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Cartographies on an emergency: monitoring Ligustrum lucidum invasion in the metropolitan Sierras Chicas of Córdoba, Argentina (2002-2020)

Cartografias em caso de emergência: monitoramento da invasão de Ligustrum lucidum nas Serras Chicas metropolitanas de Córdoba, Argentina (2002-2020)

Cartografías en la emergencia: Mmonitoreo de la invasión de Ligustrum lucidum en las Sierras Chicas metropolitanas de Córdoba, Argentina (2002-2020)

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Abstract: Invasive exotic vegetation poses a significant threat to ecosystems biodiversity conservation. *Ligustrum lucidum* (glossy privet) stands out as a prominent invasive tree species across ecosystems worldwide. The *Chaco Serrano* district in South America is one of the areas most affected in Argentina, particularly the metropolitan Sierras Chicas (Córdoba), which are home to Argentina's second most populous metropolitan area. Consequently, accurate and up-to-date information on *L. lucidum* invasion in that region is crucial for much needed management and restoration policies. I present a novel methodology to monitoring this invasion at regional scale, while generating local data with minimal use of resources. Calculating NDVI levels on Landsat imagery, I built detailed cartography spanning 20 years, showing that the affected area has increased over 10 times, affecting peri-urban areas and natural reserves. Moreover, I identified four sub-regions with different invasion patterns due to local environment and urbanization. The results prove valuable in database updates, raising awareness, diagnostic and local-control strategies, and are readily replicable in areas with comparable conditions.

Keywords: Exotic invasive species. Biodiversity lost. *Chaco Serrano*. NDVI.

Resumo: A vegetação exótica invasora representa uma ameaça significativa à conservação da biodiversidade dos ecosistemas. *Ligustrum lucidum* (alfeneiro) destaca-se como uma espécie de árvore invasora proeminente em ecossistemas em todo o mundo. O distrito de *Chaco Serrano*, na América do Sul, é uma das áreas mais afetadas na Argentina, especialmente a região metropolitana de Sierras Chicas (Córdoba), que abriga a segunda área metropolitana mais populosa da Argentina. Consequentemente, informações precisas e atualizadas sobre a invasão de *L. lucidum* naquela região são cruciais para as tão necessárias políticas de gestão e restauração. Apresento uma nova metodologia para monitorar esta invasão em escala regional, gerando dados locais -com recursos mínimos. Calculando os níveis de NDVI em imagens Landsat, construí uma cartografia detalhada abrangendo 20 anos, mostrando que a área afetada aumentou mais de 10 vezes nesse período, afetando as áreas periurbanas e também as reservas naturais. Além disso, identifiquei quatro sub-regiões com diferentes padrões de invasão devido às condições ambientais locais e à urbanização. Os resultados revelam-se valiosos na actualização de bases de dados, na sensibilização, nas estratégias de diagnóstico e de controlo local, e são facilmente replicáveis em áreas com condições comparáveis.

Palavras-chave: Espécies exóticas invasoras. Perda de biodiversidade. *Chaco Serrano*. NDVI.

Resumen: La vegetación exótica invasora representa una gran amenaza para la conservación de ecosistemas. *Ligustrum lucidum* (ligustro), se destaca entre las especies arbóreas invasoras en ecosistemas de todo el mundo. El distrito *Chaco Serrano* de Latinoamérica es una de las zonas más afectadas, en especial las Sierras Chicas metropolitanas (Córdoba), que albergan la segunda área metropolitana más poblada de Argentina. En consecuencia, la información precisa y actualizada sobre *L. lucidum* en esa región es crucial para las urgentes políticas efectivas de manejo y restauración. Presento una metodología novedosa para monitorear el área afectada a escala regional, generando simultáneamente datos a nivel local: calculando niveles de NDVI en imágenes Landsat, generé cartografía sobre la invasión en las Sierras Chicas Metropolitanas durante las últimas dos décadas con gran nivel de detalle, lo que me permitió calcular que el área afectada se ha multiplicado casi diez veces en ese período, afectando áreas periurbanas y reservas naturales. Además, identifiqué cuatro subregiones con diferentes patrones de invasión debido a las condiciones ambientales locales y la urbanización. Los resultados resultan valiosos para actualizaciones de bases de datos, sensibilización, estrategias de diagnóstico y control, y son fácilmente replicables en áreas con condiciones comparables.

Palabras clave: Especies exóticas invasoras. Pérdida de biodiversidad. *Chaco Serrano*. NDVI.

Introduction

Nowadays, ecosystems' biodiversity conservation is a strategic objective in public policies worldwide, since actively avoiding biodiversity deterioration means protecting life-support processes for human and non-human communities around the globe. Indeed, biodiversity supports ecosystem services that play a leading role in local resilience mechanisms against natural disasters and environmental changes resulting from the ongoing global climate crisis (MEA, 2005; FAO & UNEP, 2020).

Among explicitly aggressive processes that lead to biodiversity loss, such as deforestation, desertification or indiscriminate extraction of individuals, invasive exotic species pose a significant threat: introducing exotic vegetation can seriously disrupt an ecosystem balance by negatively impacting local animal and plant species, altering soil composition, increasing erosion, or disrupting nutrient cycles and climate regulation at local and regional scales (IPBES, 2019, 2023).

In this article I present a methodological approach to assess exotic invasive vegetation, focusing on the *Ligustrum lucidum W. T. Aiton* (glossy privet) invasion in Sierras Chicas, the western sector of the Metropolitan Region of Córdoba (Argentina) (RMCba), where it seems to contribute to substantial changes in the native *Chaco Serrano* forest (Figures 1-3).

In this area, historically affected by deforestation for firewood, urbanization and agricultural and mining activities (GAVIER-PIZARRO & BUCHER, 2004), the *L. lucidum* invasion affects the few remnants of native forest at an alarming rate (GAVIER-PIZARRO et al., 2012; AGUILAR et al., 2018). Consequently, it is imperative to develop control and ecological restoration initiatives, endorsed by regional development policies.

To successfully achieve this, it is crucial that stakeholders (politicians and community members) have access to reliable and up-to-date information on location and size of affected areas, rates of *L. lucidum* invasion, and invasion patterns, specifically oriented to support sustainable urban and regional development.

In that line, remote sensing has been a widely used method to survey changes both in land and vegetation cover since the end of the last century (c.f. ALVAREZ, 2020; ALVAREZ et al., 2020; FERRERAS et al., 2015). In addition, satellite imagery used as primary data is available in open access repositories, and offers a record catalog over several decades; this facilitates both the survey of large extensions of land and historical analysis.

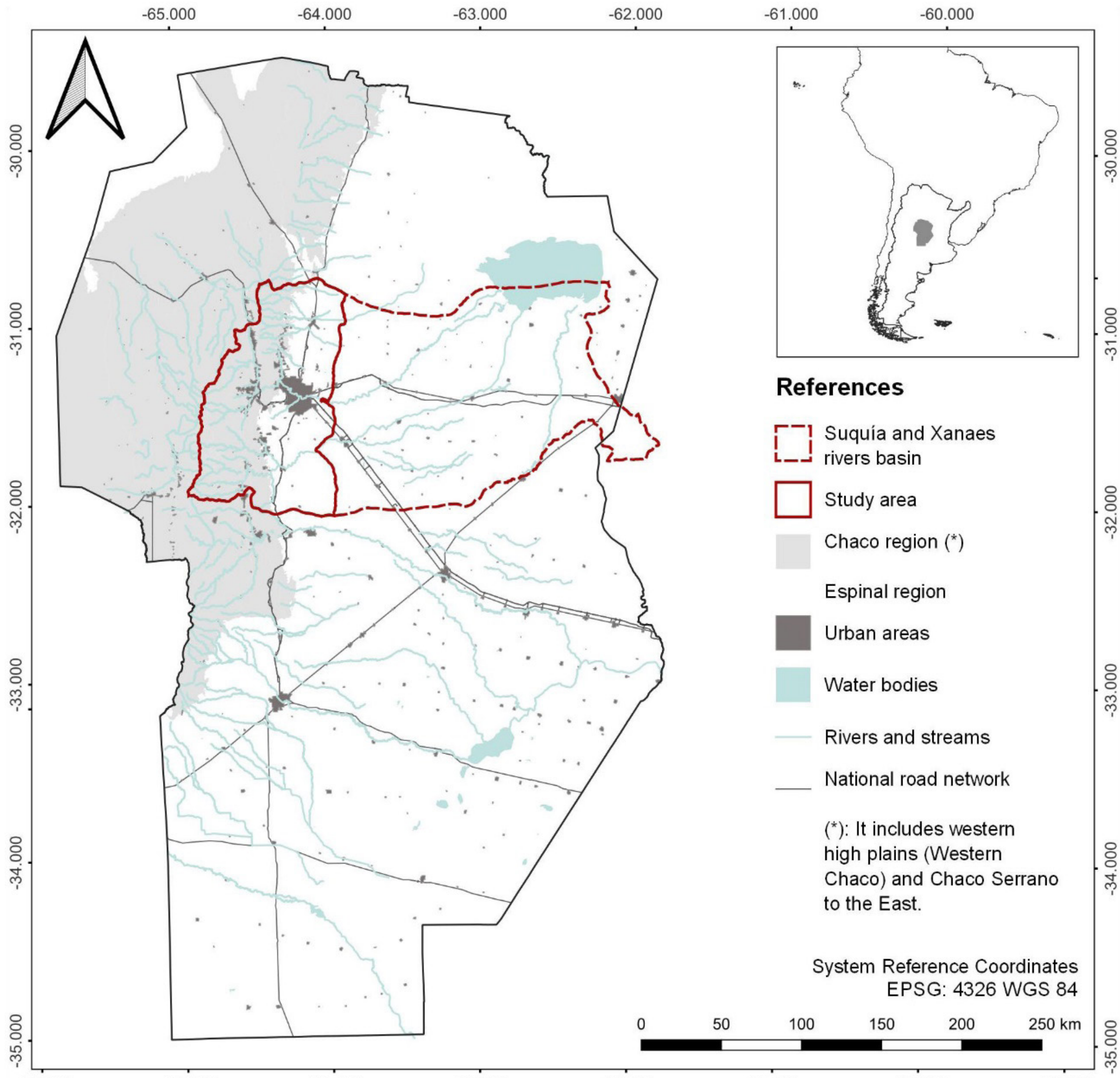

Figure 1. Study Area: Metropolitan Sierras Chicas in Córdoba

Source: the author's, and data from institutional sources: jurisdiction limits, national road network and urban areas retrieved from Instituto Geográfico Nacional WFS repository (may, 2024); hydrographic data, phytogeographic regions retrieved from IDECOR WFS repository (may, 2024).

The impact of *L. lucidum* on the native forest of metropolitan Sierras Chicas has been studied for several years. Among the investigations that explore changes and classes of land cover (c.f. CINGOLANI et al., 2022; GAVIER-PIZARRO & BUCHER, 2004), I must highlight the historical reconstruction of the invasion between 1983 and 2006 on the North-

Eastern slope of Sierras Chicas (GAVIER-PIZARRO et al., 2012), the detailed cartographic record of that same region for the year 2006 by Hoyos et al. (2010) and the mapping of the Los Quebrachitos Natural Reserve (Unquillo) in Lezcano & Romano's thesis (2017), quantifying the problem with a great level of detail.

These studies profited from the semi-automatic classification of satellite imagery, which allows quantifying differences in land cover. In the case of exotic vegetation invasion, a classification through the Normalized Difference Vegetation Index (NDVI) measures the photosynthetically active biomass as a function of the amount of visible red light absorbed and near infrared light reflected by the different soil covers, highlighting the differences between the foliage of native and exotic species in the land cover.

However, this method is based on extensive field work prior to and after NDVI classification, which requires a large amount of work-hours and resources. Although this allows great mapping precision, it also limits the extent of the area to be explored, or prevents continuing the analysis over time. This is especially serious for political agents or community organizations that, although recognizing the strategic importance of the information generated in these investigations, do not have the resources -or time- to carry out this type of study.

Due to the above, I conducted this research in order to generate reliable data to support public policies and raise community awareness through an instrument:

- that quickly generates up-to-date data;
- that encompasses both a wider regional scale (which shows the true magnitude of the phenomenon in the whole RMCba) and a local one (which allows analyzing the problem with a sufficient level of detail to propose specific intervention actions for its mitigation and control);
- that can be easily replicated in order to reliably analyze the phenomenon over time (and eventually assess the impact of control and remediation actions in affected areas).

Thus, I developed a strategy that takes advantage of remote sensing analysis combined with existing data on the phenomenon on the study area. My approach builds on the evidence that although it is relatively difficult to distinguish individual specimens or different tree species due to the resolution of the satellite imagery (30x30 m/px for Landsat), the evergreen foliage of *L. lucidum* stands out strongly against the deciduous and less leafy foliage of the native vegetation of the *Chaco Serrano (*whose leaves are small or have evolved as thorns), facilitating its detection via NDVI levels (GAVIER-PIZARRO et al., 2012; HOYOS et al., 2010; CINGOLANI et al, 2022). This difference is especially accentuated at the end of the dry season in the months of September and October, so processing images obtained in that season allows for annual land cover classifications with greater precision.

This strategy is particularly useful to extend the analysis to the entire metropolitan Sierras Chicas (near 10,136 km^2), from 2002 to 2020 (as shown in Figure 5), and generated a detailed cartographic database with a minimum of human and economic resources.

Another advantage is that it allows me to detect trends during the analyzed period, such as different invasion rates and patterns, and factors that would have a direct association with the phenomenon: the relationship between urbanized areas and invasion outbreaks; fire recurrences; deforestation; slope and accessibility; or the exodus of agricultural activities due to urbanization, leaving open fields. According to this, I identify four sub-regions where environmental and anthropic conditions determine particular invasion patterns, which should be considered in future research.

Based on these results, I conclude that through this method I obtained reliable information according to the scale of analysis, with a sufficient level of detail to plan detailed field work, optimize the use of resources, and facilitate continuous monitoring over time. This offers strategic data to local governments –and the community in general– who are committed to the ecological remediation of the affected areas.

In the following sections, I develop the methodology and results obtained in greater depth, and finally discuss their potential for a deeper understanding of the phenomenon and an effective call to action in a critical scenario.

Study Area

RMCba is an important cultural, economic, educational, financial and regional entertainment center for Argentina and Latin America. Almost 2 million people inhabit a metropolitan region that extends over more than 15,000 km^2, from the agricultural *pampa* plains to the east (part of *Espinal* phytogeographic province), to the Sierras Chicas in the west (part of *Chaco Serrano* district), along Suquía and Xanaes rivers, part of the Mar de Ansenuza basin (CABRERA, 1951) (Figure 2).

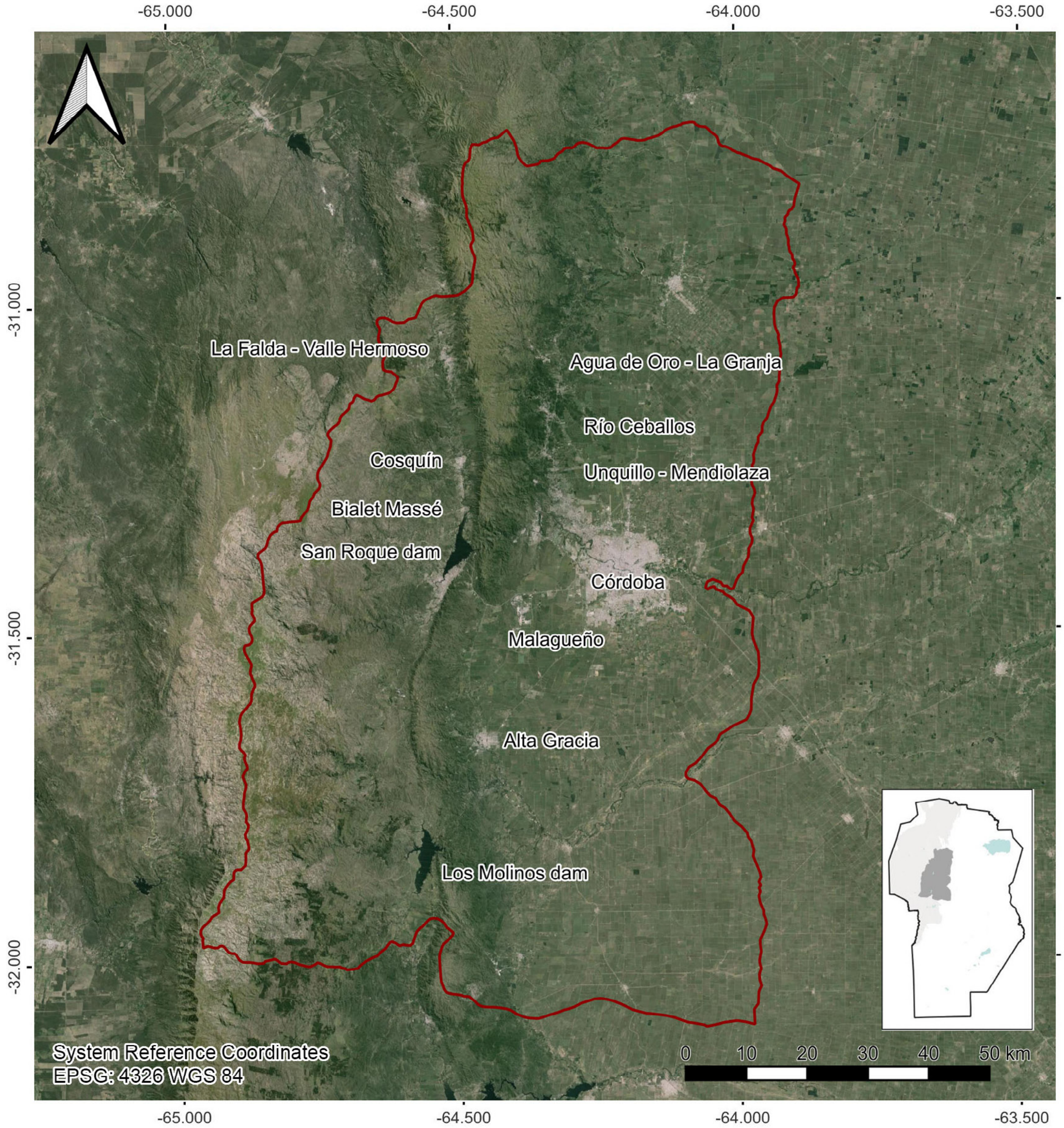

Figure 2. Study Area: Metropolitan Sierras Chicas in Metro Córdoba

Source: the author's, and data from institutional sources: jurisdiction limits retrieved from Instituto Geográfico Nacional WFS repository (may, 2024); phytogeographic regions retrieved from IDECOR WFS repository (may, 2024); Basemap Landsat 8 August 25th 2020 retrieved from USGS Earth Explorer online repository (may, 2022).

Chaco Serrano extends over hills and valleys from 500 to 2,000 meters above sea level. This semi-arid region has a temperate Mediterranean climate, where the rainfall (750 mm/year) occurs mainly in the warm season. The vegetation can be assimilated mainly to that of a xerophytic subtropical forest, characterized by *Schinopsis marginata Engl., Lithraea molleloides (Vell.) Engl., Aspidosderma quebracho-blanco, Prosopis torquata (Cav.) DC, Zizyphus mistol Griseb*, perennial herbs and graminoids. Its structure and floristic composition are highly affected by local disturbances (such as grazing pressures and fire recurrences) which generate a mosaic of patches with different traits (AGUILAR et al., 2018; GIORGIS et al., 2011) (Figure 3).

In recent decades, the migration from Córdoba city towards towns and small cities in Sierras Chicas has been increasing (BOCCOLINI, 2022, 2021), definitively transforming the *Chaco Serrano* landscape. One consequence of this is the invasion of native forests by exotic species, generally due to their introduction as ornamental vegetation in urban landscaping (BARCHUK et al., 2010; GIORGIS & TECCO, 2014; GAVIER-PIZARRO & BUCHER, 2004).

L. lucidum stands out among the invasive woody species in that region (DREYER et al. 2019), due to its rapid spread and the extension of the affected areas (VALFRÉ-GIORELLO et al., 2019).

Ligustrum lucidum

Native to forests of Central and South China, this species is the *Ligustrum* with the largest wingspan: Between 3 and 8 m, reaching 15 m when environmental conditions are favorable. Due to the lushness that its dark green foliage presents all year round, this species is considered of great ornamental value. As a result, it is actively promoted in urban landscaping and planted in sidewalks, parks and gardens on all continents (except Antarctica) since the 18th century (FERNÁNDEZ et al., 2020).

Because *L. lucidum* can easily adapt to different environments, it has spread from urban to peri urban ecosystems over the years. Currently, *L. lucidum* is considered a highly problematic invasive species in 11 countries (UN-HABITAT, 2022), although records show occurrences in at least 55 countries, including countries that host ecosystems essential for the global biological balance (i. e. Amazonian and Congo forests, tropical Andes, East Australia forests, and Indic Ocean islands) and ecosystems that support life in densely populated regions (Japan, the Atlantic piedmont in the United States, the Golden Triangle in the Yangtze river in China, the upper basin of the Paraná-Plata in Argentina, Uruguay, Paraguay and Brazil, the Po Valley in Italy, the coasts of the Mediterranean Sea in Spain and North Africa), as shown in the cartography produced by Montti et al. (2021).

Figure 3. (top) Native forest in Los Quebrachitos Natural Reserve; (middle) a private plot for pasture -while the native trees remain, the native herbaceous species has been replaced with exotic species more suitable for feeding cattle-; (bottom) L. lucidum stand.

Source: the author.

In Argentina, one of the most affected regions is metropolitan Sierras Chicas, where the invasion of *L. lucidum* drastically changes the local ecosystem (HOYOS et al., 2010): It not only reduces the diversity of native trees, but also impoverishes the vertical structure of the forest, ultimately resulting in the dominance of *L. lucidum* and the exclusion of native species (FERNÁNDEZ et al., 2020). This results in a structural simplification of the vegetation and, in more extreme cases of invasion, the total disappearance of the vegetation that grows under the tree canopy (FERRERAS et al., 2015) (Figure 3, bottom), affecting the successive links of the trophic chains, the cycle of nutrients in the soil and its ability to absorb rainwater and adapt to the periodic forest fires that characterize Sierras Chicas (TOLOCKA, 2017; VERZINO et al., 2005).

Materials and Methods

According to urban and ecological factors, I defined the study area (metropolitan Sierras Chicas) as the area occupied by the Suquía and Xanaes rivers basin, 300 m above sea level (Figure 2) according to official data from *Infraestructura de Datos Espaciales de la República Argentina*[1] (IDERA), *Infraestructura de Datos Espaciales de la provincial de Córdoba*[2] (IDECOR), *Instituto Geográfico Nacional*[3] (IGN), and *Equipo de Ordenamiento Ambiental del Territorio of Facultad de Ciencias Exactas, Físicas y Naturales at Universidad Nacional de Córdoba*[4,5].

There, I analyzed the areas covered by native forest and *L. lucidum* stands since 2002, based on the different levels of NDVI, which I obtained by processing in QGIS a series of Landsat products, selected in the Earth Explorer open access repository from the United States Geological Survey (USGS).[6]

1 https://www.idera.gob.ar/index.php?option=com_content&view=article&id=335:geoservicios&catid=33:servicios&Itemid=302

2 https://www.mapascordoba.gob.ar/#/mapas

3 https://www.ign.gob.ar/

4 https://fcefyn.unc.edu.ar/facultad/secretarias/investigacion-y-desarrollo/centros/equipo-de-ordenamiento-ambiental-del-territorio/

5 Those repositories also provided basic information and reference elements such as road network, hydrography, jurisdiction limits and urbanization extension through 2002-2020.

6 https://www.google.com/search?client=safari&rls=en&q=Earth+Explorer+open+access+repository+from+the+United+States+Geological+Survey&ie=UTF-8&oe=UTF-8

Each Landsat image has a coverage of 185x185 km, which allowed me to cover the entire study area with a single image. Moreover, these Landsat products have a resolution of 30x30 m per pixel, which allowed me to obtain information at both a regional and local scale, with a sufficient level of detail to monitor its evolution in key places.

Image Pre-Processing

The criteria for selecting the Landsat TM and ETM+ images (scene path 229/row 82) are:

- Allow maximum visibility, avoiding the presence of clouds or snow over the study area.
- Be comparable to each other, avoiding images of atypical seasons – especially with regard to the rainy season, which affects the extent and quality of areas covered with vegetation.
- Facilitate future cross-checking with official demographic and socioeconomic data, prioritizing the analysis of periods corresponding to the moments in which the national censuses were conducted (2001, 2010 and 2022) by proxy.
- Maximize reliability, selecting for each year analyzed: (a) an image of the end of the rainy season (February/April), showing the maximum difference between urbanized areas and areas covered with vegetation, and (b) an image of the end of the dry season (August-October), showing the maximum difference between native forest foliage (where deciduous species predominate[7]), and that of *L. lucidum* (perennial).

The selected images (Tables 1 and 2) correspond to the years 2002, 2006, 2010 and 2020. I converted each image to TOA reflectance, performed an atmospheric correction (via DOS1) and corrected its brightness temperature using QGIS Semiautomatic Classification plugin. Next, I visualized each image in a natural color band combination to verify compliance with the above criteria (Figure 4a), finally calculating NDVI values per pixel with the equation:

7 Although some native perennial species are present (e. g. *Schinus molle var. areira (L.) DC)*.

NDVI=(NIR-red)/(NIR+red)

where:

NDVI: Normalized Difference Vegetation Index

NIR: Near Infrared Radiation Band

Red: Band corresponding to red radiation within the visible spectrum.

Then, for Landsat 8 bands, NDVI=(5-4)/(5+4); for Landsat 5 bands, NDVI=(4-3)/(4+3)

In each NDVI raster obtained (Figure 4c), I subtracted the pixels corresponding to areas covered by clouds, ice, snow, and water with the Cloud Masking plugin, and refined the result with the SAGA Majority filter plugin. Finally, I clipped the Landsat stacked band raster and the NDVI raster of each image according to study area boundaries.

Classification of Areas Covered by L. lucidum Stands

At first, I used as reference the results in Hoyos et al. (2010), which identified *L. lucidum* stands and native forest in the central sector of the study area for the year 2006. Based on this data, I reclassified my NDVI raster corresponding to the 2006 dry season, obtaining a result equivalent to Hoyos et al. (2010). Then, I reclassified the dry season NDVI rasters for 2002, 2010 and 2020, adjusting NDVI values according to particular conditions, and refining the classification as very leafy vegetation, leafy vegetation and slightly leafy vegetation, the first assimilable to areas totally occupied by perennial vegetation (*L. lucidum* by proxy), the second, assimilable to invaded areas where native species still remain, and the latter, assimilable to native forest with presence of perennial species. (Table 1).

Table 1: NDVI Levels Classification for Dry-Season Imagery

Original Landsat Image	Date	NDVI Levels Classification				
		Very leafy vegetation	Leafy vegetation	Slightly leafy vegetation	Deciduous vegetation	No vegetation
Landsat 5 March 30th 2001	2001	>0.69	0.6 a 0.69	0.5 a 0.6	0 a 0.5	<=0
Landsat 5 September 20th 2006	2006	>0.5	0.37 a 0.5	0.32 a 0.37	0 a 0.32	<=0

Landsat 5 September 15th 2010	2010	>0.5	0.37 a 0.5	0.32 a 0.37	0 a 0.32	<=0
Landsat 8 August 25th 2020	2020	>0.67	0.51 a 0.67	0.41 a 0.51	0 a 0.41	<=0

As a second reference, I compared the results with data obtained in Giorgis et al. (2021) for 2020, corroborating a high level of correspondence with the invaded area detected in my dry season NDVI raster for 2020.

Then, I re-refined and vectorized each raster, obtaining a Shapefile of polygons classified into 5 categories according to Table 1, and eliminated those polygons corresponding to built-up areas, crops and bare soil on each image.

Classification of Areas Covered by Native Forests

I reclassified the NDVI raster corresponding to the Landsat image obtained in the 2006 rainy season, identifying areas covered by forests equivalent to Hoyos et al. (2010) for 2006. Based on those results, I reclassified the rainy season NDVI rasters of 2002, 2010 and 2020, adjusting the values according to particular conditions (Table 2).

Table 2: NDVI Levels Classification for Rainy-Season Imagery

Original Landsat Image	Date	NDVI Levels Classification			
		Very leafy vegetation	Leafy vegetation	Slightly leafy vegetation	No vegetation
Landsat 5 july 7th 2002	2002	>0.74	0.67 a 0.74	0.53 a 0.67	<=0.53
Landsat 6 March 30th 2006	2006	>0.74	0.67 a 0.74	0.53 a 0.67	<=0.53
Landsat 5 February 16th 2009	2009	>0.74	0.67 a 0.74	0.53 a 0.67	<=0.53
Landsat 8 March 2nd 2020	2020	>0.82	0.65 a 0.82	0.53 a 0.65	<=0.53

I then refined, vectorized and corrected each file, repeating the same procedure executed for dry-season imagery (Figure 4d).

Figure 4 shows the different processing stages to generate the 2006 cartography.

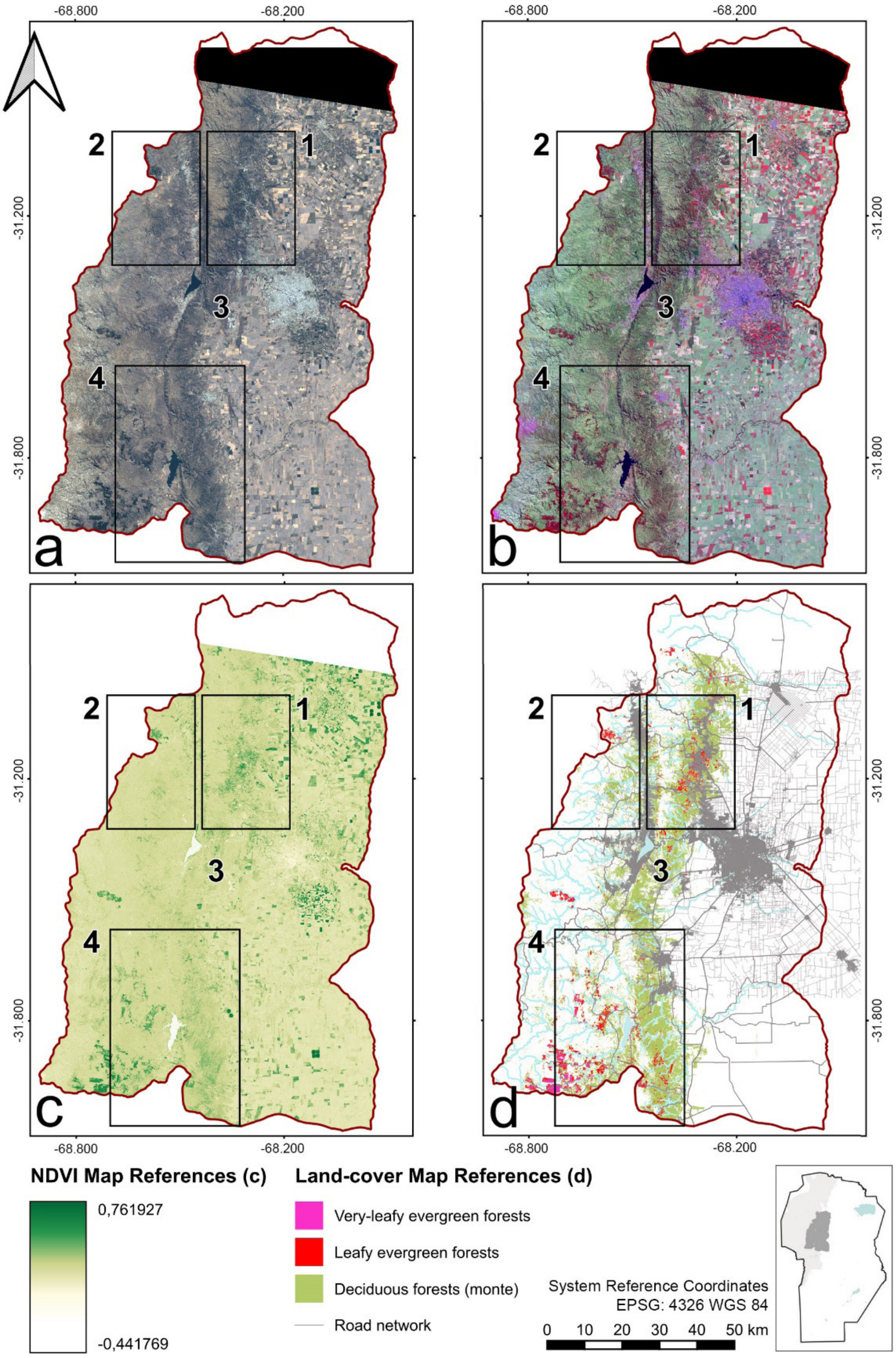

Figure 4. Landsat 5, September 20, 2006, Cropped to Study Area

(a) Bands 3-2-1 (natural color); (b) Bands 4-5-2 (purple shows urbanized areas, red shows irrigated crops); (c) calculated NDVI values; (d) estimated land covers.
The numbers refer to the four sub-regions identified:
(1) North-Eastern slope of Metropolitan Sierras Chicas; (2) Northern Punilla Valley; (3) La Defensa Natural Reserve in Malagueño city; (4) Paravachasca Valley.
Source: the author's, and data from institutional sources: jurisdiction limits, national road network and urban areas retrieved from Instituto Geográfico Nacional WFS repository (may, 2024); hydrographic data, and phytogeographic regions retrieved from IDECOR WFS repository (may, 2024); Landsat 5 imagery retrieved from USGS Earth Explorer online repository (may, 2022).

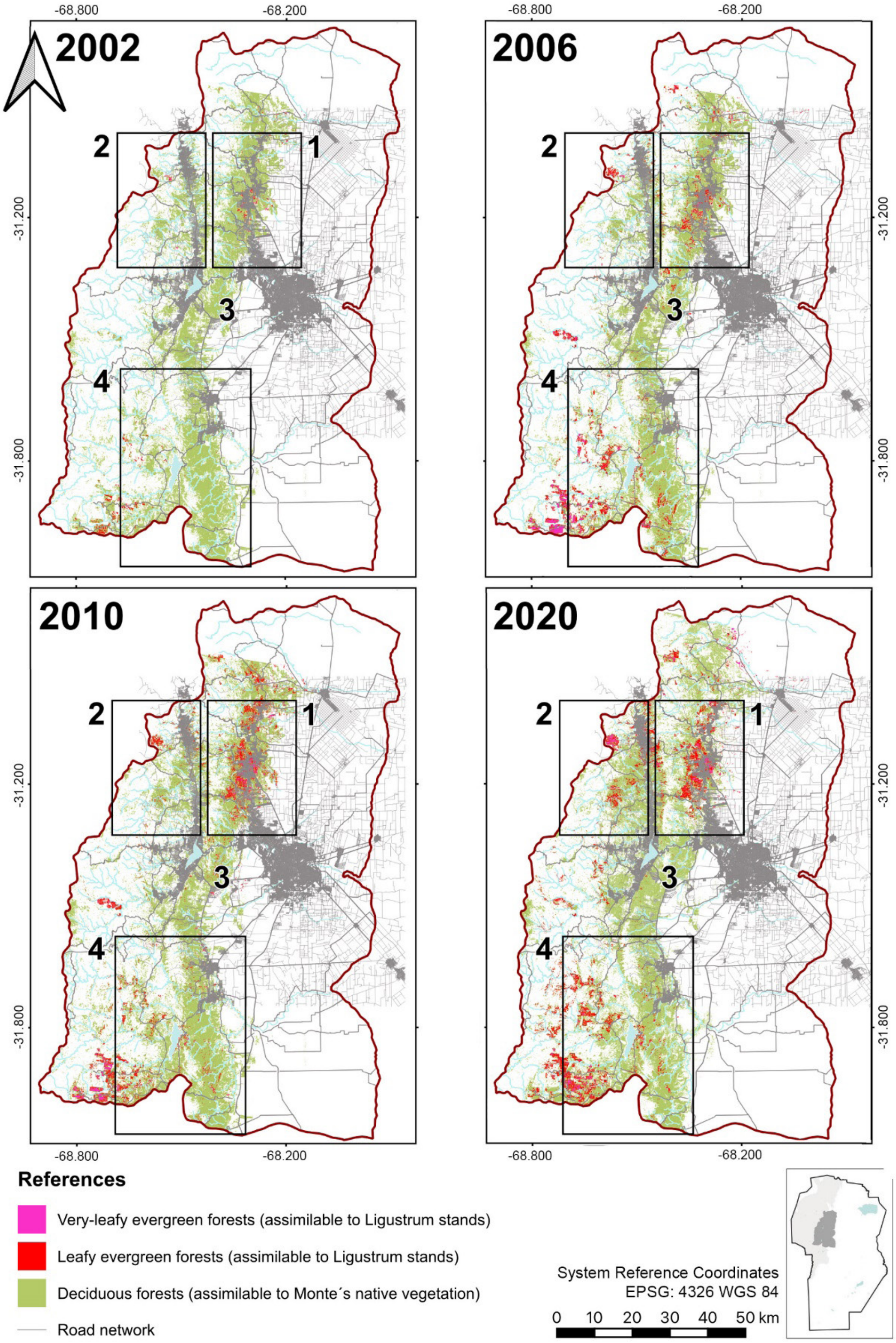

Figure 5. Resulting Land Cover Maps

The numbers refer to the four sub-zones identified:
(1) North-Eastern slope of Metropolitan Sierras Chicas; (2) Northern Punilla Valley; (3) La Defensa Natural Reserve in Malagueño city; (4) Paravachasca Valley.
Source: author's, and data from institutional sources: jurisdiction limits, national road network and urban areas retrieved from Instituto Geográfico Nacional WFS repository (may, 2024); hydrographic data, and phytogeographic regions retrieved from IDECOR WFS repository (may, 2024); Landsat 8 and 5 imagery retrieved from USGS Earth Explorer online repository (may, 2022).

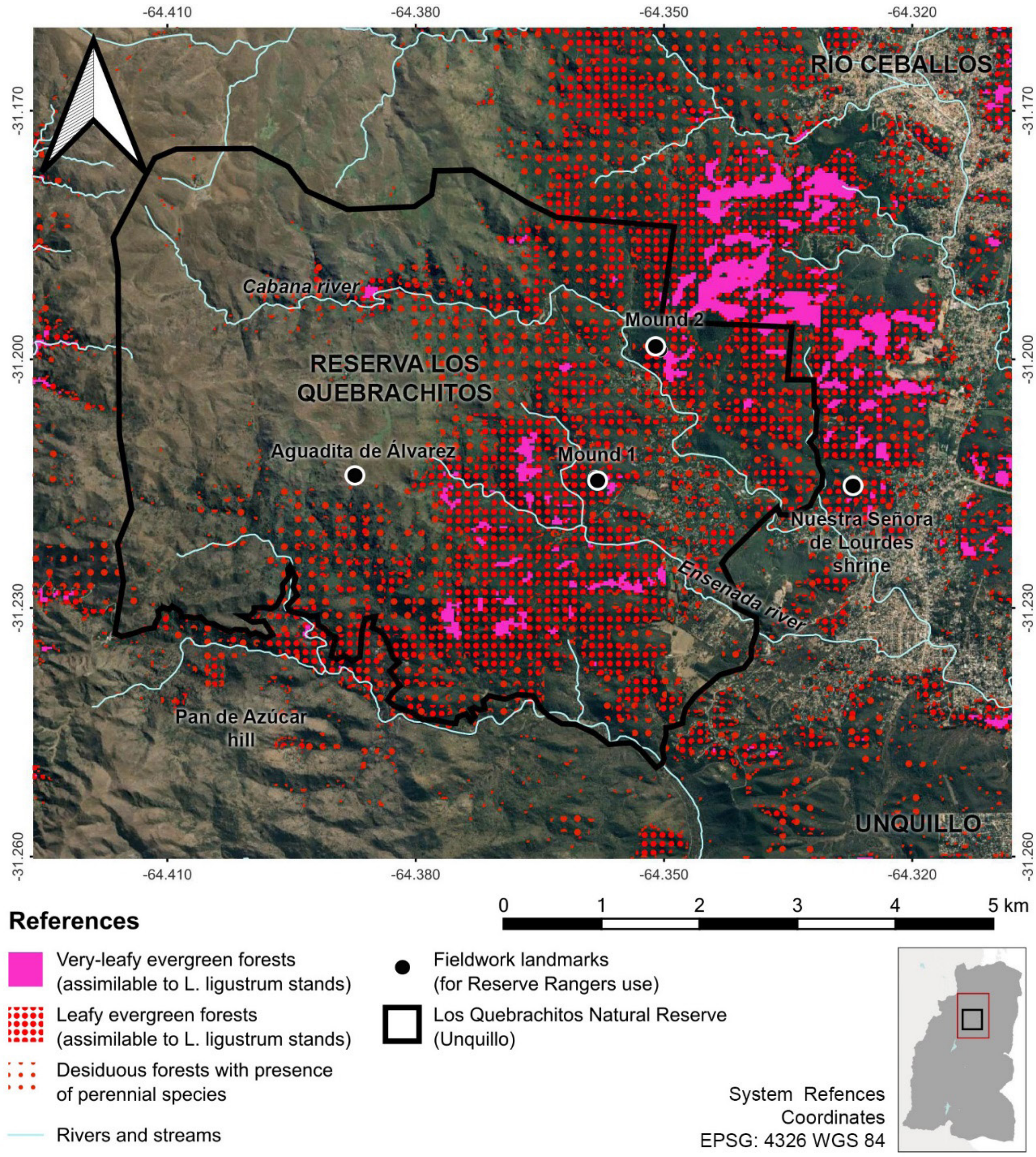

Figure 6: Los Quebrachitos Natural Reserve

(part of North-Eastern slope of Metropolitan Sierras Chicas)
Source: the author's, and data from institutional sources: jurisdiction limits, national road network and urban areas retrieved from Instituto Geográfico Nacional WFS repository (may, 2024); hydrographic data, and phytogeographic regions retrieved from IDECOR WFS repository (may, 2024); Landsat 8 imagery retrieved from USGS Earth Explorer online repository (may, 2022).

Results

The data allowed me to generate detailed cartography for the entire study area, covering 10,136 km^2 with a resolution of 30x30 m per pixel, for 2002, 2006, 2010 and 2020 (Figure 5), identifying:

- vegetation with high NDVI levels only in the rainy season, which does not correspond to crops (assimilable to native forest).
- vegetation with high NDVI levels even in the dry season, which does not correspond to crops (as proxy to invasive exotic species, mainly *L. lucidum*, together with *Ulmus* and *Gleditsia triacanthos*).
- urbanized areas.

Figure 6 shows the level of detail of the data generated in Los Quebrachitos Natural Reserve, near Unquillo.

Almost half of the study area belongs to the *Chaco Serrano* district (4,903.5 km^2), and less than 10% of it is urbanized or occupied with water reservoirs. The affected area represented just 0.55% in 2002, but increased almost 10 times in 2020 (Table 3). The affected areas increased in extent almost uninterruptedly. But the growth rate is not constant: it is higher between 2002 and 2006, slowing down significantly in 2010 and resuming towards 2020.

Table 3: Areas Covered with Vegetation Assimilable to L. lucidum (2002-2020) (km^2)

	2002	2006	2010	2020
Very leafy vegetation	1.47	31.57	31.99	30.17
Leafy vegetation	25.26	157.36	161.62	236.51
TOTAL	26.73	188.93	193.61	266.69
% *Chaco Serrano* disctrict affected	0.55%	3.85%	3.95%	5.44%

Despite the low growth rates, it is during 2006-2010 when new invaded areas appear in Northern Punilla Valley and in Paravachasca Valley (Figure 5), becoming main invasion foci in each of these sub-regions.

The results corroborate the close link between *L. lucidum* invasion and urbanization: The oldest invasion outbreaks registered are located surrounding urbanized areas (Figures 7-9). And a factor that favors *L. Ligustrum* subsequent dispersion is deforestation, either to prepare the land for urbanization projects (that fail later), to sow pastures, to extract rocks and minerals or simply to obtain firewood. Bare land close to a

L. lucidum stand is highly prone to be invaded before native vegetation can prosper, Ñú Porá hill in Río Ceballos city being the paradigmatic example (see Figure 7).

L. lucidum later invades matured native forests, mainly in ravines and by river or streams, occupying privileged areas with high water availability, in a region where this resource is scarce (e. g. Eastern slope in Punilla Valley, Figure 8).

Added to that, *L. lucidum* densification and spread rates seem to depend on inaccessibility and slope, which, in tandem, hinder the occupation of such land with buildings, crops or livestock, increasing the opportunities for *L. lucidum* to thrive (e. g. Villa Los Altos surroundings, Figure 7).

Finally, it is necessary to mention perennial vegetation stands that appear suddenly, completely occupying regular areas of the land. It is my conjecture that they result from deforestation practices on privately-owned plots and cultivation of exotic species for logging (e. g., there are records of *Pinus elliottii* plantations in Paravachasca, Figure 9). These regular patches do not follow the invasion patterns recorded, and therefore, might not involve *L. lucidum*; this should be further studied. Moreover, it is necessary to complement the cartography with field work in order to identify other invasive exotic species, e. g. *Ulmus*, *Gleditsia triacanthos* and *Morus*.

Despite this, the detail level of the data makes it possible to distinguish four sub-regions with particular invasion conditions, as shown in Figure 5. Their differential growth rates are shown in Table 4.

Table 4: Areas Covered with Vegetation Assimilable to L. lucidum (2002-2020) in Each Sub-Region (km²)

	2002	2006	2010	2020
North-Eastern slope of metropolitan Sierras Chicas	9.92	50.59	90.96	83.41
Northern Punilla Valley	1.,71	26,51	28.14	63.39
Paravachasca Valley	15.09	111.81	74.50	119.88
TOTAL	26.73	188.93	193.61	266.69

The color red shows a decrease for that year.

North-Eastern Slope of Metropolitan Sierras Chicas

This sub-region has the oldest and largest area affected by the invasion. The main invasion outbreaks in 2002 surround Río Ceballos (especially on the southeastern slope of the Ñu Porá hill), Los Quebrachitos Natural Reserve, La Quebrada Dam, Villa Los Altos and La Granja and Agua de Oro peri urban areas (Figure 7).

It is worth noting that, although in 2002 the urbanized areas there were not very extensive (compared to, e. g., Northern Punilla Valley), areas covered by very leafy perennial vegetation already had a significant extension, and expanded rapidly, forming extensive stands and displacing native forest and grasslands. Those stands eventually merged with each other, forming continuous areas of perennial forest, spreading away from populated centers, in highly inaccessible areas.

However, the affected area seems to decrease between 2010-2020 (Table 4).

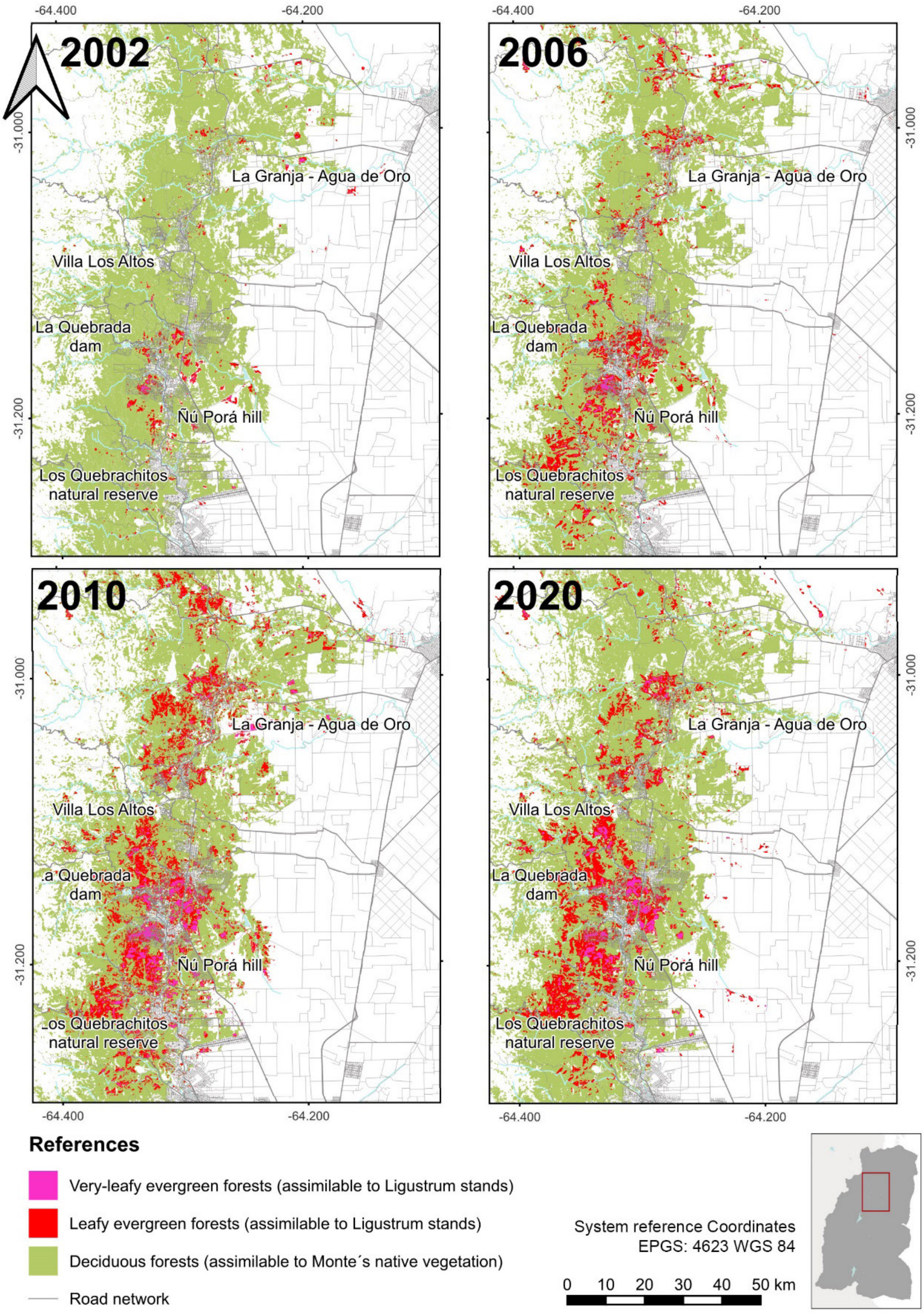

Figure 7. Resulting Land Cover Maps for the North-Eastern Slope of Metropolitan Sierras Chicas

Source: the author's, and data from institutional sources: jurisdiction limits, national road network and urban areas retrieved from Instituto Geográfico Nacional WFS repository (may, 2024); hydrographic data, and phytogeographic regions retrieved from IDECOR WFS repository (may, 2024); Landsat 8 and 5imagery retrieved from USGS Earth Explorer online repository (may, 2022).

Northern Punilla Valley

This sub-region presents a late evolution of the process, since the major outbreaks were detected only in 2006 (Table 4); however, they multiplied rapidly between 2010 and 2020, when the affected area extended from Bialet Massé to beyond the northern limits of Villa Giardino (Figure 8).

There, the invasion outbreaks are also linked to urbanization, especially the most populated areas i. e. Cosquín and the Valle Hermoso-Villa Giardino conurbation. But unlike the previous sub-region, these stands have a linear pattern, following the water runoff lines on the western slope of Sierras Chicas, and they do not yet form continuous areas.

Besides that, this sub-region shows regular-shaped and compact patches covered by very leafy vegetation, suggesting the replacement of native forest with exotic perennial species for lumber production. One of them is located in El Guindo site, along the Piedras Grandes stream in an important archaeological site of Comechingonean culture, which shows a high degree of invasion since 2002. Another patch, which grew exponentially between 2010 and 2020, is located along Yuspe river; another one is upstream, expanding up to the Curnerio river (Figure 8). These patches should not be assimilated to *L. Ligustrum* stands without further visual confirmation.

La Defensa Natural Reserve in Malagueño City

This sub-region presents isolated stands between 2006-2010, which seem to be significantly reduced by 2020 (Figure 5), too small to be included in Table 4. They are relatively far from urbanized areas, where *L. lucidum* is introduced, and surrounded by crops, so it is very possible that those stands were felled to allow for agricultural exploitation.

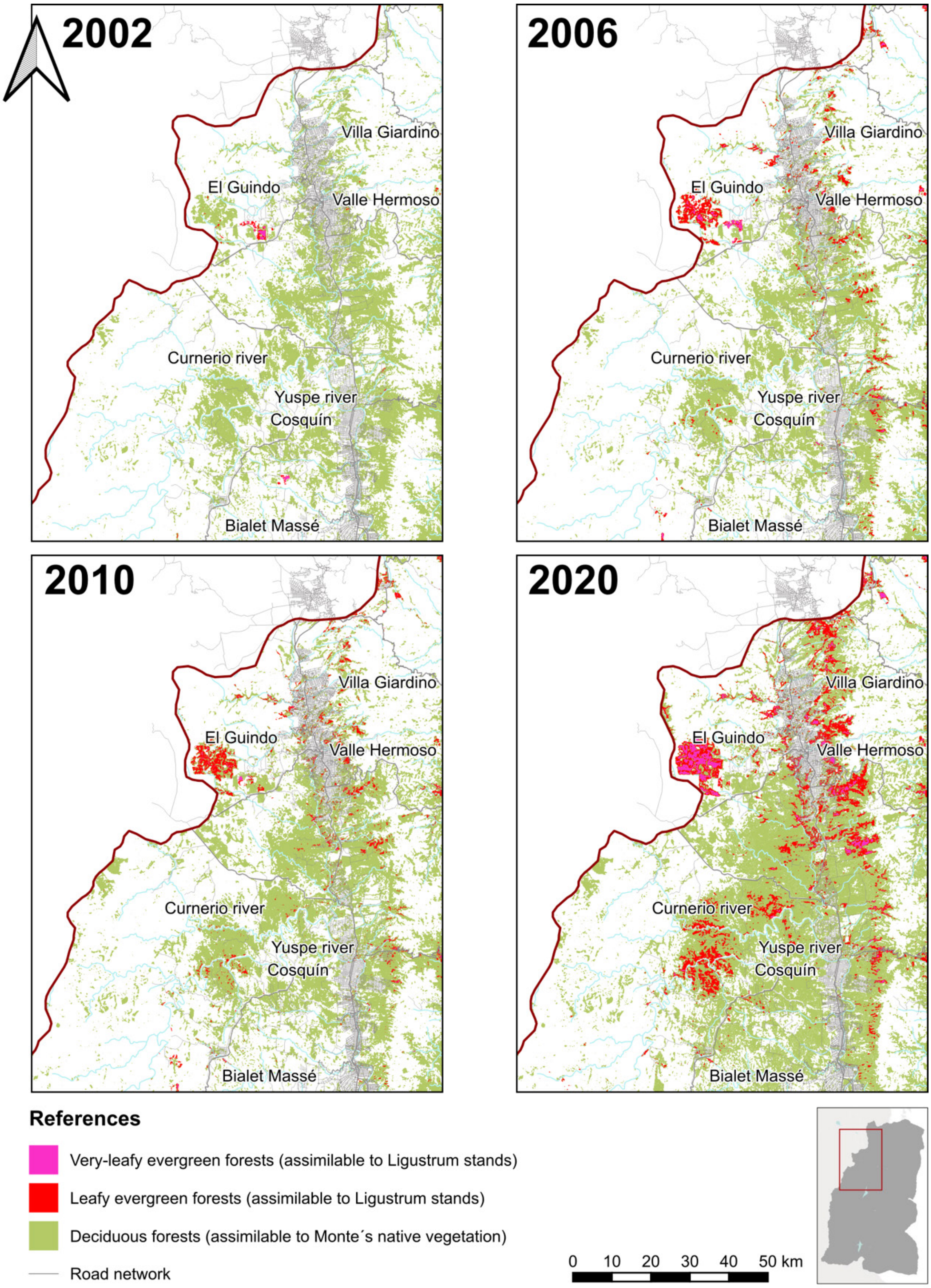

Figure 8. Resulting Land Cover Maps for Northern Punilla Valley

Source: the author's, and data from institutional sources: jurisdiction limits, national road network and urban areas retrieved from Instituto Geográfico Nacional WFS repository (may, 2024); hydrographic data, and phytogeographic regions retrieved from IDECOR WFS repository (may, 2024); Landsat 8 and 5 imagery retrieved from USGS Earth Explorer online repository (may, 2022).

Paravachasca Valley

Despite being the sub-region with the largest affected area, the perennial vegetation does not form a continuous patch, but extends in a more dispersed pattern than in Sierras Chicas and Punilla Valley. There, I distinguish three sub-zones (Figure 9):

The first, around La Cumbrecita town, with perennial vegetation stands detected as early as 2002, which increased in foliage during the analyzed period, but did not begin to spread until 2010. This pattern corresponds to the regular patches assimilable to the replacement of native vegetation with exotic perennial species for logging.

The second sub-zone is in the vicinity of Los Molinos Dam. It has extended significantly since 2006, occupying suburban areas of native forest almost entirely, although it still does not have very dense foliage.

The third sub-zone, located South of La Bolsa and Anisacate towns and nearby Los Molinos and El Carmen settlements, also has extended between 2006 and 2020, occupying the suburban slopes. However, it has not generated dense stands either.

Another point to highlight is the relative absence of affected areas around Alta Gracia, the largest and most populated city in this sub-zone; that requires a particular study that incorporates other variables into the analysis, such as local policies and urbanization practices.

Discussion

On the one hand, the methodological strategy employed allowed me to reinforce the hypotheses raised by previous research on *L. lucidum*: Although the factors that favor and stimulate the invasion of *L. lucidum* are multiple and depend on the local environment, the origin is unequivocally its introduction as an ornamental species in urban and suburban areas (following i. e. Gavier-Pizarro et al., 2012); and *L. Ligustrum* dispersion is facilitated by human practices that generate bare soil in peri-urban areas.

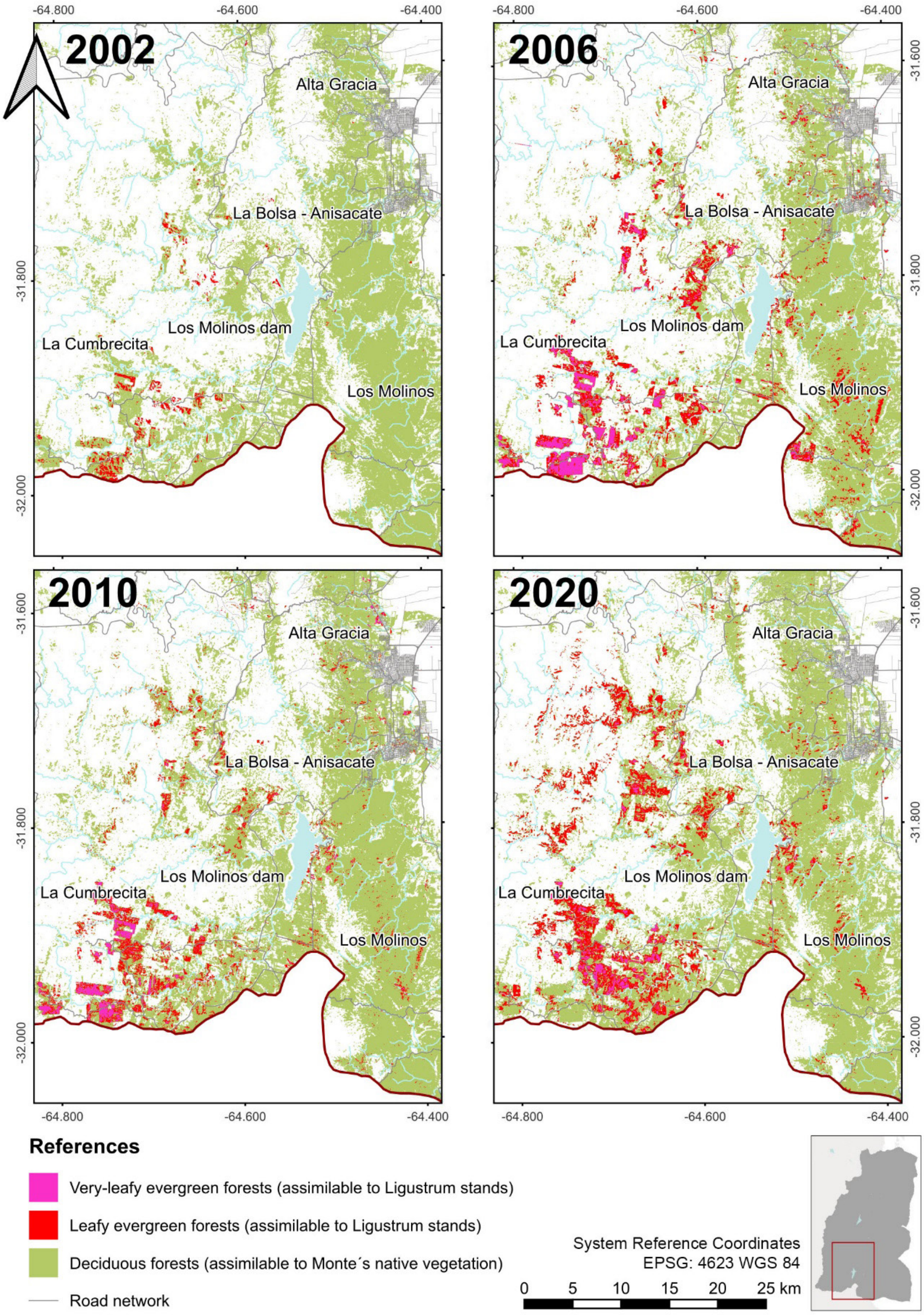

Figure 9. Resulting Land Cover Maps for Paravachasca Valley

Source: the author's, and data from institutional sources: jurisdiction limits, national road network and urban areas retrieved from Instituto Geográfico Nacional WFS repository (may, 2024); hydrographic data, and phytogeographic regions retrieved from IDECOR WFS repository (may, 2024); Landsat 8 and 5 imagery retrieved from USGS Earth Explorer online repository (may, 2022).

Moreover, forest fires recurrences and rainfall regimes could be decisive factors for this phenomenon. Metropolitan Sierras Chicas are seriously affected by forest fires, especially in the dry season (VERZINO et al., 2005). The tendency to invade humid spaces could mean an advantage for *L. lucidum* stands, since it also means additional protection: Although there is evidence that *L. lucidum* is affected by fire to a greater extent than native vegetation (TOLOCKA, 2017), the stands located near watercourses keep the substrate moist, which slows down or prevents herbs and grass from conducting the flames to the upper strata of vegetation, protecting the individuals of *L. lucidum*. The need of reliable data on the relation between *L. lucidum*, forest fires and hydrological cycles should be further analyzed, both for ecologic remediation projects and water reservoirs sustainable management in this semi-arid region (CHIAVASA et al., 2013).

On the other hand, the data obtained also allowed me to recognize critical lines for future research:

One such line could be to study the increasingly intense feedback loop that all the factors that favor *L. lucidum* invasion seem to generate in this region: *L. lucidum* invasion is documented since the end of the 19th century in the northeast slope of Sierras Chicas, where deforestation rates are among the highest in Latin America. Besides that, demographic statistics indicate that this region has the highest rates of population and urbanized area growth in the RMCba for the last twenty years. Urbanization not only results in more deforestation for future urbanization, but also causes grazing fields to be abandoned (moving livestock further away from urban areas), resulting in even more peri-urban bare soil lands that favor new *L. Ligustrum* outbreaks[8].

A second line should consider the fact that, despite all the evidence, there are few local laws that restrict *L. lucidum* (or other exotics) in sidewalks and gardens; protected areas are scarce and legislation restricting these practices has limited success (CABIDO & ZAK 1999, cited in GAVIER-PIZARRO et al., 2004; BARCHUK et al., 2010).

A third point should consider that, when planning local management strategies to counter *L. lucidum* invasion, it is necessary to study each

8 There is empirical evidence -still to be corroborated- that cattle could contain the advance of *L. lucidum* in grazing areas by feeding on its soft shoots, which lack the thorns that native vegetation usually has.

sub-zone individually, articulating the specific conditions with the factors common to all the areas invaded by *L. lucidum*. In this line are the *L. lucidum* invasion patterns in the northeast slope (extensive stands that merge with each other generating large areas covered almost exclusively with *L. lucidum*), the patterns detected in Punilla Valley (mainly fragmented stands that extend along streams and rivers), and the regular patches of perennial vegetation located there and in Paravachasca Valley, where it is a common practice to replace native forest with timber species (such as *Pinus elliotii*).[9]

Considering all the above, the methodology allowed me to show the true scope of the invasion and highlight the urgency of policies to manage the problem at a regional level: In a metropolitan region with near 2 million inhabitants, that host to contra-urbanization processes that accelerate sub-urbanization rates in metropolitan Sierras Chicas (BOCCOLINI, 2021), this invasion -even though not explicitly planned- is a large-scale landscape reorganization process, with great impact on its inhabitants´ quality of life and long-term sustainable development.

Thus, one of the main contributions of this research is to systematize data on the entire Metropolitan Sierras Chicas in Córdoba, contrast them with hypotheses validated in local field studies and compile this information as part of the background for urban and regional planning.

Added to that, the easy accessibility and economy of resources required to generate this amount of data prove to be of great value for prevention, management and control of the *L. lucidum* invasion in this critical scenario. Although the information requires subsequent verification in the field, it facilitates early stages of planning and management, and allows to project field work in affected areas with a greater level of detail, optimizing human, technical and material resources.

Indeed, this methodology, as well as the obtained data, could work as a starting point, both for future research on the invasion of *L. lucidum* in metropolitan Sierras Chicas, and for those seeking to investigate similar regions. Thus, just as my research relies on local studies to

9 The presence of this species could also explain why Paravachasca is the only area where perennial vegetation is located higher than 1,000 m above sea level, since *L. lucidum* seems to stop its advance at 950 m in other sub-zones.

achieve a mapping on a larger scale and a longer temporal scope, this methodology can be easily replicated in other research projects (adjusting it to different socio-environmental contexts) on ecosystems with predominantly deciduous native vegetation affected by *L. lucidum*.

Last but not least, the results obtained are essential to disseminate sound information on the magnitude of the problem in political spheres and in the community: The generated cartography, which is easy to read and interpret, made it easier to obtain the commitment and willingness to act of local stakeholders and to deepen the results obtained at the local scale, and to finance research projects to be developed in the medium term: In a region seriously affected by accelerated urbanization, biodiversity loss, desertification and climate change, these cartographies on the emergency are an essential instrument for political agents and organizations committed to management and control of one of the most urgent problems of metropolitan Sierras Chicas today.

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