values of such landscapes at different scales. Landscape metrics and the systematic analysis of the change in metrics with grain size and landscape extent allow us to describe the spatial heterogeneity of these landscapes and compare to it with other landscapes with different history and management. However, these methods have been applied to agricultural landscapes in the tropics despite the fact that this type of landscape is often close to critical biodiversity points. We focus on the municipality of Villa de Zaachila in an agricultural landscape in Oaxaca, Mexico, for which we mapped and quantified the land-use classes and evaluated heterogeneity metrics. We also examined the response of heterogeneity metrics to changes in grain and extent scales and identified some key grain sizes and extent to better understand the metrics. Based on our results, we discuss the potential role of this matrix in the conservation of biodiversity, as well as the relevance of joint conservation and production strategies.

Introducción general

El paisaje está en constante cambio y sabemos que la principal causa de los cambios en los paisajes somos los humanos (Geist et al., 2006). Kolb y Galicia (2018) han descrito el cambio de uso de suelo como un disturbio a gran escala tanto temporal como espacial, causado en parte por políticas y motores asociados al sistema económico-político actual, mismas que determinan dinámicas regionales. En escalas regionales, el cambio de uso de suelo y la transformación de los paisajes se han relacionado fuertemente con la tenencia de la tierra y políticas de desarrollo agrícola (Tadesse et al., 2014; Kolb and Galicia, 2018).

El cambio de pastizales y bosques a zonas agrícolas es uno de los cambios de uso de suelo más importantes de acuerdo con la FAO (2004), el cual ha determinado que en la actualidad un tercio de la superficie terrestre del planeta tenga uso agrícola (Millennium Ecosystem Assessment, 2003; FAO, 2004; Foley et al., 2010). En México, uno de los usos de suelo más importantes es el agropecuario que representa el 22.3% del territorio nacional. Estimaciones de la SAGARPA mencionan que hasta el 57% podría estar dedicado a actividades agropecuarias si consideramos la ganadería extensiva en el territorio (INEGI, 2007; SAGARPA, 2013).

Debido a lo extendida que está la agricultura en la superficie terrestre y lo común que es el cambio de uso de suelo de vegetación primaria a agrícola, podemos encontrar muchos paisajes dominados por una matriz agrícola que conecta parches de vegetación primaria. Esta matriz agrícola puede facilitar la migración de metapoblaciones locales o impedirla dependiendo de su calidad (Perfecto et al., 2009; Perfecto et al., 2010). Se les llama matrices de buena calidad, justamente, a aquellas que son permeables para la migración de las metapoblaciones por medio de prácticas amigables con la biodiversidad, y que están en un paisaje con alta conectividad espacial (Perfecto et al., 2010; Fahrig, 2011, Ramos et al., 2018).

En este trabajo definimos a los paisajes como un complejo sistema socioecológico que comprende un mosaico dinámico de usos de suelo y vegetación (Parrott and Meyer, 2012). Dentro de los distintos usos de suelo que se reconocen en los paisajes, existen grados y formas de intensificación y manejo que afectan a su relación con los otros elementos del paisaje. Estos usos de suelo proveen a las metapoblaciones distintos nichos, recursos y permeabilidad para la migración (Kupfer et al., 2006; Fahrig et al., 2011; Parrott and Meyer, 2012). Las características estructurales de estos paisajes, como la forma y tamaño de los parches, la densidad de los bordes y la distancia entre parches del mismo uso de suelo también pueden tener efectos importantes en la biología de las metapoblaciones. Por ejemplo Liao *et al*., (2016) encontraron que ciertas configuraciones de los parches compensan la pérdida de hábitat y reducen los riesgos de extinción. Los paisajes pueden afectar a la biodiversidad, ya sea en la dinámica de las poblaciones, en la selección de caracteres evolutivos, en los patrones de la biodiversidad o sus efectos en el manejo del paisaje (Tscharntke et al., 2012; Fahrig et al., 2013; Fahrig, 2017).

Desde la perspectiva agrícola, existen estudios que demuestran que la calidad del paisaje que rodea las zonas agrícolas tiene un fuerte impacto en la polinización, la dinámica de herbivoría, la fertilidad y la productividad de las parcelas (Fahrig, 2003; Tscharntke et al., 2005; Poveda et al., 2012; Connelly et al., 2015; Boesing et al., 2017). Muchos de los pueblos rurales cercanos a las grandes ciudades en México demuestran una tendencia hacia la urbanización (Ávila Sánchez, 2009) y es necesario entender la relación espacial que tendrán los parches urbanos con las parcelas agrícolas y, también, el efecto de estas parcelas agrícolas en la vegetación primaria. Este es el tipo de paisaje y relaciones que podemos estudiar en la Villa de Zaachila, que de ahora en adelante llamaremos Zaachila en este trabajo. Zaachila es un pueblo cercano a la ciudad de Oaxaca, que pasó de tener un paisaje con una cobertura urbana de 3% en 2002 al 20% en 2016, urbanizando en particular terrenos destinados a la agricultura de temporal (INEGI serie III, 2002; INEGI serie VI, 2016).

En el estudio de paisajes complejos, sean rurales o urbanos, el estudio de la heterogeneidad espacial brinda herramientas formales para entenderlos con más claridad. La heterogeneidad espacial estudia qué compone al paisaje y cómo está estructurado en el espacio. Esto se entiende como heterogeneidad composicional y configuracional, respectivamente (Fahrig et al., 2011; Turner and Gardner, 2015). Para estudiar la heterogeneidad de los paisajes podemos utilizar distintas herramientas. Los mapas de uso de suelo y vegetación son caracterizaciones visuales que permiten ver de manera cualitativa la heterogeneidad composicional y configuracional. Por otro lado, las métricas del paisaje son herramientas cuantitativas que analizan imágenes satelitales, también en términos de heterogeneidad composicional y configuracional y que son cada vez de más fácil acceso (Mcgarigal and Cushman, 2002).

Otro elemento clave de la complejidad del paisaje es la escala en la que la entendemos y estudiamos. Por escala nos referimos aquí a la resolución y al área en la que observamos un fenómeno espacial, mejor llamados grano y extensión (Turner and Gardner, 2015). El grano se refiere a la resolución espacial más fina que se puede obtener de los datos, la unidad mínima de mapeo. La extensión se refiere al tamaño del área de estudio, es decir la cantidad en km^2 que se van a estudiar (Turner and Gardner, 2015). Los paisajes agrícolas se pueden estudiar en una gran cantidad de escalas espaciales, desde los milímetros cuando trabajamos con microorganismos hasta kilómetros cuando trabajamos con aspectos como tenencia de la tierra o dinámica de macrorganismos. Por ejemplo, estudiar el incremento de uso de plaguicidas o fertilizantes industriales en una escala local, sin considerar un cambio de la complejidad del paisaje en una escala mayor puede llevar a resultados muy distintos a los que se llegaría considerando la escala mayor. Esta escala mayor suele ser la escala del paisaje, la cual puede variar enormemente dependiendo del grado de heterogeneidad espacial (Tscharntke 2005).

Existen diversos estudios sobre los efectos de considerar distintas escalas al estimar la heterogeneidad espacial de paisajes en Estados Unidos (Wu, 2004; Wu, 2002; Cardille et al., 2005; Miller et al., 2015) y en China (Li et al., 2001; Zhang et al., 2007; Zhang and Zhang, 2011; Zhang and Li, 2013; Teng et al., 2016). En la Unión Europea los estudios de la heterogeneidad espacial se han centrado en los efectos que el manejo puede tener en las parcelas agrícolas, en particular relacionado con el programa de los esquemas agroambientales (agri-environment schemes) promovido por la propia Unión Europea) (Aviron et al., 2005; Purtauf et al., 2005; Concepción et al., 2008; Schindler et al., 2013; Vasseur et al., 2013; Plexida et al., 2014). En climas tropicales y subtropicales los estudios del paisaje se han enfocado en los bosques tropicales (Arroyo-RodrÍguez et al., 2009; Hickey and Carroll, 2012; Correa Ayram et al., 2014; Baumgartner et al., 2015; Sánchez-de-Jesús et al., 2016) y en América Latina se han realizado pocos esfuerzos por caracterizar paisajes agrícolas campesinos, que aún son los más ampliamente distribuidos en el territorio nacional (CEMDA, 2017; Bellon et al., 2018). Debido a su prevalencia, su relación con diversos tipos de hábitat y con una gran diversidad biocultural, es necesario estudiar estos paisajes, cuyas historias de manejo son muy distintas a las de los paisajes agrícolas descritos con mayor frecuencia en la literatura (Mcgarigal and Cushman, 2002). Caracterizar, comparar y entender la heterogeneidad espacial que compone a los paisajes agrícolas tropicales y campesinos podría permitirnos vincular la estructura espacial de estos paisajes con nuevas estrategias para la agricultura sostenible y la conservación de la biodiversidad.

Por lo anterior, el objetivo general de esta tesis fue caracterizar la heterogeneidad espacial y su dependencia ante los cambios de escala en una zona agrícola de Oaxaca. Los objetivos particulares fueron 1) sistematizar la información sobre la cobertura vegetal y el uso de suelo del municipio de Zaachila, 2) caracterizar la heterogeneidad espacial del municipio utilizando métricas del paisaje, 3) investigar el efecto de la escala espacial en estas métricas e identificar aquellas que son menos dependientes de la escala o dependan de forma fácilmente predecible y 4) identificar la escala espacial más adecuada para realizar diversos tipos de estudios del paisaje en Zaachila y paisajes similares y 5) proveer de elementos para delinear estrategias articuladas de conservación y producción en la zona de estudio.

De acuerdo con la modalidad de titulación por artículo científico, en la siguiente sección se presenta el artículo que sintetiza el trabajo realizado durante la maestría, el cual se encuentra en revisión en la revista Agriculture, Environment and Ecosystems. En las últimas secciones de este documento se discute y concluye en torno a este trabajo de manera breve.

Landscape heterogeneity of peasant-managed agricultural matrices

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ABSTRACT

In agricultural landscapes, management practices and other environmental and social factors shape complex agricultural matrices. In turn, the structure of such matrices impacts biodiversity conservation, for instance, by mediating wildlife migration between agricultural and habitat patches and thus determining the persistence of metapopulations. One way to formally characterize a matrix, its structure and potential role in the persistence of wild metapopulations, is characterizing heterogeneity metrics and systematically examining how such metrics change with grain size and landscape extent. These metrics provide valuable information regarding the matrix connectivity and patch diversity and shape. However, heterogeneity metrics have rarely been applied to tropical or subtropical, peasant-managed landscapes, even though this type of landscape occupies most of the agricultural surface in or near biodiversity hotspots. We focus on a peasant-managed agricultural landscape in Oaxaca, Mexico, for which we mapped and quantified the land-use classes and calculated heterogeneity metrics. We also examined the response of heterogeneity metrics to changes in grain and extent scales. This allowed us to further understand the structure and conservation potential of the agricultural matrix in this type of landscape, in comparison with other agricultural landscapes in Eastern North America. Our results also enabled us to recommend specific landscape metrics for different types of studies involving the link between agricultural matrices and conservation. We conclude that this type of agricultural matrix is ideal to pursue joint agricultural and conservation strategies in an integrated landscape.

1. INTRODUCTION

Biodiversity conservation research at the landscape scale has mainly focused on the characteristics of habitat patches (primary vegetation). Nevertheless, attention to the anthropogenic matrix surrounding the habitat has increased in recent years (Fahrig et al., 2011; Franklin and Lindenmayer, 2009; Perfecto et al., 2009). Several studies have shown that this matrix has a great impact on species persistence, preventing or allowing migration and re-colonization amongst habitat patches in the landscape, thus promoting or preventing regional extinctions (Dunning et al., 1992; Franklin and Lindenmayer, 2009; Levins, 1969; Perfecto et al., 2009; Tscharntke et al., 2012). It is also known that matrices are not homogeneous nor are they equally beneficial for the persistence of all species. The quality of a matrix, understood as its permeability for the transit of local biodiversity, varies largely depending on its spatial structure and on the type of human activities that are performed in it (Fahrig et al., 2011; Perfecto et al., 2009; Tscharntke et al., 2012; Vandermeer and Perfecto, 2007). For instance, a matrix with a structure such that connectivity among classes of land use and vegetation is large may promote biodiversity transit and, in turn, persistence at the landscape scale (Perfecto et al., 2010; Ramos et al., 2018).

To fully understand the quality of a matrix in terms of is potential for conservation, a formal landscape perspective is needed. Landscape ecology, through the study of landscape heterogeneity, has been characterizing the effects of spatial patterns in ecological processes for more than thirty years (Burel, 1989; Gökyer, 2013; Levin, 1992; Wu, 2004; Wu et al., 2002). Spatial heterogeneity is divided into compositional heterogeneity, which refers to the number and types of patches that constitute a landscape, and configurational heterogeneity, which corresponds to the arrangement of these patches in the landscape, how fragmented the landscape is, the density of its borders and the connectivity among classes of patches, among other features (Fahrig et al., 2011; Wu, 2004; Wu et al., 2002). All of these attributes partially determine the quality of a matrix, as they define how accessible are different resources for biological populations in a landscape and how reachable are habitat patches for wild metapopulations (Jaeger, 2014; Reis Madeiros et al., 2019; Thies and Tscharntke, 1999; Tscharntke et al., 2012). Even though there are well established metrics to assess such landscape features (Cushman et al., 2008; Mcgarigal, 2001), their potential to inform on conservation issues in agricultural landscapes has not been fully exploited, specially outside template regions.

Currently, most of the world's habitat matrix composition is agricultural (Fahrig et al., 2011; Foley, 2005; Kremen, 2015). This highlights the central role of agricultural practices and their distribution in a landscape on biodiversity conservation. Indeed, depending on its composition and configuration, the agricultural matrix can act as a refuge for biodiversity, as a facilitator for the movement of organisms among habitat patches, and may thus help maintaining metapopulation dynamics and long-term survival of wild species (Philpott et al., 2008; Vandermeer and Carvajal, 2001; Vandermeer and Perfecto, 2007). Then, reaching such potential roles on biodiversity conservation largely depends on the type of agricultural practices and the spatial organization of agriculture and other land-use classes in the matrix (González González et al., 2016; Ramos et al., 2018).

In order to understand the effects of agricultural management on biodiversity, landscape metrics provide a formal way to measure the spatial characteristics of the matrices under study. Since management strategies alter both the composition and configuration of matrices, we expect that contrasting types of agricultural practices and histories will show differences on standard landscape heterogeneity metrics. In turn, different types of matrix, as measured by formal methods, are more suitable for specific conservation strategies. It has been suggested, for instance, that highly heterogeneous landscapes dominated by small-scale or peasant agriculture are more suitable for integrated, rather than separated, production and conservation areas (Fahrig et al., 2011; Kremen, 2015; Perfecto et al., 2009). The design of proper conservation and production strategies would thus benefit from being informed by the spatial characterization of the particular landscapes in question.

In order to properly spatially characterize an agricultural matrix we need to consider some scale issues. Ecological patterns and processes that matter at a certain scale may not be relevant at another one, or may be extremely scale-specific. For this reason, a great deal of information can be lost when delimiting a particular spatial area (extent) and a particular grain size to study a landscape. These scale-related issues have been studied for decades as part of the modifiable areal unit problem, and they have driven the sought for methods capable of preserving information across different scales or at least able to quantify the loss of information when scales change (Teng et al., 2016; Turner, 1990; Wu, 2004; Zhang and Li, 2013).

To address how landscape metrics change with grain size or extent several authors have used scalograms (Teng et al., 2016; Wu, 2004; Wu et al., 2002; Zhang and Li, 2013).

Based on these graphic representations, metrics can be classified by their diverse behaviors and based on how consistent these behaviors are across landscapes, how predictable responses are to changes of scale, and whether relationships between scale and metrics can be represented with simple scaling equations or are staircase-like or erratic (Teng et al., 2016; Wu, 2004; Wu et al., 2002; Zhang and Li, 2013). Examining how metrics behave with scale changes is thus crucial because the interpretation, comparison and application of landscape metrics across different conditions and with different objectives could differ markedly among scales. Therefore, in order to fully understand the ecological processes occurring in a landscape, it is crucial not only to calculate landscape metrics, but also to explore how the inference of landscape properties changes across scales (Peters et al., 2007; Wu, 2004; Wu et al., 2002).

Landscape studies examining the effect of scale change have been carried out mainly in simulated landscapes or in temperate regions (Fahrig, 2003; Mcgarigal and Cushman, 2002; Shen et al., 2004), which tend to have fewer land uses and land-cover types (Brown, 2014; Gliessman, 1992) than the tropics. Given that geological, biological, and human processes that determine these landscape properties can be very different in the tropics, studies examining landscape heterogeneity metrics are urgently needed for these areas of the world. Agricultural landscapes in the tropics tend to be dominated by small plots or farms managed by peasants, and have been postulated to be relatively diverse in terms of land use and highly connected among land-use classes (Fahrig et al., 2011). Although heterogeneity studies have been conducted in tropical areas, they have mostly focused on fragmented tropical forests (Arroyo-Rodríguez et al., 2017; Concepcion et al., 2008; Sánchez-de-Jesús et al., 2015), and have not usually considered agricultural landscapes. Considering the key role of the agricultural matrix in the conservation of tropical biodiversity (Perfecto et al., 2009), studies examining heterogeneity in agricultural landscapes could guide integrative productive and conservation policies.

Peasant agriculture is highly representative of national agricultural practices as it contributes with 25.5% of national maize production and has the potential to feed half of the population of Mexico (Bellon et al., 2018; CEMDA, 2017). These kind of agriculture is usually associated to a relatively fragmented and heterogeneous landscape, as most of the agricultural plots are small (<5 ha) and very diverse in terms of management (Bellon et al., 2018; Fahrig et al., 2011). However, the formal characterization of peasant driven landscapes in the tropics remains largely unexplored. In this work, we focused on an peasant-driven agricultural landscape in a rural region of Mexico, for which we generated a land-use and vegetation map. We calculated landscape metrics and examined their behavior with changes in grain size (affecting level of resolution), and extent (total studied area). In contrast to intensive agriculture in temperate regions, we expect to find a high number of patches, high patch richness and high values in connectivity and intercalation metrics, such as the intercalation and juxtaposition index. We postulate specific metrics and scales that could be used in future studies aiming to identify high quality matrices in tropical and subtropical landscapes with a similar history and management as the landscape under study. Finally, we discuss the potential conservation strategies associated to this type of landscape and point to land use classes that can potentiate these efforts.

2. MATERIAL AND METHODS

2.1 Study site

La Villa de Zaachila, henceforth Zaachila, is a municipality in the Central Valleys of the state of Oaxaca, Mexico. It is located 17 km south of the city of Oaxaca, between 96 ° 40 'and 96 ° 47' longitude and 16 ° 54 'and 17 ° 05' latitude, and has an area of 81 km^2 at an elevation of 1500 m. Zaachila has a semi-dry-semi-warm climate, the rainy season is from June to October with an annual average temperature of 17.5°C. The primary vegetation type is deciduous lowland rainforest, along with oak-pine forest in mountain ranges in the east and west borders of the municipality (INEGI, 2010). The municipality is located in the Zapotec Tetratonostratigraphic terrain. The basement is from the pre-Cambrian Oaxacan Complex constituted by metasedimentary rocks such as gneiss de facies and granulite marbles. To the north and west of the valley of the basement is colluvial and to the east we find sedimentary and metamorphic rocks (sandstones, shales and limestones) (Belmonte-Jiménez et al., 2005; Ortega-gutierrez, 1981; Sedlock et al., 1993).

The known history of landscape management of Zaachila begins with the Zapotec, about 3500 years ago. Throughout its history, the municipality has had different management and land holding systems (Ruiz Medrano, 2011). Zaachila currently has a total of 17 human settlements (2 urban and 15 rural) and had 34101 inhabitants in 2010, of which 80% is concentrated in the two urban locations: La Villa de Zaachila and Vicente Guerrero (INEGI, 2010). The agricultural plots are mostly managed by peasants for family or local consumption (Mora Van Cauwelaert, 2016). In contrast with most agricultural sites in many other countries, a large percentage of these plots represent communal land, the so-called *ejidos* (INEGI 2010; Mora Van Cauwelaert, 2016). Historically, Zaachila has been an important point for regional commerce, as its traditional market has existed since before the fifteenth century, and even now it gathers farmers and peasants from all the surrounding villages. The village and the market are also reservoirs of great culinary diversity that is often associated with local landraces and management practices (Mora Van Cauwelaert, 2016).

2.2 Land use and vegetation map

To create the land use and vegetation map, we used a remote sensing image (Copernicus Sentinel-2 2017) from the dry season (May of 2016) and considered five land-use classes (Urban, Grassland, Rainfed agriculture, Irrigated agriculture, and Forest) based on INEGI's Series V chart of land use and vegetation use, scale 1: 250 000 with spatial resolution of 30m (Series V, INEGI 2013) and the NALCMS, land use map made by CIEC for North America, scale 1:2500 000 with spatial resolution of 250m (Colditz et al., 2012). The polygon delimitation corresponds to the political boundaries of the Zaachila municipality, which in turn correspond to the organization of public databases and fieldwork permits.

In order to map and verify specific land uses, we obtained through QGIS 2.18.7 (QGIS Development Team 2017), 278 random points for Zaachila and visited them from September to October 2017. The status of the vegetation and land use classes was assessed by visual inspection with the support of local informers. We georeferenced points using the GPS map 64 of Garmin (error range ~ 3m), with a minimum distance of 5m between each reference point.

We performed a supervised classification with the maximum likelihood algorithm of ENVI version 4.7 (Chuvieco, 1996; Schuster et al., 2012). We based the selection of the training areas on the Normalized Vegetation Index (NDVI) and the combination of natural and infrared RGB bands. These areas included 404 training points, each one corresponding to a ROI (region of interest). 200 of these training points were obtained from those registered the field trips and 204 were obtained by manually determining their class through inspecting their band composition, two-dimensional dispersion graphics and position in the INEGI maps. We determined the accuracy of the classification with the remaining 78 validation points from the field trips. We used the confusion matrix and the Cohen's Kappa statistic to determine accuracy. We manually added the classes of water and greenhouses in QGIS 2.18.7 (QGIS Development Team 2017), which were plotted using the INEGI topographic chart for water bodies and corroborating field trips. However, in the final heterogeneity analyses, we did not include the data of the greenhouse class due to its negligible area (0.089%) (Series V, INEGI 2013). In order to improve the accuracy of the map we carried out a post-classification process to reduce the so-called salt and pepper effect. To do so, we reclassified manually the classes of patches conformed of 4 or less pixels to the class of the closest patch with more than 4 pixels.

2.3 Spatial heterogeneity characterization and scalograms

We characterized the site's heterogeneity by estimating several landscape metrics. We calculated eight metrics of spatial heterogeneity for the landscape level and eight metrics for the land use class level (hereafter called class level). Six of these metrics apply to both landscape and class level, while two are specific for landscape level (patch richness and shannon’s diversity index) and two for class level (total (area) class and percentage of landscape), for a total of ten different metrics (Table 1). We selected these metrics to include both compositional and configurational heterogeneity, and for their suitability to characterize the agricultural matrix in terms of area, density, edge, shape, isolation, proximity, interspersion and diversity (Table 1). We analyzed spatial heterogeneity using FRAGSTATS 4.2.1 (McGarigal, et al. 2012).

Table 1. Landscape metrics used in this study.

Landscape metric	Abbreviation	Landscape metric	Land use Class metric	Description (McGarigal et al. 2012)
Number of Patches	NP	x	X	Number of patches in the landscape. Simpler fragmentation metric.
Patch Richness	PR	x		Number of different types of patches in the landscape. Simpler spatial composition metric, does not reflect the relative abundance of patch types.
Shannon's Diversity Index	SHDI	x		Metric of landscape diversity particularly sensitive to rare patch types. It is the sum for all the patches, of the proportional abundance of each type of patch

				multiplied by the proportion.
Largest Patch Index	LPI	x	X	Percentage of the total area that is covered by the largest fragment of a class type in the total if it is calculated at the landscape level. LPI approaches 0 when the largest fragment area of the corresponding class is very small and is equal to 100 when the landscape total consists of a single class that occupies 100% of the landscape.
Edge Density	ED	x	X	Useful metric when comparing edge of different landscapes. Sum of the lengths of all the edge segments of the landscape, divided by the total area of the landscape, multiplied by 10000 (ha).
Shape Index Mean	SHAPE_MN	x	X	Measure that allows to understand the degree of dispersion of each patche in the landscape. It is the perimeter of the patches divided by the minimum possible perimeter for the most compact patch possible.
Interspersion and Juxtaposition Index	IJI	x	X	Metric that evaluates the adjacencies of the patches and measures the interrelation between different types of patches. It is the subtraction of the length of each type of unique edge that involves a particular type of patch, divided by the total length of the edge that involves the same type, multiplied by the logarithm of the same quantity, added with each type of unique edge divided by the logarithm of the number of patch types minus 1, multiplied by 100.

Proximity Index Mean	PROX_MN	x	X	This metric characterizes the degree of spatial isolation of the fragments, taking into account all the closest fragments that are within a specified search radius. High proximity values indicate that neighboring fragments, of the same type of coverage, are less isolated, large and aggregated. Low values indicate that the fragments are isolated and may have small sizes.
Total (Class) Area	CA		X	Area of the landscape that occupies the class or how much of the landscape is composed by a type of patch.
Percentage of Landscape	PLAND		X	Percentage occupied by one type of coverage in the total landscape. It is the most elementary metric in the study of landscape patterns. The percentage changes in time give information about the increase and decrease of the areas of a certain type of coverage. PLAND approaches 0 when the type of coverage decreases its area and approaches 100 when the landscape total dominates.

In order to study the effect of the spatial scale on the landscape metrics, we built scalograms that described the response of each metric to changes in extent and grain size. Scalograms show how a metric responds to scale changes, and have been widely used to study sudden shifts in curves that could suggest hierarchical occurrences or critical scales (Zhang and Li, 2013). To test the effect of change in grain size we took the initial spatial resolution of the raster, which was 10 x 10 m in a total extent of 81 km^2. The spatial resolution of the entire map was increased by 1 until it reached 100 x 100 pixels, keeping the extent constant. We assigned the grain identity resampling by majority. As for the effect of the extent, we took the complete extent of the quadrant surrounding the municipality (441 km2) and reduced it by 10 km2 until it reached 10 km2 (a similar approach to generate grain and extent scalograms was followed by Wu et al., 2002; Wu, 2004; Zhang and Li, 2013; Teng et al., 2016). Thus, we generated a total of 2000 images to represent the vegetation and land use of Zaachila.

We built scalograms plotting metric values against grain size or extent in R 3.4.3 (R Core Team, 2017). We used scalograms to: i) describe the behavior of the class level metrics, ii) classify the landscape level metric behavior in the face of scale changes, iii) test if changes in the metric with scale variation could be fitted with simple functional models, and iv) explore the sensitivity of metrics to scale change (Supplementary material Table 2, Table 3 and Table 4). Besides describing the overall trends of metric behavior with grain or extent scale change, it is important to characterize their sensitivity to small changes in the scale. To that end, we employed the coefficient of variation (CV), which expresses the standard deviation as a proportion of the average metric value. We used the CV to compare variation levels across landscape metrics. The larger the CV, the higher the sensitivity of the metric to changes in scale was (Teng et al., 2016)(Supplementary Material Table 4).

To examine whether a simple model could fit to scalograms we used linear, polynomial or exponential functions and calculated residuals. Model residuals were used to visually inspect whether there were trends in the lack of fit with the change in grain size or extent (predictor variable in models) (Supplementary Material Figures 1 and 2).

2.4 Comparisons with other agricultural landscapes

In order to test if and how different conservation/production strategies were reflected on landscape heterogeneity metrics, once landscape metrics were calculated, we compared them with those of 12 other agricultural landscapes of the METALAND database corresponding to extent agricultural sites in the east of the United States, all of them in the Fruitful Rim and Basin and Range USDA Farm resource regions (previously located in the Pacific USDA Farm region) (Cardille et al., 2017; USDA, 2000). METALAND includes landscape metrics previously calculated with FRAGSTATS in landscapes of 6.5 km x 6.5 km in 8 million km2 in Eastern USA. We chose 12 landscapes that had the same percentage of agricultural land use as Zaachila, and had similar percentages of urban land use and primary vegetation. For it to be comparable with the Zaachila landscape, we took a fragment of the map of the municipality that had an extent (6.5 km x 6.5 km) and grain size (30 x 30 m) equal to the one obtained in METALAND. We compared most of the landscape level metrics from Zaachila with the METALAND database, with the exception of proximity index mean and patch richness, metrics that were not comparable because of the particular characteristics that have to be defined for each metric.

3. RESULTS

3.1 Land use and vegetation characterization

The general accuracy of the land use map was 88.85%, with a Kappa statistical index of 0.85, which is well above the minimum Kappa values required for reliable land use and vegetation maps. The class that had the highest precision values in the confusion matrix was seasonal agriculture (96.1%), while grassland was the lowest (79.25%). (Supplementary Material Table 1) (Congalton, 1991). The landscape of Zaachila is mainly agricultural (48%), being rainfed agriculture the most prevalent land use class in the municipality (39%). The next most represented class is the secondary forest (23%), followed by the urban zone (19%). The classes with less coverage in the landscape are water bodies and greenhouses (Figure 1). This makes Zaachila a predominantly rainfed agricultural landscape with few with forest remnants, useful to study the potential of an agricultural matrix connecting habitat patches (Figure 1).

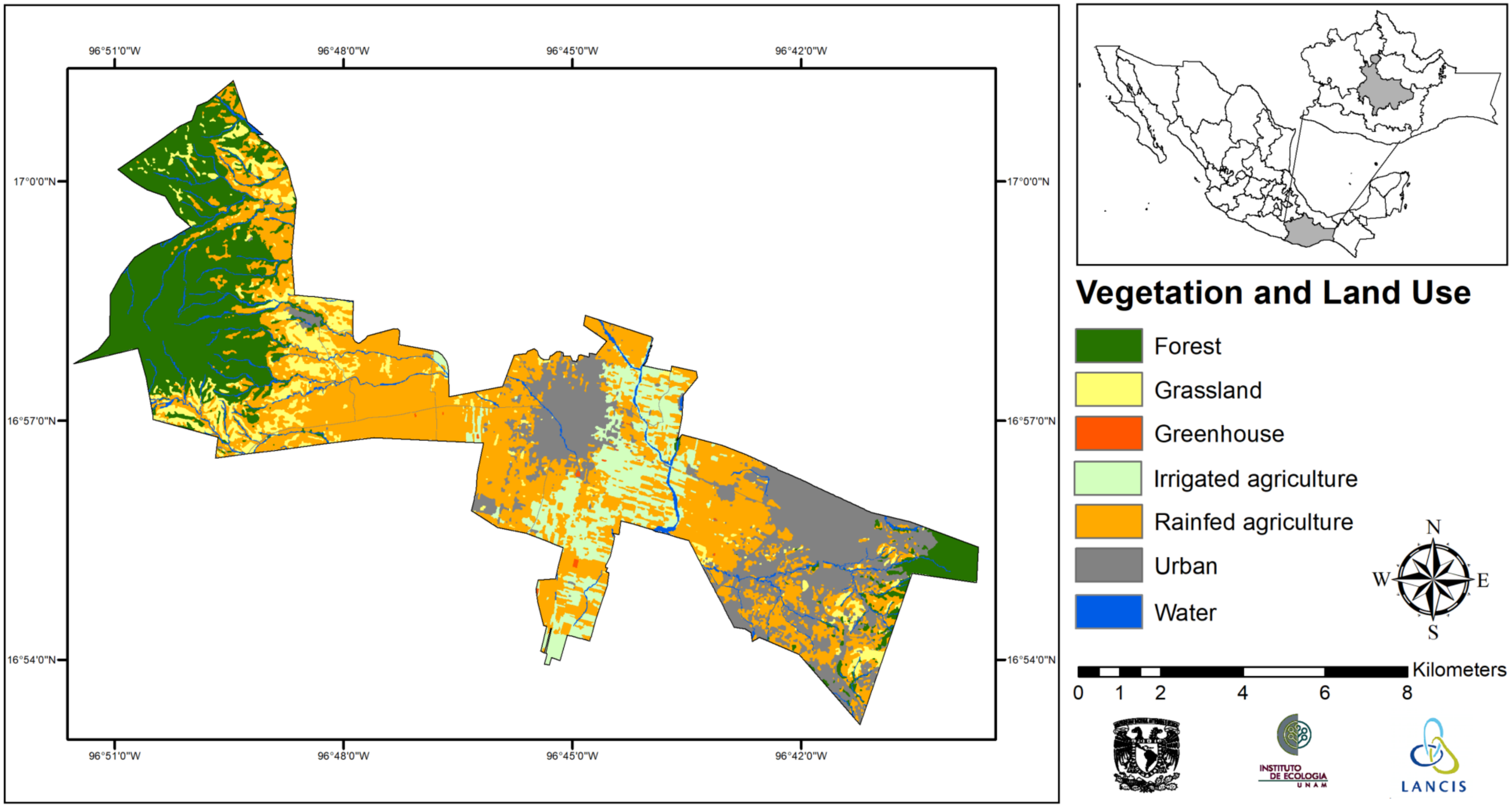

Figure 1. Zaachila's land use and vegetation map with seven patch types, grain of 10 x 10 m and extent of 81 km2.

3.2 Landscape characterization

In terms of landscape level metrics, we found a very high number of patches (1867) and Shannon diversity index (1.54) (see also section below), with high dominance of forest patches in terms of area (the largest forest patch occupies 13.8% of the landscape). The edge density was 125.13 m per ha and the average shape was 1.55, which means that the patches tend to be elongated. The interspersion and juxtaposition index was 74.97% and the average proximity index mean within an area of 400 m was 1140, describing an intricate array of patches with a relatively high connectivity among them (Supplementary Material Table 5).

Regarding the class level metrics, the rainfed agriculture patches had the largest edge density (85.57 m/ha) and the highest interspersion and juxtaposition index (88.31%), which means that this patch type is the most connected with other patch types, even if the largest patch in the landscape is a forest patch. However, the patch type with the highest proximity index mean (2961.07) was urban, which means that urban patches are the less isolated (Supplementary Material Table 6).

3.3 Response of metrics to changing scale at the landscape level

We plotted scalograms for the metrics in Table 1 and classified their behavior following Wu et al. (2002, 2004) and Teng et al. (2016) into four types: 1) consistent scaling relation (adjusted to a linear, polynomial or exponential function), 2) staircase-like response 3) invariant or non-answering to scale change and 4) erratic response (Figure 2, Table 2 and Supplementary Material Figure 1). In most cases, data violated homoscedasticity assumptions, so fits were only used for visual inspection of trends (Figure 2). Type 1 scalograms were the most common and pointed to metrics that are useful to describe matrix heterogeneity, as they appear to have a predictable behavior in response to scale changes. Metrics with type 1 scalograms were number of patches, largest patch index, shape index mean and interspersion and juxtaposition index (Figure 2 and Table 2).

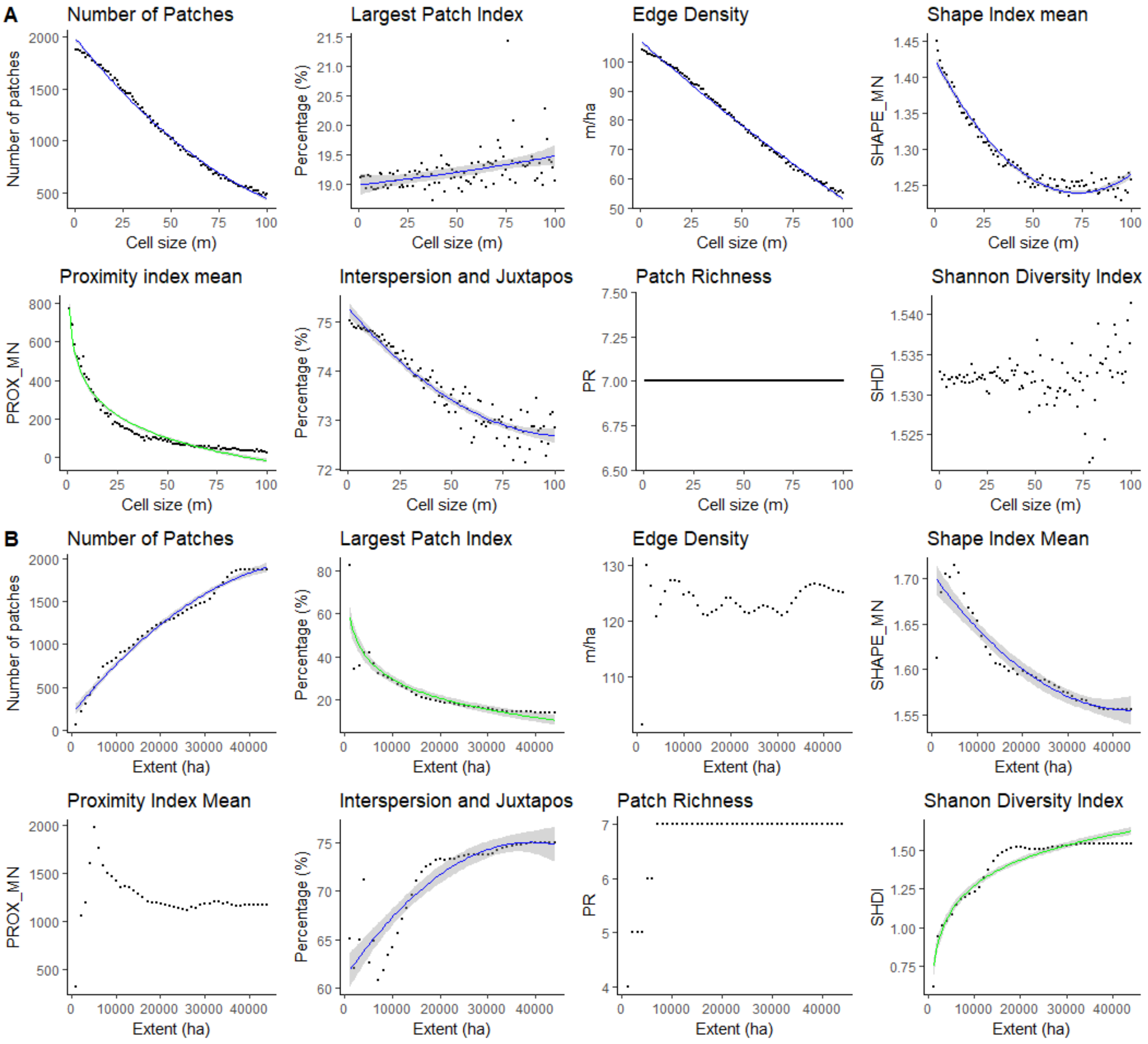

Figure 2. Scalograms showing the effects of changing grain size (a) and extent (b) on landscape metrics for Zaachila. For scalograms with type 1 (consistent scaling relations) we present in green logarithmic fits and in blue power law fits.

Table2. Categories of behaviors observed in scalograms for landscape level

Scale change	Metric	Response	Scaling relationship	Direction
Grain size	NP	Type 1	Power law	Decreasing
Grain size	LPI	Type 1	Power law	Increasing
Grain size	ED	Type 1	Power law	Decreasing

Grain size	SHAPE_MN	Type 1	Power law	Decreasing
Grain size	PROX_MN	Type 1	Logarithmic	Decreasing
Grain size	IJI	Type 1	Power law	Decreasing
Grain size	PR	Type 3	-	-
Grain size	SHDI	Type 4	-	-
Extent	NP	Type 1	Power law	Increasing
Extent	LPI	Type 1	Logarithmic	Decreasing
Extent	ED	Type 4	-	-
Extent	SHAPE_MN	Type 1	Power law	Decreasing
Extent	PROX_MN	Type 4	-	-
Extent	IJI	Type 1	Power law	Increasing
Extent	PR	Type 2	-	-
Extent	SHDI	Type 1	Logarithmic	Increasing

3.4 Responses of metrics to changing scale at the class level

We also plotted scalograms for class level metrics (Table 1). In general, the behavior of each class level metric was different,therefore, we could not classify them as we did for landscape level metrics. The scale change of the extent had a greater effect on these metrics than the change of grain size. For Zaachila, for an extent greater than 300 km^2 we can observe a stabilization of the following metrics: total (class) area, percentage of landscape, number of patches, largest patch index, edge density and interspersion and juxtaposition index (Figure 3B). For extent <300 km^2, metrics had steps or non stabilized behavior. Moreover, for two metrics (number of patches and proximity index mean), there seems to be a 60 m grain size threshold above which it becomes harder to differentiate information between classes (Figure 3A and Supplementary Material Figure 2).

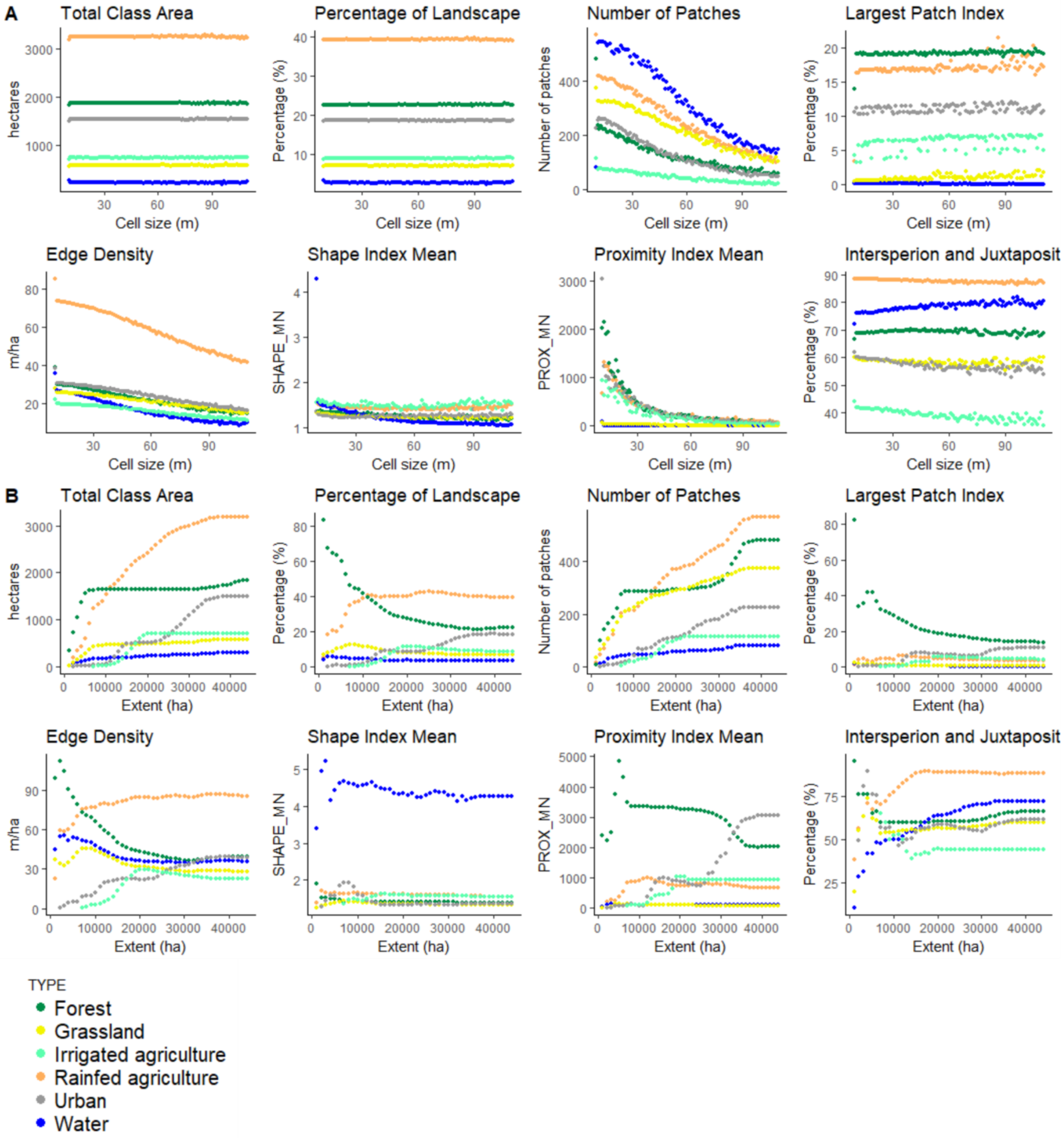

Figure 3. Scalograms showing the effects of changing grain size (a) and extent (b) on the class metrics taken for Zaachila's land use and vegetation map. Since the behavior types for class level are highly different from class to class the classification was different and it is not possible to graphic the strongest scaling relations.

3.5 Comparison with metrics and scalograms in other agricultural systems

Compared with the values of the average metrics of twelve North American landscapes, the number of patches and the Shannon index in Zaachila were strikingly high. On the other hand, the shape index mean was visibly lower, perhaps due to the arrangement and distribution of small agricultural units into elongated plots, unlike the large land units of North American farmers (Figure 4). It is also worth noting that the Zaachila landscape exhibits a significantly higher patch diversity (Shannon index, Figure 4) and significantly less dominance of any class (Largest patch index, Figure 4) than agricultural landscapes in North America.

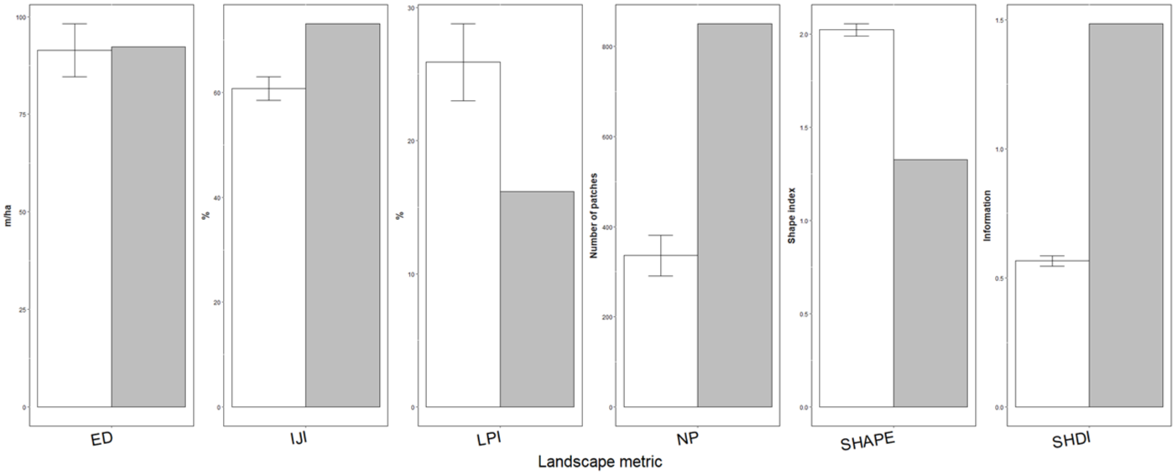

Figure 4. Bar graph comparing six landscape metrics from Zaachila versus thirteen different landscapes from the United States of America. The y axe is a compound of all the possible values of the different landscape metrics.

3.6 Sensitivity of the matrix descriptors response to scale change

Sensitivity can be understood as the size of variations or fluctuations around fitted models and can be examined through residuals (when it is possible to fit a functional model) and also using the coefficient of variation (see Methods). Most of the landscape level metrics show low sensitivity for small changes in scale. Class level metrics, on the contrary, show relatively high sensitivity for small changes in scale (Supplementary material Table 4).

5. DISCUSSION

In this work, we have characterized elements of the composition and configuration of a peasant-managed landscape in Oaxaca, Mexico, which is representative of largely understudied agricultural landscapes of the tropics, which also have great potential to implement joint agricultural and conservation strategies.

Overall, Zaachila's landscape is considerably fragmented with a high number of patches and a small largest patch index, as previously suggested (Fahrig et al., 2011), specially when contrasted with comparable agricultural landscapes in North America. While the edge density between both types of landscapes was similar, the interspersion and juxtaposition index was higher in Zaachila (Figure 4), revealing an intricate arrangement of patches. Notably, the high patch interspersion and juxtaposition that characterizes Zaachila suggests that this landscape has large connectivity among patches. The Shannon index for patch diversity was also significantly higher in Zaachila in comparison with North American landscapes. Altogether, the diversity, complexity and potential connectivity of the Zaachila landscape reveals how different the tropical and peasant-managed landscapes can be in comparison with the agricultural landscapes that have been the focus of studies on agricultural landscape heterogeneity so far. As hypothesized (Fahrig et al., 2011; Perfecto et al., 2010), Zaachila's landscape is associated to an agricultural matrix with high number of patches, high patch richness and high values in connectivity and intercalation metrics. While the comparison between Zaachila and Eastern North American landscapes of similar size and percentage of agricultural land is rather rough, it recovers the expected differences in most of the metrics used to characterize these landscapes and provides a more nuanced comprehension of the differences in their spatial arrangements. This also validates and highlights the value of landscape metrics for the formal assessment and comparison of agricultural landscapes.

In order to further discuss the quality and potential of Zaachila's agricultural matrix in terms of biodiversity conservation, we will focus on the metrics describing the forest and rainfed agriculture classes, the two key classes in terms of strategies to articulate agricultural production and biodiversity conservation. Rainfed agriculture has a large interspersion and juxtaposition index, edge density and has little dominance (small largest patch index) (Supplementary Material Table 6). This is, rainfed agriculture is in contact with all types of patches. In contrast, the forest patch distribution is dominated by the largest patches, has little edge density and small interspersion and juxtaposition index (Supplementary Material

Table 6). In other words, the forest class is concentrated in few, large patches with relatively little contact with the rest of the matrix. Considering that forest patches are in general apart from each other and that this may hinder metapopulation migration and recolonization dynamics, the matrix surrounding forest patches becomes central for the conservation of wild metapopulations. Since such matrix is dominated by rainfed agriculture, which in turn has a potentially high connectivity, it is crucial to maintain and foster agricultural practices that provide this class with a high permeability for local biodiversity (Vandermeer and Perfecto, 2007; Gonzalez-Gonzalez, 2019). This would point to integration strategies for shared areas of agricultural production and biodiversity conservation (Fahrig et al., 2011; Perfecto and Vandermeer, 2010).

It is noteworthy that half of the scalograms exhibit similar behavior at the landscape level for Zaachila and for other agricultural landscapes previously studied (Teng et al., 2016; Wu, 2004; Wu et al., 2002; Zhang and Li, 2013; Zhang et al., 2007) (Supplementary Material Table 7). This is the case for number of patches, largest patch index and edge density for grain size change. Number of patches, edge density and patch richness also showed the same behaviors for the change in extent. These results point to a set of metrics that are likely to be robust and reliable for their use in a wide range of landscapes differing in geography, land use management and history of management (Supplementary Material Table 7). In contrast, the other half of the landscape metrics exhibited qualitatively different behaviors between this study and others in response to scale change, such as shape index mean and Shannon’s diversity index. Most of the differences were between responses reported as erratic or staircase-like responses in other studies but that presented consistent scaling relations in Zaachila. The different behavior of this group of metrics highlights the importance of testing metric behavior in landscapes with diverse geophysical and social contexts.

Taking into consideration the metrics and their behaviors at different scales we reckon that the most appropriate metrics for a study depend strongly on the goals of each study. For comparative research between landscapes with different geography and management history, in which metrics may not have been taken at the same scale, we propose to focus on metrics that are sensible enough to show differences across landscapes, but that are invariant to scale change (type 3). Metrics with consistent scaling relations (type 1) could be somewhat useful given that metric changes based on scale can be anticipated and that their sensitivity to scale change (CV and residuals) is small or moderate (Supplementary

Material Table 4, Figure 1 and Figure 2). In order for these metrics to be useful, their behaviors must be robust, that is, they must show similar behavior in landscapes with very different geography, geomorphology, land use management and history of management. If the metrics comply with these characteristics we can assume a simple relation between the metrics, no matter the scale at which they were taken. In this study, metrics that had these characteristics include the number of patches, interspersion and juxtaposition index and largest patch index. The last two have small CV values, which also indicates that they are metrics with relatively low sensitivity to scale change (Supplementary Material Table 4). These three metrics are useful for describing landscape fragmentation and class dominance and differed between Zaachila and other landscapes (Figure 4). They had behaviors type 1 and 3 (Figures 2 and 3), i.e., behaviors that make these metrics robust across different agricultural landscapes (Teng et al., 2016; Wu, 2004; Wu et al., 2002) and had low sensitivity to scale change (Supplementary Material Table 4 and Table 7).

For studies aiming to describe the potential of a landscape for having a good quality matrix, we propose those metrics that reveal more information about connectivity, fragmentation per se, diversity and permeability of the classes, as they jointly reflect how a given matrix facilitates or hinders migration and re-colonization of habitat patches or remnants. Information beyond the landscape metrics is necessary for the assessment of the matrix quality, particularly information on the concrete activities that are performed on each class and how they affect the ecological processes of the species in question. Nevertheless, these metrics helped us identify the class with the biggest potential, as given by its spatial distribution, to improve the quality of the matrix if activities aimed at improving its permeability are performed within it (Watling et al., 2011). Metrics that best inform the conservation strategies for Zaachila are percentage of landscape, edge density, and interspersion and juxtaposition index.

In terms of which scale should be used in future works that address how landscape features affect agricultural plots (e.g. Avelino et al., 2012; Connelly et al., 2015; Poveda et al., 2012), we found no characteristic scale for the landscape level metrics. For the class level metrics a grain size below 60 m is recommended, while the change of extent shows a pattern in which the metrics stabilize for all classes from 300 km^2 onwards. Stabilization is desirable for comparisons among different landscapes because it allows comparing them knowing that the metrics will be robust. However, for studies within a single landscape it is interesting to retain variation among classes, so the best scale for studies within Zaachila's municipality and similar landscapes should be smaller than 300 km2. This also suggests that a change in hierarchical structure happens at 300 km^2 in this landscape (Wu, 2013; Zhang and Li, 2013). However, the results obtained for changes in extent scale must be taken with care because they are highly dependent on the starting point of the smallest extent.

It is important to consider some of the limitations of this study. The shape of Zaachila's polygon is one of them, given that it has an irregular shape. Some of the agricultural landscapes studied before are also defined by irregular polygons (Teng et al., 2016; Zhang and Li, 2013) but most are squared landscapes (Cardille et al., 2017; Wu, 2004; Wu et al., 2002). This is particularly relevant for extent scalograms. It is also necessary to highlight that more than 150 other metrics have been developed to describe landscapes and that they would also need to be examined in terms of their stability with scale changes. Although it is true that many landscape metrics are highly correlated (Wu et al., 2002), it is still necessary to characterize the correlation among this large set of potential metrics in the type of landscape that we study here. Moreover, we think this kind of studies should also take into account the effects of different time scales on the metric behavior. Finally, in Zaachila the main land use is rainfed agriculture, which is modified by peasants and other actors throughout seasons, years and decades, so that the values of the landscape metrics could exhibit non-trivial dynamics along time points.

We show that Zaachila's peasant-driven and subtropical landscape involves an agricultural matrix conformed mainly by rainfed agriculture with a great potential for conservation if agricultural practices that increase the permeability of the matrix are maintained or promoted (e.g. pesticide-independent practices; Gonzalez-González, et al., 2019). That would facilitate migration between natural patches, and ultimately, the maintenance of metapopulations. In general, formally studying spatial heterogeneity through landscape metrics is essential to characterize agricultural matrices, compare them and link landscape structure to potential strategies for sustainable agriculture and biodiversity conservation.

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Discusión general

En este trabajo, caracterizamos elementos de la composición y configuración de un paisaje agrícola en Oaxaca, México. En cuanto a la composición observamos que el uso de suelo de agricultura de temporal es más importante, en términos de extensión y conectividad, para este paisaje que la agricultura de riego. También caracterizamos este paisaje en términos formales de su heterogeneidad composicional y configuracional al estimar ocho métricas a nivel del paisaje y otras ocho a nivel de clases de usos de suelo. Examinamos la respuesta de estas dieciséis métricas ante los cambios de escalas, que desglosamos en cambios de tamaño de grano y de extensión. Esto nos permitió comparar este paisaje con otros paisajes agrícolas y argumentar en torno a esquemas de conservación pertinentes para la zona de estudio.

En el paisaje de Zaachila encontramos algunas características semejantes con los paisajes del Oeste de EE.UU. con los que se comparó, por ejemplo la densidad de bordes fue parecida en todos los paisajes agrícolas. Sin embargo, se encontraron importantes diferencias entre los paisajes, el número de parches, el índice de diversidad de Shannon y el porcentaje del índice de intercalación y yuxtaposición fueron más elevados en el paisaje de Zaachila que en los paisajes agrícolas del Oeste de EE.UU. Estas tres métricas hablan de la diversidad, complejidad y conectividad potencial del paisaje de Zaachila y son un buen ejemplo de las diferencias que pueden existir entre los paisajes en zonas agrícolas de América Latina, manejados por campesinos, y los paisajes agrícolas que han sido el foco de los estudios de heterogeneidad del paisaje agrícola hasta el momento (Mcgarigal and Cushman, 2002; Wu et al., 2002; Wu, 2004; Peters et al., 2007; Poveda et al. 2012; Connelly et al. 2015). Así, esta comparación destaca la importancia de estudiar y caracterizar paisajes en los trópicos para poder entender los procesos socioecológicos que ocurren ahí.

De las clases de uso de suelo y vegetación de Zaachila, el bosque y la agricultura de temporal son las dos más importantes para discutir estrategias de integración de la producción agrícola y la conservación de la biodiversidad. Los parches de agricultura de temporal están relativamente atomizados y en contacto con parches de diferentes clases. En contraste, el bosque está concentrado en pocos parches grandes con menos contacto con el resto de la matriz que la agricultura de temporal (Figura 1 y Material Suplementario Tabla 5). Teniendo en cuenta que los parches de bosque en general están separados unos de otros y que esto puede dificultar la dinámica de la migración y la recolonización de las metapoblaciones, la matriz que rodea los parches de bosque se vuelve central para la conservación de las metapoblaciones silvestres. Dado que dicha matriz está dominada por la agricultura de temporal, que a su vez mostró tener un alto potencial para tener buena conectividad (alto índice de intercalación y yuxtaposición), es crucial mantener y fomentar las prácticas agrícolas que proporcionan a esta clase una alta permeabilidad para la biodiversidad local (Vandermeer y Perfecto, 2007) De acuerdo con otros estudios del grupo de trabajo, las prácticas asociadas a la alta permeabilidad pueden ser agrupadas en una tipología gruesa como prácticas campesinas o tradicionales e incluyen al policultivo y el uso de variedades locales (Mora Van Cauwelaert, 2016; Gonzalez-Gonzalez, 2019).

En cuanto al efecto de la escala espacial en las métricas, se realizaron escalogramas de los cuales, la mitad mostró un comportamiento similar para los paisajes de Zaachila y para otros paisajes estudiados anteriormente (Wu et al., 2002; Wu, 2004; Teng, 2016; Zheng, 2014) (Material Suplementario Tabla 6). La otra mitad de las métricas del paisaje exhibieron comportamientos cualitativamente diferentes entre este estudio y otros en respuesta al cambio de escala. La mayoría de las diferencias fueron entre respuestas reportadas como erráticas o parecidas a escaleras en otros estudios pero que presentaron relaciones de escala consistentes en Zaachila. Estos resultados apuntan a un conjunto de métricas que pueden ser robustas y confiables para su uso en una amplia gama de paisajes que difieren en geografía, manejo del uso del suelo e historial de manejo, como el número de parches, el índice de parches más grande y la densidad de bordes para cambio de tamaño de grano; y número de parches, densidad de bordes y riqueza de parches para la extensión (Material Suplementario Tabla 7). En contraste, el diferente comportamiento de las métricas, como la media del índice de forma y el índice de diversidad de Shannon a través de los tipos de paisajes, resaltan la importancia de probar el comportamiento de las métricas en paisajes con diversos contextos geofísicos y sociales que pueden conducir a diferencias en la configuración de la heterogeneidad.

Teniendo en cuenta las métricas y sus comportamientos en diferentes escalas, consideramos que las métricas más adecuadas para un estudio dependen en gran medida de los objetivos de cada estudio. Conjuntando los resultados con los objetivos de la tesis apreciamos tres objetivos principales i) Para la investigación comparativa entre paisajes con diferente geografía e historia de manejo, en los que las métricas pueden no haberse tomado en la misma escala ii) Para los estudios que pretenden describir el potencial de un paisaje para tener una matriz de buena calidad y iii) Para realizar estudios replicables y detallados en paisajes como el de Zaachila. Para estos objetivos son importantes las aproximaciones multifactoriales que tomen en cuenta métricas con comportamientos robustos, que revelen más información acerca de la conectividad, la fragmentación per se, la diversidad y la permeabilidad de las clases (aunque información más allá de las métricas del paisaje es necesaria para caracterizar la calidad de la matriz, en particular la permeabilidad (Watling et al., 2011)) y la sensibilidad de las métricas (coeficiente de variación y residuos).

Dado que este trabajo forma parte de un esfuerzo grupal por estudiar los procesos agroecológicos en Zaachila, es importante proponer qué escala se debe usar en trabajos futuros al interior de este sitio, por ejemplo para investigar el efecto del paisaje inmediatamente circundante sobre las parcelas. Para las métricas de nivel de clase se recomienda un tamaño de grano inferior a 60 m, mientras que el cambio de extensión muestra un patrón en el que las métricas se estabilizan para todas las clases desde 300 km^2 en adelante. La estabilización puede ser muy buena para comparaciones entre diferentes paisajes porque permite compararlos sabiendo que las métricas serán sólidas. Sin embargo, para los estudios dentro de un solo paisaje es interesante mantener la variación entre clases, por lo que la mejor escala para los estudios dentro del municipio de Zaachila debería ser menor a 300 km^2. Esto también sugiere que un cambio en la estructura jerárquica ocurre a 300 km^2 en este paisaje (Zhang y Li, 2013). Sin embargo, los resultados obtenidos para los cambios en la escala de extensión deben tomarse con cuidado porque dependen del punto de partida de la extensión más pequeña.

La alta heterogeneidad del paisaje de Zaachila nos habla de un paisaje complejo. Un paisaje agrícola que tiene un gran potencial para la conservación de metapoblaciones locales. Considerando la larga historia de uso de suelo agrícola de los Valles Centrales de Oaxaca y la importancia de la agricultura para la vida cotidiana de estas zonas la mejor propuesta para favorecer las conexiones entre los parches de bosque es propiciar agricultura que cumpla con las características de la buena matriz. Muchas de éstas ya las vemos en Zaachila como potencial para una buena conectividad con el alto índice de intercalación y yuxtaposición y la alta diversidad de usos de suelo, pero será importante reforzarlas y vincularlas estrechamente con las prácticas agrícolas de los campesinos de la zona.

Conclusiones

En este estudio encontramos que Zaachila tiene una matriz agrícola conformada por distintos tipos de uso de suelo entre los que destaca la agricultura de temporal, en porcentaje y por su potencial para facilitar la conectividad en el paisaje. Es gracias a la caracterización espacial del sitio que podemos describir a este paisaje como una probable matriz agrícola de buena calidad y proponer actividades de conservación enfocadas a mejorar la permeabilidad de la agricultura de temporal que podría llegar a interconectar las dos cordilleras con vegetación conservada en los extremos este y oeste de Zaachila y facilitar la migración de las metapoblaciones que se encuentran en el municipio.

Es necesario caracterizar otros paisajes campesinos tropicales para proponer estrategias de conservación que sean adecuadas para otros paisajes con historias de manejo, fisiografías y practicas semejantes, y para entender hasta qué grado las estrategias que se han propuesto para otros paisajes en climas templados pueden resultar efectivas en paisajes distintos.

Las métricas del paisaje resultaron ser herramientas útiles para la descripción de la complejidad de los paisajes, haciendo las caracterizaciones espaciales comparables y permitiendo señalar cuáles aspectos del paisaje son los que nos permitirán identificar la calidad de la matriz o manejos amigables con la biodiversidad. Utilizar herramientas de la ecología del paisaje, como son las métricas utilizadas en este trabajo, en estudios de la matriz agroecológica permite conocer la complejidad del paisaje, que es sujeto de estudio de ambas disciplinas, de una manera crítica y cuantificable.

Fue importante considerar diferentes escalas para el estudio, nos permitieron caracterizar de manera más minuciosa los paisajes e identificar características únicas de algunas de las métricas con respecto a los cambios de escala que podrían causar confusión en la interpretación de las métricas. Pudimos identificar cuatro respuestas generales de las métricas al cambio de escala entre las que las respuestas con relaciones escalares consistentes (tipo 1) y las respuestas invariables a la escala (tipo 3) fueron las más recomendadas para los diferentes estudios del paisaje que pueden ser útiles para Zaachila. Sin embargo, aún es necesario considerar las escalas temporales, tanto el estacional como los grandes fenómenos climáticos, en particular el cambio climático que de ahora en adelante jugará un papel muy importante tanto en los ciclos agrícolas como en la conservación de la biodiversidad.

En general estudiar la heterogeneidad espacial a través de las métricas del paisaje es fundamental para determinar los efectos y la importancia de las prácticas agrícolas para la conservación de la diversidad. El estudio de la heterogeneidad permite evaluar el efecto que tienen distintas prácticas agrícolas en el paisaje y viceversa, por lo que, si bien es necesario seguir estudiando los paisajes ya estudiados también queda claro que hace falta estudiar de manera formal más paisajes ubicados en distintos puntos geográficos, con distintas fisiografías, historias de manejo y usos de suelo actuales.

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Suppementary material

SUPPLEMENTARY MATERIAL FOR:

Landscape heterogeneity of peasant-managed agricultural matrices

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Table 1. Confusion matrix in percentage for the supervised classification with the maximum likelihood algorithm of Zaachila'a municipality.

Class	**U**	**IA**	**RA**	**G**	**F**
No classified	0	0	0	0	0
Urban	90.15	0.36	1.42	10.79	0.74
Irrigated agriculture	0.08	84.8	0	0	0
Rainfed agriculture	3.76	0	96.1	9.94	9.68
Grassland	4.56	0	2.27	79.27	0.12
Bosque de encino	1.44	14.84	0.21	0	89.46
Total	100	100	100	100	100

Table 2. Regressions to test consistent scaling relations in the full landscape of Zaachila with respect to grain size.

Metric-level	**Function**	**variable**	**sqr_err**	**slope**	**intercept**	**R2**	**est_F**	**valrP**
Landscape	Linear	NP	4030.61057	-15.377	1865.328	0.98	4936.36349	0
Landscape	Linear	LPI	0.33315586	0.008	18.772	0.136	15.5866235	0
Landscape	Linear	ED	4.68701541	-0.552	106.766	0.982	5464.67404	0
Landscape	Linear	SHAPE_MN	0.00111813	-0.002	1.372	0.68	210.345225	0
Landscape	Linear	PROX_MN	15338.3178	-4.961	407.854	0.577	135.049104	0
Landscape	Linear	IJI	0.08735667	-0.026	74.887	0.866	640.399213	0
Landscape	Linear	PR	1.49E-28	0	7	0.499	98.7318367	0.086
Landscape	Linear	SHDI	9.29E-06	0	1.532	0.005	0.45952707	0.499
Landscape	Polynomial	NP	1088.35216	-4505.387	1096.495	0.995	9180.81739	0
Landscape	Polynomial	LPI	0.32313987	2.302	19.165	0.162	9.47250681	0

Landscape	Polynomial	ED	3.87025049	-161.649	79.181	0.985	3285.87739	0
Landscape	Polynomial	SHAPE_MN	0.00025891	-0.49	1.289	0.926	612.231564	0
Landscape	Polynomial	PROX_MN	6111.36602	-1453.71	159.782	0.831	241.741686	0
Landscape	Polynomial	IJI	0.05935008	-7.555	73.598	0.909	489.659894	0
Landscape	Polynomial	PR	1.41E-28	0	7	0.501	49.2055906	0.08
Landscape	Polynomial	SHDI	8.22E-06	0.002	1.532	0.119	6.635649	0.475
Class	Linear	CA	1098362.02	0.011	1179.109	0	6.51E-05	0.994
Class	Linear	PLAND	161.04702	0	14.286	0	6.93E-13	1
Class	Linear	NP	13219.9963	-2.197	288.442	0.237	218.72805	0
Class	Linear	LPI	56.1854772	0.007	7.357	0.001	0.55897171	0.455
Class	Linear	ED	278.582376	-0.158	32.081	0.07	53.4472247	0
Class	Linear	SHAPE_MN	0.0356948	-0.001	1.367	0.045	33.1480987	0
Class	Linear	PROX_MN	68244.0155	-5.119	475.733	0.246	230.081572	0
Class	Linear	IJI	235.731889	-0.031	65.04	0.004	2.47997145	0.116
Class	Polynomial	CA	1098361.77	8.469	1179.764	0	0.00011216	0.994
Class	Polynomial	PLAND	161.04702	0	14.286	0	2.80E-12	1
Class	Polynomial	NP	13159.9502	-1702.876	156.642	0.24	111.313298	0

Class	Polynomial	LPI	56.1763146	5.612	7.791	0.001	0.33654789	0.455
Class	Polynomial	ED	278.515701	-122.195	22.623	0.071	26.7763622	0
Class	Polynomial	SHAPE_MN	0.03473353	-1.089	1.283	0.071	26.7504397	0
Class	Polynomial	PROX_MN	59862.9441	-3968.152	168.605	0.339	180.242494	0
Class	Polynomial	IJI	235.727472	-24.213	63.166	0.004	1.24484644	0.116

Table 3. Regressions to test consistent scaling relations in the full landscape of Zaachila with respect to extent.

Metric-level	**Function**	**variable**	**sqr_err**	**slope**	**intercept**	**R2**	**est_F**	**valrP**
Landscape	Linear	NP	10839.9816	0.038	385.87	0.956	904.391746	0
Landscape	Linear	LPI	61.4125117	-0.001	38.857	0.581	58.3425279	0
Landscape	Linear	ED	15.0570482	0	121.854	0.051	2.24302846	0.142
Landscape	Linear	SHAPE_MN	0.00043293	0	1.679	0.805	173.108686	0
Landscape	Linear	PROX_MN	47354.644	-0.005	1360.553	0.089	4.09849898	0.049
Landscape	Linear	IJI	5.50221805	0	64.277	0.727	112.072756	0

Landscape	Linear	PR	0.31146614	0	6.064	0.323	20.0598611	0
Landscape	Linear	SHDI	0.01505598	0	1.104	0.652	78.8128688	0
Landscape	Polynomial	NP	4462.59949	3204.751	1245.727	0.982	1101.56018	0
Landscape	Polynomial	LPI	35.1435429	-61.266	22.418	0.76	65.0856447	0
Landscape	Polynomial	ED	14.9736906	5.948	123.45	0.056	1.21502837	0.145
Landscape	Polynomial	SHAPE_MN	0.00031017	-0.28	1.604	0.86	126.046243	0
Landscape	Polynomial	PROX_MN	47350.3009	-450.916	1239.569	0.089	2.00252163	0.052
Landscape	Polynomial	IJI	3.77762978	25.417	71.096	0.813	89.0339696	0
Landscape	Polynomial	PR	0.15887438	2.558	6.75	0.655	38.8843944	0
Landscape	Polynomial	SHDI	0.00351584	1.115	1.403	0.919	232.021475	0
Class	Linear	CA	714420.419	0.021	367.874	0.085	27.5018214	0
Class	Linear	PLAND	236.20641	0	16.46	0.003	0.94703638	0.331

Class	Linear	NP	21018.3894	0.005	65.924	0.158	55.318844	0
Class	Linear	LPI	77.0364256	0	7.684	0.016	4.79475775	0.029
Class	Linear	ED	662.533324	0	40.124	0.005	1.56817779	0.211
Class	Linear	SHAPE_MN	1.13822735	0	1.976	0.003	0.99332462	0.32
Class	Linear	PROX_MN	1206330.84	0.008	663.858	0.008	2.46124882	0.118
Class	Linear	IJI	196.628093	0	54.808	0.051	15.7267937	0
Class	Polynomial	CA	710631.721	4447.591	855.526	0.09	14.5610844	0
Class	Polynomial	PLAND	235.248723	-15.007	14.815	0.007	1.0722647	0.331
Class	Polynomial	NP	20961.4804	1081.941	184.552	0.16	28.0395952	0
Class	Polynomial	LPI	76.1106583	-19.284	5.57	0.028	4.20633898	0.029
Class	Polynomial	ED	656.395758	-32.342	36.578	0.015	2.16324717	0.21
Class	Polynomial	SHAPE_MN	1.13669969	-1.067	1.859	0.005	0.6932025	0.32

Class	Polynomial	PROX_MN	1206168.33	1728.933	853.425	0.008	1.24642381	0.118
Class	Polynomial	IJI	196.314147	55.797	60.926	0.052	8.08435682	0

Table 4. Sensitivity to scale change for the selected metrics

Metric level	**Scale change**	**Metric**	**mean**	**sd**	**cv**	**Sensitivity**
Landscape	Grain size	NP	1096.495	455.034	41.499	Moderate sensitivity
Landscape	Grain size	LPI	19.165	0.624	3.256	Low sensitivity
Landscape	Grain size	ED	79.181	16.311	20.600	Low sensitivity
Landscape	Grain size	SHAPE_MN	1.289	0.059	4.577	Low sensitivity
Landscape	Grain size	PROX_MN	159.782	191.375	119.773	High sensitivity
Landscape	Grain size	IJI	73.598	0.812	1.103	Low sensitivity
Landscape	Grain size	PR	7.000	0.000	0.000	Insensitive
Landscape	Grain size	SHDI	1.532	0.003	0.196	Insensitive
Landscape	Extent	NP	1245.727	499.939	40.132	Moderate sensitivity

Landscape	Extent	LPI	22.418	12.253	54.657	High sensitivity
Landscape	Extent	ED	123.450	4.029	3.264	Low sensitivity
Landscape	Extent	SHAPE_MN	1.604	0.048	2.993	Low sensitivity
Landscape	Extent	PROX_MN	1239.569	230.617	18.605	Moderate sensitivity
Landscape	Extent	IJI	71.096	4.545	6.393	Low sensitivity
Landscape	Extent	PR	6.750	0.686	10.163	Moderate sensitivity
Landscape	Extent	SHDI	1.403	0.211	15.039	Moderate sensitivity
Class	Grain size	NP	156.642	131.704	84.080	High sensitivity
Class	Grain size	LPI	7.791	7.504	96.316	High sensitivity
Class	Grain size	ED	22.623	17.324	76.577	High sensitivity
Class	Grain size	SHAPE_MN	1.283	0.193	15.043	Low sensitivity
Class	Grain size	PROX_MN	168.605	301.072	178.566	High sensitivity
Class	Grain size	IJI	63.166	15.391	24.366	Low sensitivity
Class	Grain size	CA	1179.764	1048.770	88.897	High sensitivity

Class	Grain size	PLAND	14.286	12.699	88.891	High sensitivity
Class	Extent	NP	184.552	158.253	85.750	High sensitivity
Class	Extent	LPI	5.570	8.863	159.120	High sensitivity
Class	Extent	ED	36.578	25.852	70.676	High sensitivity
Class	Extent	SHAPE_MN	1.859	1.070	57.558	High sensitivity
Class	Extent	PROX_MN	853.425	1104.765	129.451	High sensitivity
Class	Extent	IJI	60.926	14.416	23.661	Low sensitivity
Class	Extent	CA	855.526	885.247	103.474	High sensitivity
Class	Extent	PLAND	14.815	15.420	104.084	High sensitivity

Table 5. Values obtained for Zaachila’s landscape-level metrics at grain size 10 and for the whole landscape

Landscape metric (Landscape-level)	**Result**
Number of patches(NP)	1867
Patch richness (PR)	7
Shannon's Diversity Index (SHDI)	1.542
Largest Patch Index (LPI)	13.88%
Edge Density (ED)	125.13 m/ha

Shape Index Mean (SHAPE_MN)	1.56
Interspersion and Juxtaposition Index (IJI)	74.98 %
Proximity Index Mean (PROX_MN)	1140.07

Table 6. Values obtained for Zaachila's class-level metrics at grain size 10 and for the whole landscape

Landscape metric (Class-level)	**Urban**	**Irrigated Agriculture**	**Grassland**	**Rainfed Agriculture**	**Forest**	**Water**
Number of patches (NP)	227	116	376	570	482	81
Total (Class) Area (CA)	1505.37 ha	713.58 ha	571.03 ha	3187.98 ha	1834.42 ha	291.89 ha
Percentage of Landscape (PLAND)	18.5585 %	8.7972 %	7.0398 %	39.302 %	22.6151 %	3.5985 %
Largest Patch Index (LPI)	10.5752 %	4.3081 %	0.5031 %	3.4891 %	13.8825 %	0.2749 %
Edge Density (ED)	38.68 m/ha	22.39 m/ha	28.12 m/ha	85.57 m/ha	39.05 m/ha	35.90 m/ha
Shape Index Mean (SHAPE_MN)	1.3597	1.5567	1.3341	1.5578	1.3728	4.2802
Interspersion and Juxtaposition Index (IJI)	61.89 %	44.04 %	59.85 %	88.31 %	66.52 %	71.98 %
Proximity Index Mean (PROX_MN)	2961.07	914.60	67.31	650.85	1965.03	84.18

Table 7. Comparison between the results obtained for Zaachila and landscapes studied by Wu et al.,(2002). (-) Is data not available.

Scale change	**Metric**	**Response**	**Scaling relation**	**Direction**	**Wu**	**Scaling relation and direction**
Grain size	NP	Type 1	Power law	Decreasing	Type 1	Power function (D)
Grain size	LPI	Type 1	Power law	Increasing	Type 1	Power law or logatithmic (I)
Grain size	ED	Type 1	Power law	Decreasing	Type 1	Power function (D)
Grain size	SHAPE_MN	Type 1	Power law	Decreasing	Type 4	
Grain size	PROX_MN	Type 1	Logarithmic	Decreasing	Not available	
Grain size	IJI	Type 1	Power law	Decreasing	Not available	
Grain size	PR	Type 3	-	-	Type 2	
Grain size	SHDI	Type 4	-	-	Type 2	
Extent	NP	Type 1	Power law	Increasing	Type 1	Power function (I)
Extent	LPI	Type 1	Logarithmic	Decreasing	Type 4	
Extent	ED	Type 4	-	-	Type 4	
Extent	SHAPE_MN	Type 1	Power law	Decreasing	Type 4	

Extent	PROX_MN	Type 4	-	-	Not available	
Extent	IJI	Type 1	Power law	Increasing	Not available	
Extent	PR	Type 2	-	-	Type 2	
Extent	SHDI	Type 1	Logarithmic	Increasing	Type 2	

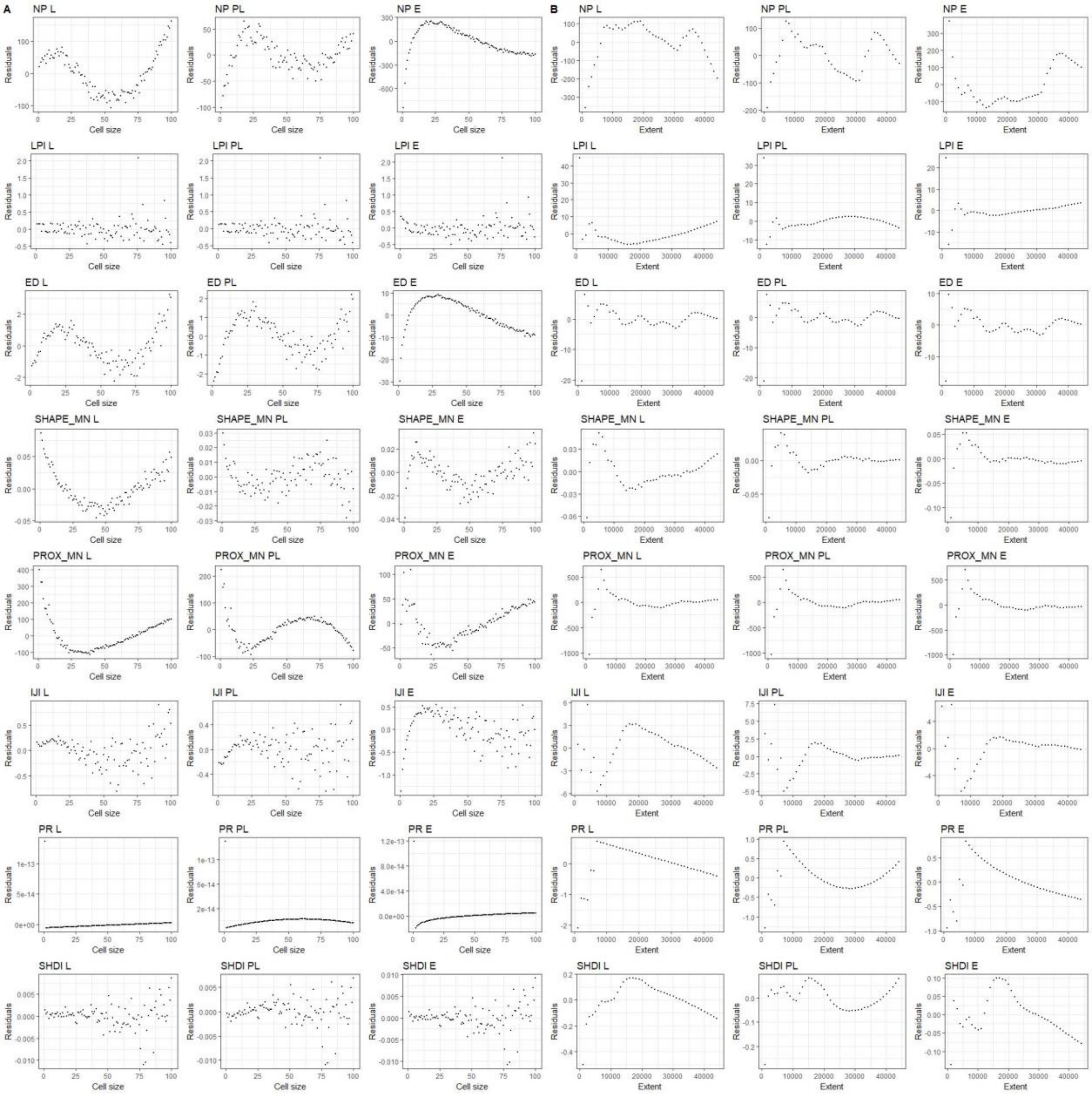

Figure 1. Landscape level metrics sensitivity tests. A) are the residuals values in different cell sizes and B) are the residuals in different extents. L stands for the sensitivity of the metrics to linear regressions, PL stands for the sensitivity of the metrics to polynomial regressions and E is for the sensitivity of the metrics to exponential regressions.

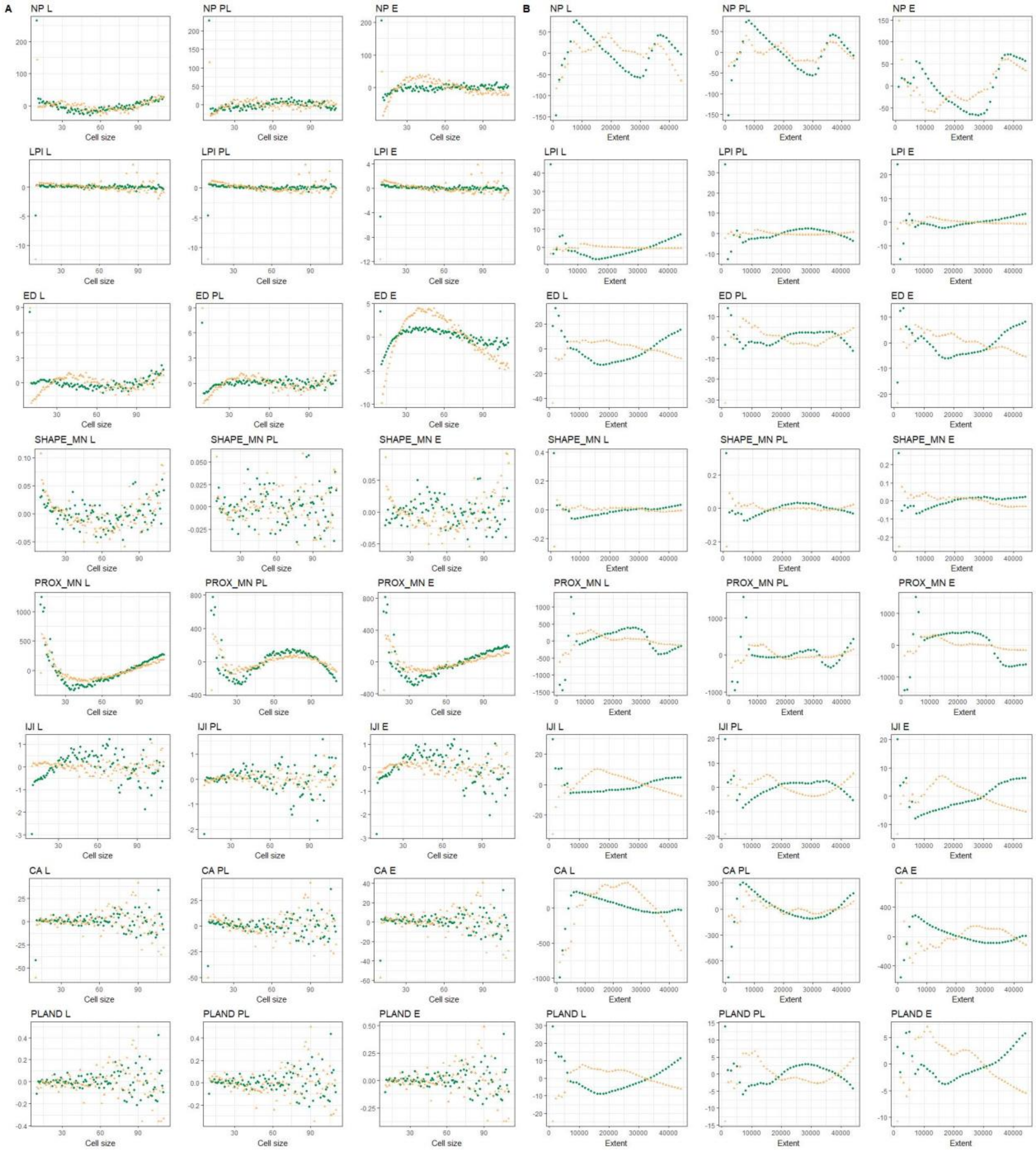

Figure 2. Class level metrics sensitivity tests for forest (green) and rainfed agriculture (yellow). A) are the residuals values in different cell sizes and B) are the residuals in different extents. L stands for the sensitivity of the metrics to linear regressions, PL stands for the sensitivity of the metrics to polynomial regressions and E is for the sensitivity of the metrics to exponential regressions.