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# A Diachronic Geospatial Analysis of Cochineal-Induced Degradation of Prickly Pear (*Opuntia* spp.) in the Rhamna Province (Morocco): An Innovative Framework using Remote Sensing and GIS

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**Abstract**

Prickly pear (Opuntia spp.) is more than a conventional crop in Morocco; it serves as a keystone species sustaining rural livelihoods and enhancing ecosystem resilience. Owing to its remarkable tolerance to drought, poor soils, and heat stress, Opuntia has become integral to sustainable agriculture, land restoration, and national programs such as the Green Morocco Plan aimed at combating desertification. However, this success has been critically threatened by the rapid spread of the cochineal (Dactylopius opuntiae), a devastating pest that has decimated cactus plantations nationwide. To quantify the magnitude and spatial extent of this invasion, we performed a high-resolution geospatial analysis in Rhamna Province—one of Morocco's main cactus-producing regions—between 2014 and 2020. A grid-based visual interpretation method was applied to sub-meter Google Earth imagery, supported by 3,305 ground control points and GIS post-processing. Cactus cover declined sharply from 23,326 ha in 2014 to only 267 ha in 2020 (−98.9%), with remaining stands highly fragmented across roughly ten communes. The corresponding annual revenue loss, estimated from fruit and biomass conversion factors and farm-gate prices, reached approximately 230.6 million MAD (≈ 23.8 million USD). Accuracy assessment based on confusion matrices yielded high overall agreement (overall accuracy and Cohen's κ with 95% confidence intervals), confirming the reliability of the results. These spatially explicit, accuracy-controlled findings reveal the dramatic contraction of Opuntia cultivation and provide a quantitative baseline for recovery monitoring. The study highlights the urgent need for coordinated pest management and deployment of resistant genotypes, while demonstrating the value of expert-guided visual interpretation for monitoring bio-invasions in fragmented arid agroecosystems where conventional spectral classification often fails to capture fine-scale dynamics.

**Keywords:** *Opuntia spp.*, *Dactylopius opuntiae*, invasive pest, GIS, arid agro-ecosystems, bioinvasion monitoring, land use dynamics, ecological monitoring

## 1. INTRODUCTION

Prickly pear (*Opuntia spp.*) plays a dual role in Morocco as a drought-resilient crop and as a source of food, fodder, and income for rural households. Its cladodes and fruits are used in human nutrition, animal feeding, and cosmetic industries, while its ecological functions include soil stabilization and biodiversity support. These multiple services explain why the crop has been promoted under national strategies such as the Green Morocco Plan (GMP) [1]. The invasive cochineal insect,

*Dactylopius opuntiae*, is a sap-sucking hemipteran that feeds exclusively on *Opuntia* species. It causes rapid tissue necrosis, pad desiccation, and eventually plant death, leading to large-scale field collapse within months. Since its introduction in Morocco in 2014, outbreaks have spread rapidly across major cactus-growing provinces, including Rhamna Province. Similar devastation has been reported in Mexico, Ethiopia, and India, highlighting the global threat posed by this pest to arid agro-ecosystems. Its biology parthenogenetic reproduction, high dispersal capacity, and absence of natural predators explains its destructive impact and underscores the urgent need for monitoring and management, where the plant was initially introduced for soil erosion control, fencing, and livestock feed. In the years following the GMP's implementation, the cactus sector flourished, with the planted area expanding significantly and production increasing [2]. However, while the cactus sector was on an upward trajectory, it faced a severe setback with the introduction of the invasive cochineal insect (*D. opuntiae*) in 2014.
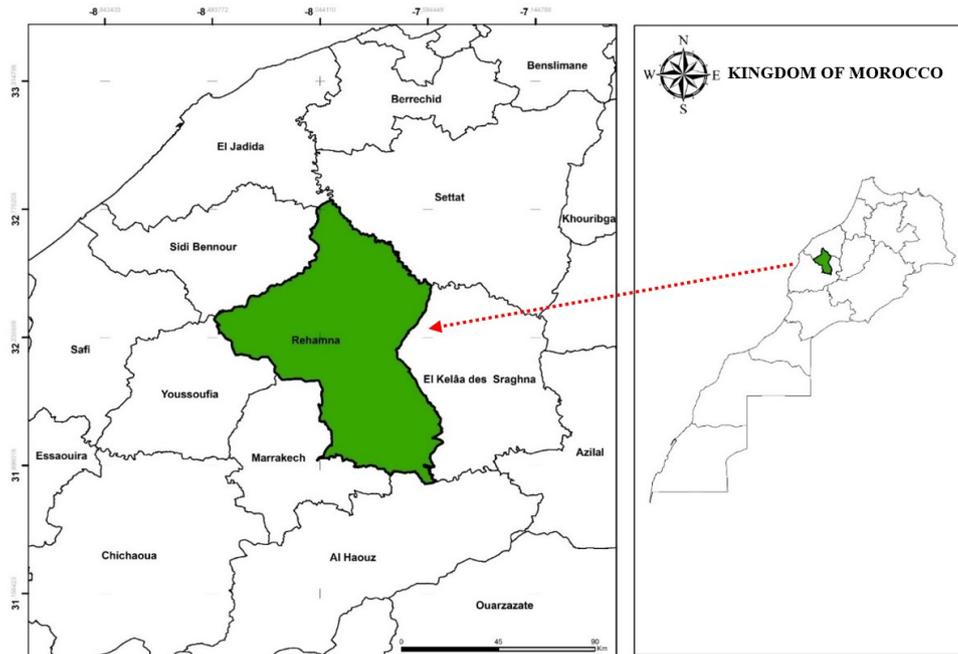
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**Figure 1.** Geographic situation of Rhamna Province-Morocco.

This pest has caused significant damage to cactus production in, Doukkala plain, Morocco, and has rapidly spread to other key cactus-growing areas nationwide [3]-[5]. The cochineal insect infestation has had a devastating impact on both cactus fruits and cladodes in Morocco, severely affecting the livelihoods of farmers and jeopardizing the long-term sustainability of the cactus value chain. In particular, the Rhamna region, historically a key producer of cactus, has experienced considerable losses in cactus yield. Prior to the introduction of the cochineal pest, Rhamna was producing approximately 265 000 tons of cactus fruit annually [6]. The region was recognized for its extensive cactus plantations, which produced a diverse range of products, including fresh fruit, fodder, and various value-added items such as cactus jam, juice and seed-oil. The cactus was originally introduced to the region for its ability to aid in soil restoration and conservation. Specifically, spined prickly-pear known locally as "Dribina," used as natural fencing for agricultural parcels, and non-spiny ecotypes "Rhmania" and "Haddaouia" were primarily used for human consumption and livestock feed [7]. This cultivation decision was motivated by the plant's relatively low water requirements and minimal maintenance needs. Currently, the area dedicated to cactus cultivation in Rhamna spans approximately 40,000 hectares, with regional agricultural plans forecasting an annual production of 400,000 tons [8][9].

The expansion of cactus production and the subsequent valorization of both fruits and cladodes have led to the development of several specialized products in the region. These include processed items such as cactus fillets made from younger, non-lignified cladodes, animal feed derived from older, lignified cladodes, fresh large-caliber fruits, and transformed products like cactus jam and juice from smaller fruits. Additionally, the seeds of the cactus are used for the extraction of cactus oil. Approximately 80% of this production is sold in nearby major cities, further contributing to the region's economic activity [10]. However, despite the significant efforts to promote cactus cultivation within Morocco's rural development framework, the infestation of the cochineal pest has undermined these initiatives. The widespread damage caused by this pest has led to a sharp decline in cactus production, further restricting socio-economic opportunities in the region. The infestation has exacerbated existing challenges, hindering progress and limiting the potential benefits of cactus cultivation for local communities [11].

To date, no scientific study has provided a spatially explicit and scientifically validated assessment of the impact of *D. opuntiae* infestations

in Morocco. Therefore, to address the challenges posed by the cochineal insect infestation and to assess the potential for cactus cultivation in the affected regions, it is imperative to first understand the scope and severity of the damage caused. In this context, remote sensing and geographic information systems (GIS) have become necessary tools for monitoring land use and vegetation dynamics [12]. These tools provide a robust framework for evaluating land degradation and tracking changes in vegetation cover in response to pest infestations, offering an efficient means of large-scale monitoring. The use of spatial remote sensing in studying the degradation of natural resources has gained significant attention lately, particularly in the fields of land use change and agricultural statistics [12]. Vegetation cover evolution or regression is typically managed through a variety of approaches, which facilitate the detection and monitoring of changes in land cover. These changes often result in shifts from one land use type to another, leading to a reduction in land cover density, loss of biodiversity, and overall environmental degradation [13].

The dynamic nature of these processes can be effectively assessed using various methods, which can be further enhanced through complementary analytical processes to yield more precise results.

Such methods are broadly categorized into regular inventory techniques, diachronic analysis, and Food and Agriculture Organization of the United Nations (FAO) classification methods [14][15]. Remote sensing and GIS, through their integrated capabilities, play an increasingly pivotal role in operational planning and decision-making processes, particularly in emergency and risk management operations. The integration of satellite imagery and GIS tools has empowered specialists in cartography, land resources, and environmental management to effectively utilize remote sensing data for a wide range of applications, including thematic cartography, geological and hydrological studies, land use inventory, and environmental monitoring. In particular, visual imagery interpretation has emerged as an efficient and cost-effective approach to extracting valuable information from satellite images. This process involves the detection, delineation, and identification of features within an image, followed by an evaluation of their significance in the context of the land cover or vegetation being studied. Several image parameters, including color, texture, shape, size, structure, shadow, and temporal variations, play a critical role in the accuracy and reliability of the interpretation process [16]. These parameters are influenced by both the physical
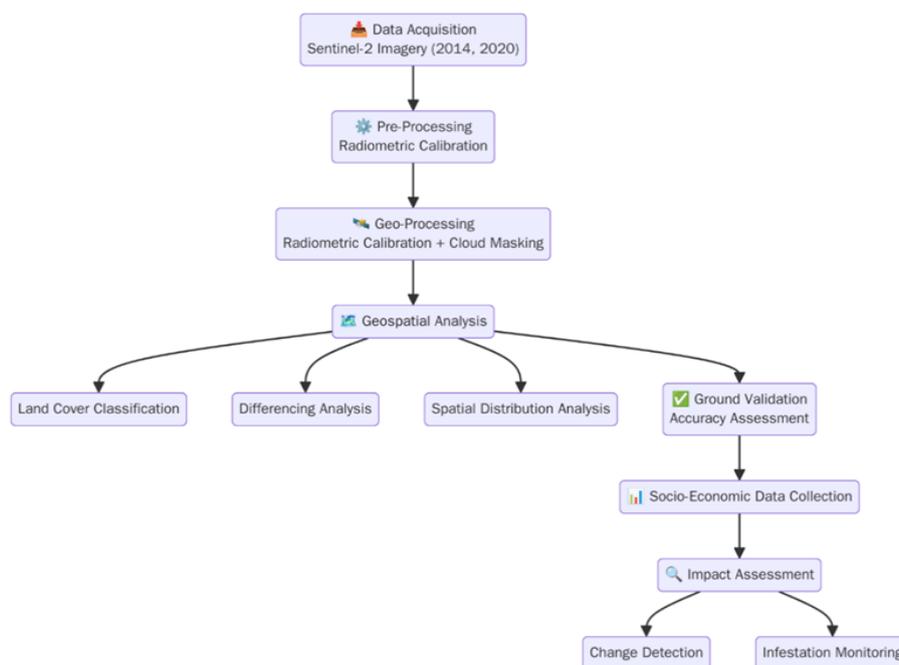


**Figure 2.** The methodological steps followed in this study to assess the impact of cochineal infestation on *Opuntia* spp.
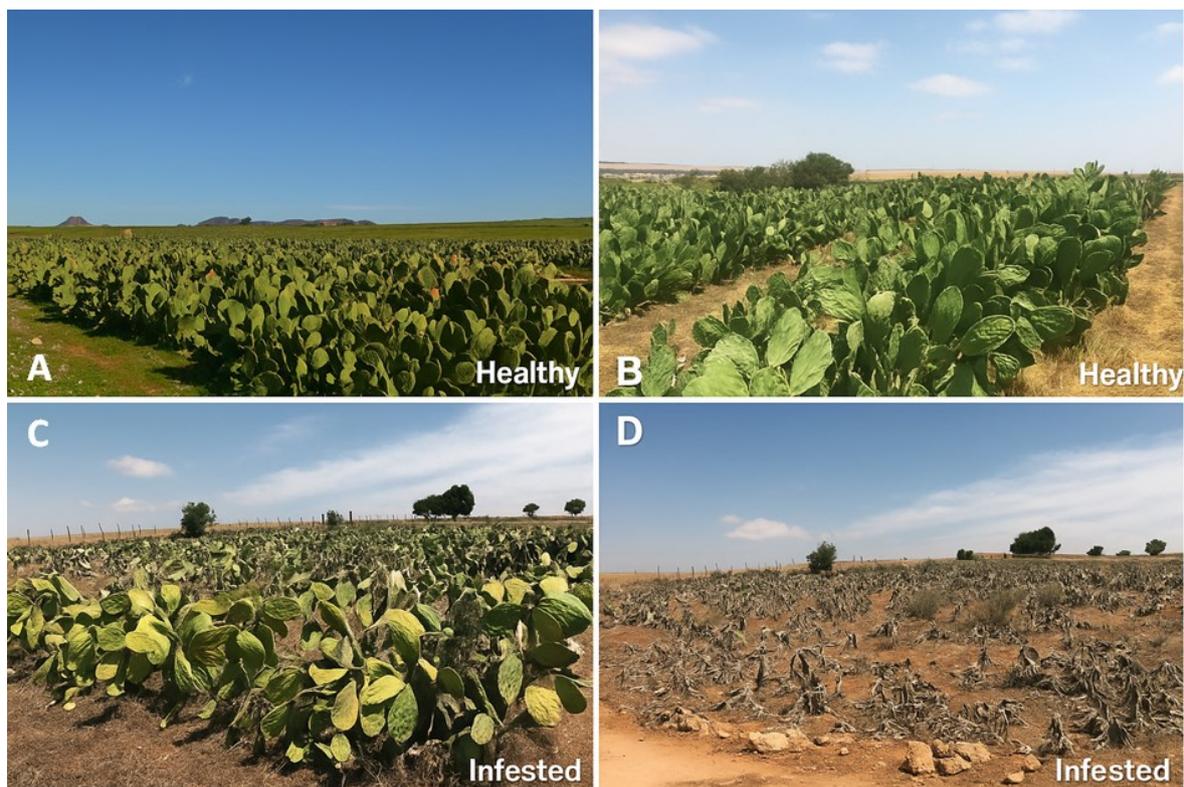
**Figure 3.** Photos showing the comparative visual assessment of prickly pear (Opuntia spp.) fields in Rhamna Province. (A) and (B): Healthy cactus plantations showing vigorous and uniform green pads with no signs of pest infestation. (C) and (D): Infested cactus plantations exhibiting advanced symptoms of Dactylopius opuntiae infestation, including yellowing, wilting, and near-total pad collapse.

characteristics of the objects being studied and the temporal changes that occur, providing a comprehensive basis for understanding and monitoring vegetation health and land use transitions [17][18].

This study adopts a visual approach based on high-resolution imagery combined with field validation, an approach particularly well suited to fragmented agro-ecosystems. Unlike Normalized Difference Vegetation Index (NDVI)-based methods, this protocol can better capture edge effects and fine-scale heterogeneity. This methodological framework is designed to generate reproducible, accuracy-audited maps of cactus degradation that are directly applicable for restoration planning and policy decisions. The main scientific objective of this study is to introduce a novel geospatial methodology based on high-resolution visual interpretation and field validation for assessing vegetation loss caused by cochineal infestation. Unlike traditional approaches, this method enables fine-scale spatial quantification in fragmented agro-ecosystems, offering new insights into degradation dynamics in arid environments. Specifically, this research addressed the following questions: (i) what was the spatial extent of cactus loss in Rhamna between 2014 and 2020? (ii) how accurate and reliable is a visual/manual interpretation approach compared to automated NDVI/ Object-Based Image Analysis (OBIA) methods?, and (iii) what are the associated economic losses, and how do they vary across communes? Our working hypothesis was that accuracy-audited visual interpretation, supported by field validation, provides superior detection of fragmented cactus collapse in arid landscapes.

## 2. MATERIALS AND METHODS

### 2.1. Study Area

Rhamna Province located in West-Central Morocco (Fig. 1) of 5,877 km², a predominantly flat-to-valley terrain with an average elevation of 445 m and an arid Mediterranean climate (less than 200 mm/year) [19], is one of the areas known for its cactus cultivation for fruit, cladodes, and added

value subproducts such as cactus-seed oil, juice, jam, and silage in addition to traditional medicinal use. It contains a variety of interesting cactus genotypes, making it a promising zone for cactus production. This newly created province has benefited from an important investment to develop the cactus crop value chain given its important role in the local farmers' economy. However, all the 23 the territorial rural communes of the Rhamna Province has been invaded by the cochineal (*D. opuntiae*) attacks of the country, making it an important area for our study. Therefore, selection of this province enables a focused investigation of spatial degradation dynamics over time in one of Morocco's most impacted provinces, thereby serving as a representative case study for arid agro-ecosystems threatened by biological invasions. Visual interpretation of satellite imagery can be a highly effective technique for identifying changes in vegetation cover, but it can be time-consuming and labor-intensive. Therefore, we decided to focus our study on a specific area, justified by the high density of cactus cover and the severity of the cochineal infestations.

## 2.2. Tools and Approach

ArcGIS software by ESRI is utilized for structuring and organizing digital cartographic data, as well as creating thematic maps. Google Earth, a Google software, offers a virtual world map with satellite imagery for visual analysis. It allows zooming in on specific locations and provides features for measuring distances and areas. In this study, Google Earth was used to visually analyze satellite imagery and create digital layers for cacti distribution mapping [20]. The methodology of this study employs a scientifically novel approach that integrates high-resolution visual interpretation, grid-based field validation, and GIS modelling to assess the impact of cochineal infestation on cactus plantations. Unlike traditional automated metho contemporary and historical satellite imagery are compared to identify areas where previously thriving cacti have deteriorated. Remote sensing techniques such as NDVI, automated classification, and OBIA quantify temporal alterations. However, limitations in automated methods necessitate visual interpretation, especially in discerning variations in cacti coverage due to spatial resolution constraints. Visual interpretation involves manual analysis, considering factors like cacti morphology and distribution to identify infestation-affected areas. Despite being labour-
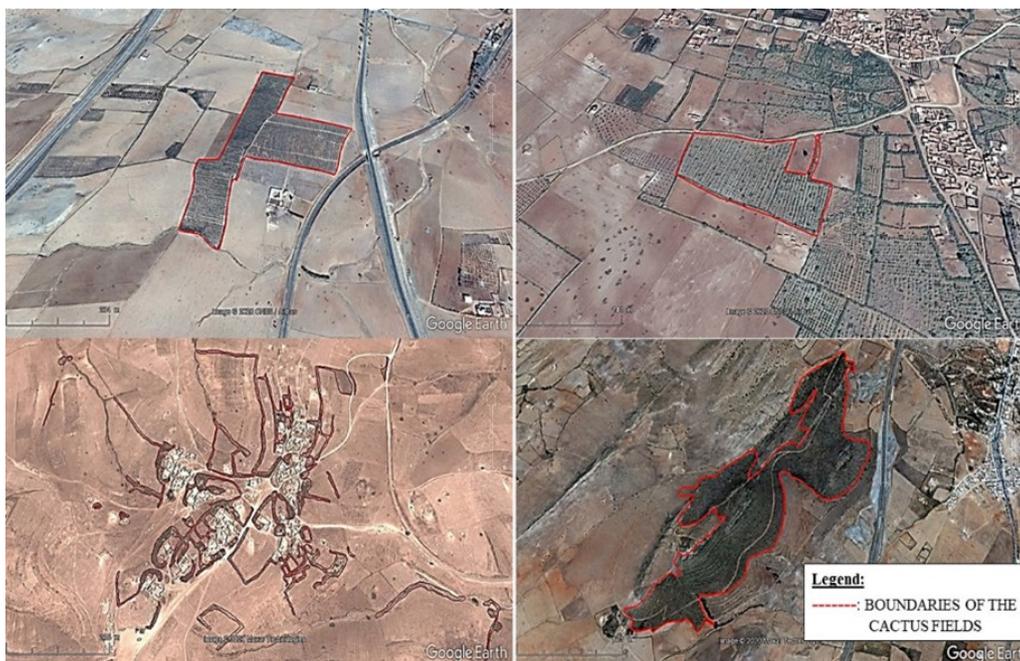


**Figure 4.** Digitalization of cactus plantations in the Rhamna Province during the year 2014. The images illustrate different vegetation types; cacti are identified by their distinctive green clusters with regular spatial distribution.
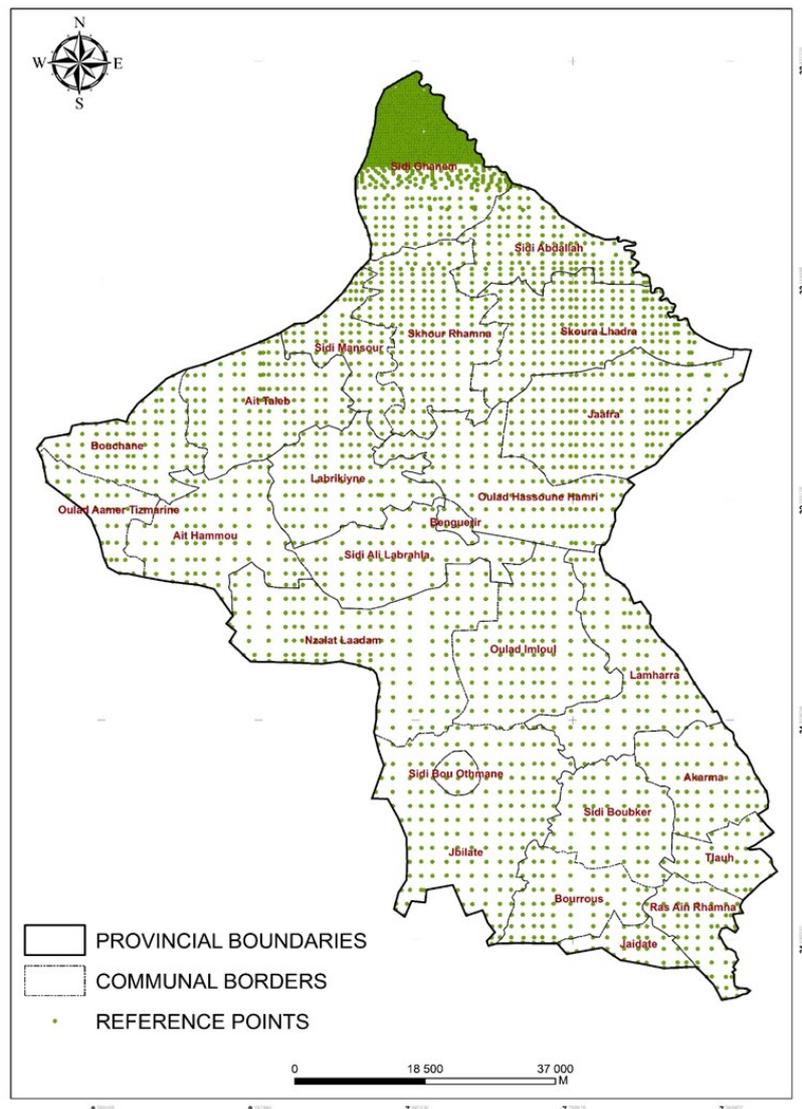
**Figure 5.** Reference points distribution map.

intensive, visual interpretation provides a nuanced understanding of vegetation dynamics [21].

The study in the Rhamna Province underwent three phases: satellite imagery selection, visual interpretation, and reconstruction, mapping, and analysis. Using Google Earth, high-resolution mono-spectral imagery was chosen based on reports of cochineal infestation. Visual interpretation involved digital delineation of cactus surfaces, categorizing plantation density, and ensuring comprehensive coverage with reference points. Data underwent analysis in GIS software, generating distribution maps, illustrating cactus surface evolution, and providing area statistics. Correlating with parameters related to vegetation biomass and forage plant units allowed for assessment of socio-economic damages from

cactus cultivation in Rhamna [22], this hybrid methodological approach constitutes one of the core scientific contributions of this study. By prioritizing human-guided visual analysis over standard automated classifications, it addresses a critical gap in remote sensing applications for pest -specific vegetation monitoring. This novelty enables accurate spatial quantification of biological damage, particularly in low-data, arid environments where cochineal impact patterns are heterogeneous [16].

### 2.3. Steps Followed in This Study to Assess the Impact of Cochineal Infestation on Opuntia spp

To ensure the reliability of the obtained results, field visits were conducted to validate the delineated parcels and the accuracy of the

interpretations. The methodological approach (Fig. 2) followed for the analysis included the following steps; acquisition of satellite imagery. High-resolution satellite images covering different periods, including pre- and post-cochineal infestation, were obtained to assess temporal changes in cactus plantations. For preprocessing of imagery, the acquired images were subjected to preprocessing steps to correct potential distortions and artifacts, including atmospheric and geometric corrections, ensuring accurate spatial and spectral analyses. We used very high-resolution Google Earth imagery (0.3–0.6 m) acquired in cloud-free scenes from 2014 and 2020. All images were orthorectified by the provider, and standard atmospheric corrections were applied, followed by histogram matching to harmonize radiometric properties between years.

For familiarization with the study area, a preliminary analysis was conducted using field observations and existing literature to characterize the spectral signatures of healthy and infested cacti, facilitating accurate interpretation of the imagery. For comparative analysis of temporal data, the processed satellite images from different periods were analyzed using visual interpretation software, allowing a side-by-side comparison to detect changes in plant density and health status. For ground truth validation, the interpreted results were validated through extensive field surveys, using a grid-based reference system with 3,305 control points. This approach ensured comprehensive spatial coverage and high accuracy in identifying fine-scale cactus degradation. The validation results confirm a high correlation between satellite interpretations and actual field conditions,
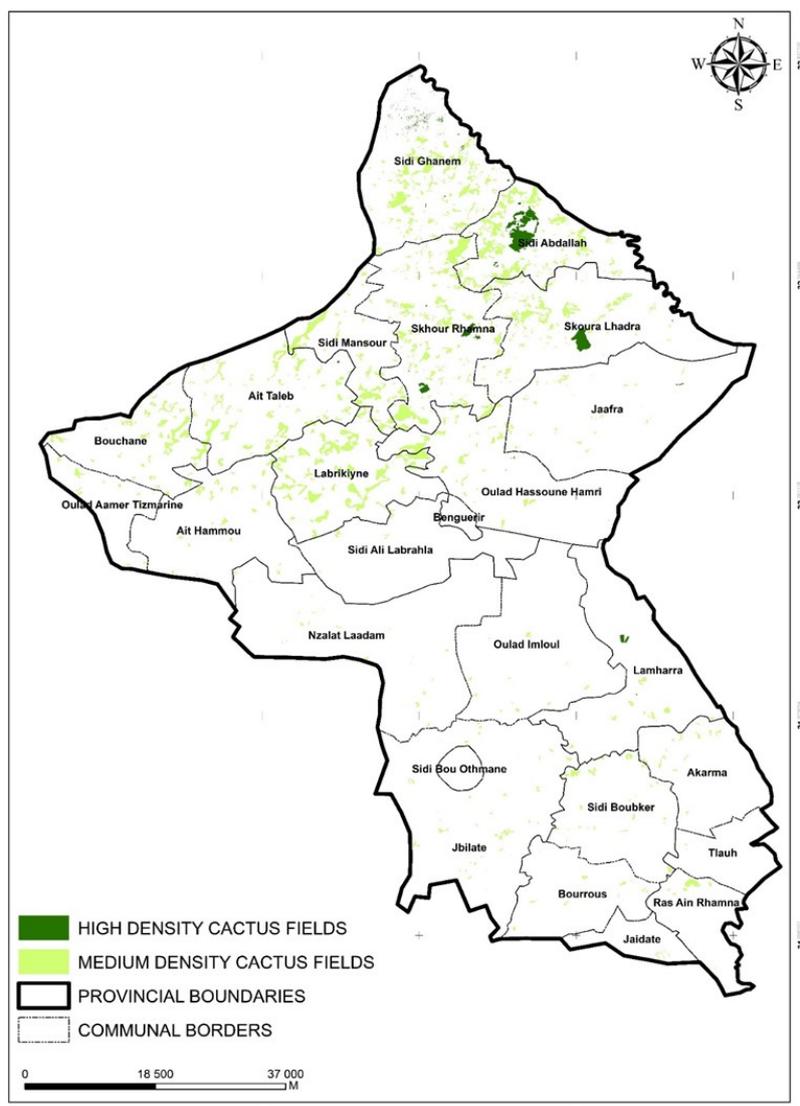


**Figure 6.** Spatial and density distribution of cactus stands in 2014 in Rhamna Province-Morocco.
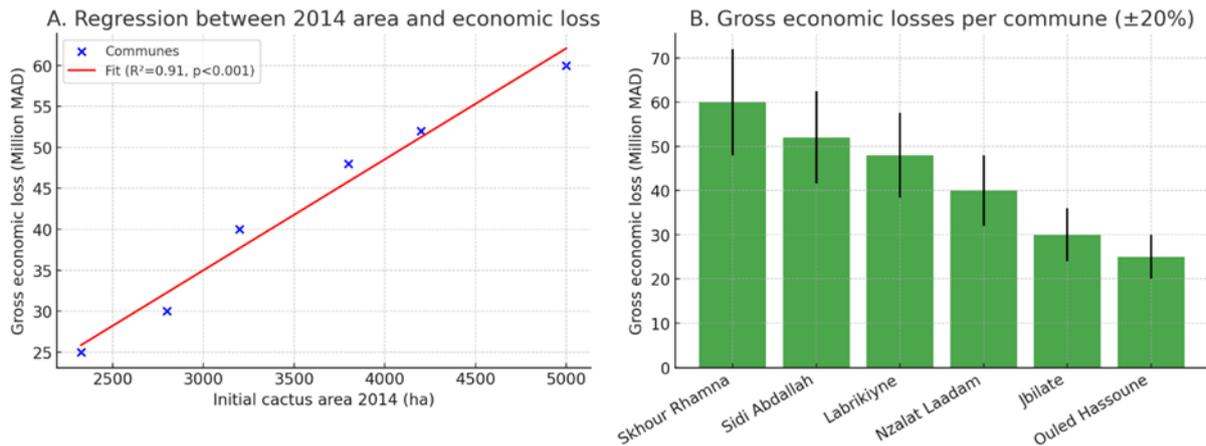
**Figure 7.** Relationship between initial cactus area (2014) and commune-level economic losses. (A) Linear regression between 2014 area (ha) and gross economic loss (million MAD) (R² = 0.91, p < 0.001). (B) Gross economic losses per commune (million MAD), with error bars representing ±20% variation in yield and price assumptions.

supporting the reliability of the visual interpretation method. Additional validation was performed using other reliable sources, such as historical records and previous studies. For field validation and observations, field surveys were conducted across selected sites in the Rhamna region in addition to satellite-based analysis. Photographic evidence was collected to illustrate the visible degradation of cactus plantations and validate remote sensing observations. Fig. 3 shows examples of cactus fields heavily infested by cochineal insects, resulting in the near-total collapse of vegetation cover.

### 2.4. The Main Steps for Analysis of Actus Evolution

The analysis of cactus area evolution in the Rhamna province was conducted in three main steps.

### 2.4.1. Selection and Identification of Satellite Imagery

Satellite imagery was obtained and analyzed using the Google Earth Pro platform (https://www.google.com/earth/versions/) was used for image acquisition and visual interpretation, allowing direct access to high-resolution temporal imagery critical for mapping cactus field evolution. The visual interpretation was conducted by a single trained examiner to ensure consistency across the entire dataset. Although no formal inter-observer reliability test was performed, the interpretation was systematically cross-checked against 3,305 ground control points, which provided independent validation of mapping accuracy. Software platform, which provides "open-source" mono-spectral real-color imagery with very high spatial resolution, facilitating straightforward interpretation through visual inspection. The selection of imagery dates was guided by a thorough analysis of the studied phenomenon and the species under investigation. As the first reports of cochineal infestation in the Rhamna Province date back to 2015, the year 2014 was selected as the reference period for evaluating the spatiotemporal evolution of cactus distribution in the region. The choice of 2014 as the baseline year is supported by national pest surveillance records which confirm the absence of cochineal infestations prior to this date in the Rhamna region. This year also coincides with peak cactus plantation development, offering a reliable reference point for diachronic analysis. Furthermore, seasonal variation was considered when selecting imagery to ensure the accuracy of interpretation. Summer imagery was specifically chosen to minimize potential confusion with other vegetation types, such as seasonal crops, and to enhance the clear identification of cactus plantations in the landscape [23].

### 2.4.2. Visual Interpretation of Satellite Imagery

During this phase, the cactus-covered areas were accurately delineated by converting the data layers

into a polygonal format through digitalization. The identification of the cacti in the satellite imagery was primarily based on several key features: the distinctive color patterns, the unique structural characteristics, the regularity in their spatial distribution, and their size (Fig 4). These visual attributes played a crucial role in distinguishing the cacti from surrounding vegetation, enabling precise mapping of their distribution throughout the study area [24]. Based on the visual density and spatial arrangement of the plants within the plot, the cactus fields were categorized according to their distribution and representatively within the parcel. The delineation of these fields for the selected years (2014 and 2020) was carried out using Google Earth software, which provides standardized digital imagery in the Keyhole Markup Language Zipped file (KMZ) format, easily integrated into GIS platforms for further analysis. The plantation density was assessed by evaluating the extent of surface coverage, distinguishing between areas with low density and those with high density.

To enhance the precision of cactus field delimitation and ensure comprehensive coverage across the entire province, a grid system composed in total, 3,305 ground control points were generated using a systematic grid (300 × 300 m in areas with dense cactus cover and 900 × 900 m in less dense zones). This sampling density was selected to balance statistical robustness with feasibility of field verification. Based on binomial probability theory, a sample with more than 3,000 points allows estimation of accuracy with a margin of error of less than 2% at the 95% confidence level, even for relatively rare classes. The stratified grid ensured that all communes and density classes were proportionally represented, thereby reducing spatial bias in accuracy assessment [25]. The grid of reference points illustrated in Fig. 5 was systematically distributed across the same geographical area (shown in Fig. 3), ensuring complete coverage of the cactus fields identified during visual interpretation. Both figures pertain to the same study region, facilitating accurate temporal change analysis.

## 2.4.3. Reconstruction, Map Creation, and Temporal Change Analysis of Six Years (2014–2020)

In this phase, the digitized datasets were meticulously organized, analyzed, and interpreted within a GIS , all delineated cactus polygons were digitized and stored as ESRI shapefiles in vector format. The spatial reference used was WGS84 / UTM Zone 29N (EPSG:32629), which is appropriate for the geographic extent of Rhamna Province. GIS processing and statistical summaries were conducted in ArcGIS Pro 10.x, using tools such as "Clip," "Dissolve," and "Intersect" for spatial overlay, and the "Zonal Statistics" and "Summary Statistics" functions for area calculations and commune-level aggregation. Framework to produce a series of critical outputs that would help assess the dynamics of cactus cultivation over time. The key products of this analysis included maps depicting the distribution and location of cactus fields for both 2014 and 2020, providing a clear spatial representation of their spread across the region; cactus surface area evolution maps, illustrating changes in the extent of cactus fields over the selected periods, allowing for the identification of areas experiencing expansion or contraction; and density maps of cactus plantations, visualizing the intensity of cactus coverage across the study area and highlighting regions with varying levels of plantation density. Area statistics for each territorial unit for both years, derived through spatial analysis techniques such as layer superposition and intersection, which allowed for a precise quantification of cactus coverage on a per-unit basis. After the map

**Table 1.** Area analysis results of the distribution areas for cactus plantations by the types of planted fields in 2014.

| Density Classes | Planted Area (ha) |
|---|---|
| Cactus plantation (Medium density) | 21,199 |
| Cactus plantation (High density) | 2,127 |
| **Total** | **23,326** |

**Table 2.** The results of the distribution of Cactus planted areas by territorial communes in 2014.

| Territorial Communes | Plantation Density | Area (ha) | % Total |
|---|---|---|---|
| Skhour Rhamna | Medium-density cactus plantation | 3,339 | 14.3 |
| Labrikiyne | Medium-density cactus plantation | 3,062 | 13.1 |
| Sidi Abdallah | Medium-density cactus plantation | 2,646 | 11.3 |
| Sidi Ghanem | Medium-density cactus plantation | 2,501 | 10.7 |
| Ait Taleb | Medium-density cactus plantation | 1,797 | 7.7 |
| Skoura Lhadra | Medium-density cactus plantation | 1,504 | 6.4 |
| Sidi Mansour | Medium-density cactus plantation | 1,503 | 6.4 |
| Bouchane | Medium-density cactus plantation | 1,279 | 5.5 |
| Sidi Abdallah | High-density cactus plantation | 1,129 | 4.8 |
| Oulad Hassoune Hamri | Medium-density cactus plantation | 927 | 4.0 |
| Skoura Lhadra | High-density cactus plantation | 430 | 1.8 |
| Ait Hammou | Medium-density cactus plantation | 418 | 1.8 |
| Sidi Boubker | Medium-density cactus plantation | 362 | 1.6 |
| Jbilate | Medium-density cactus plantation | 329 | 1.4 |
| Skhour Rhamna | High-density cactus plantation | 294 | 1.3 |
| Jaafra | Medium-density actus plantation | 248 | 1.1 |
| Lamharra | Medium-density cactus plantation | 225 | 1.0 |
| Ras Ain Rhamna | Medium-density cactus plantation | 184 | 0.8 |
| Akarma | Medium-density cactus plantation | 179 | 0.8 |
| Sidi Ghanem | High-density cactus plantation | 176 | 0.8 |
| Oulad Aamer Tizmarine | Medium-density cactus plantation | 171 | 0.7 |
| Nzalat Laadam | Medium-density cactus plantation | 157 | 0.7 |
| Bourrous | Medium-density cactus plantation | 116 | 0.5 |
| Oulad Imloul | Medium-density cactus plantation | 116 | 0.5 |
| Sidi Ali Labrahla | Medium-density cactus plantation | 86 | 0.4 |
| Lamharra | High-density cactus plantation | 72 | 0.3 |
| Jaidate | Medium-density cactus plantation | 35 | 0.2 |
| Tlauh | Medium-density cactus plantation | 14 | 0.1 |
| Jaafra | High-density cactus plantation | 10 | 0.0 |
| Ait Taleb | High-density cactus plantation | 7 | 0.0 |
| Oulad Hassoune Hamri | High-density cactus plantation | 6 | 0.0 |
| Bouchane | High-density cactus plantation | 4 | 0.0 |
| **Total Planted Areas** | | **23,326** | **100.0** |

creation, the resultant spatial data were analyzed in relation to key environmental parameters, including vegetation biomass and forage plant unit distributions. This analysis enabled a deeper understanding of the socio-economic implications of cactus farming in the Rhamna Province, particularly concerning its effects on local agricultural productivity, land use changes, and potential socio-economic damages linked to the expansion of cactus cultivation in the examined region [26].

## 3. RESULTS AND DISCUSSIONS

### 3.1. Spatial and Density Distribution of Cactus Stands in 2014

Based on satellite imagery acquired in 2014 and a rigorous geospatial analysis involving systematic referencing and manual digitization of cactus cultivation zones, comprehensive distribution and density maps were produced to characterize the spatial organization of cactus stands across the study area (Fig. 6). The results highlight a pronounced heterogeneity in both the spatial extent and planting density of cactus fields at the provincial scale. In the northern sector particularly in the commune of Sidi Ghanem plantations are relatively small in surface area but exhibit high planting densities, indicative of intensive land use practices. Conversely, the central region is dominated by larger cultivation units, also displaying elevated planting densities, which may reflect a trend toward more commercial or mechanized cactus production systems in relatively fertile soils and favourable climate conditions (cooler temperatures with more than 180 mm/year). In the southern part of the province, both the extent and density of cactus plantations decline markedly as result of agroecological constraints such as shallow unfertile marginal soils and unfavourable climate conditions (low rainfall less than 150 mm/year and high spring and summer temperatures) causing therefore lower level of investment in cactus cultivation. This spatial variability underscores the influence of, land tenure patterns, and local agricultural practices in addition to the precited biophysical conditions on the development of cactus-based agro-ecosystems.
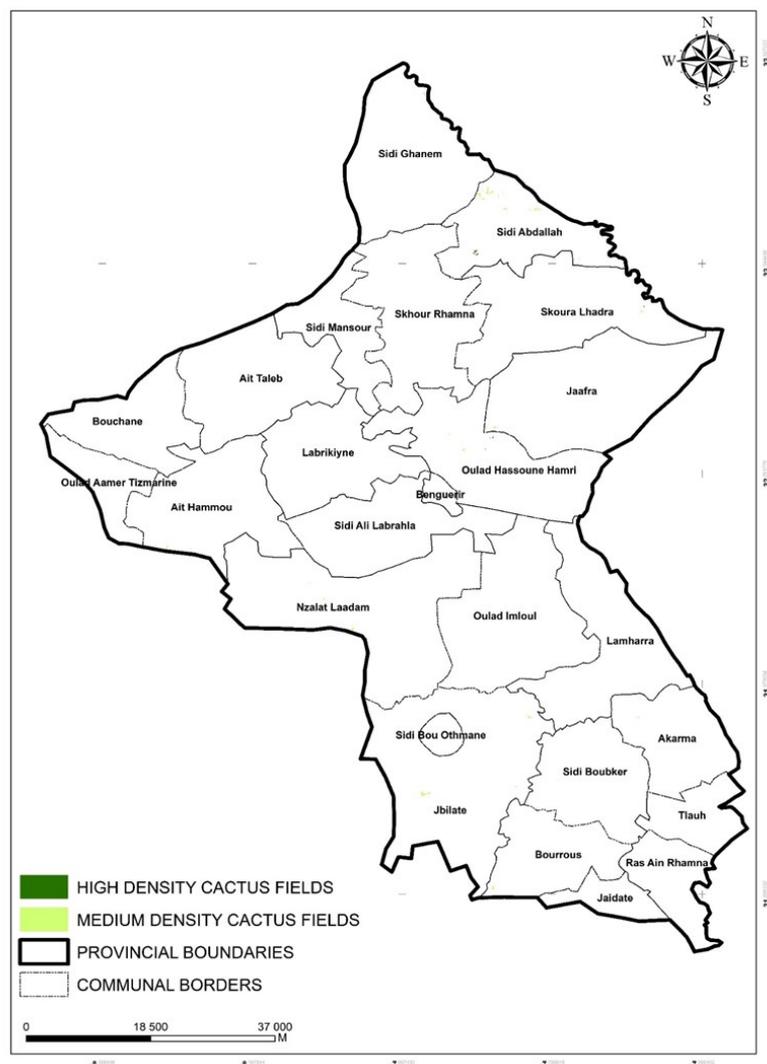


**Figure 8.** Spatial and density distribution of cactus stands in 2020 in Rhamna Province-Morocco.

**Table 3.** Area analysis results of the distribution areas for cactus plantations by the types of planted fields in 2020.

| Density Classes | Planted Area (ha) |
|---|---|
| Cactus plantation (Medium density) | 27 |
| Cactus plantation (High density) | 240 |
| **Total** | **267** |

To further illustrate the economic impact, we analyzed the relationship between the initial cultivated area (2014) and the gross economic losses per commune. The regression analysis showed a very strong correlation ($R^2 = 0.91$, $p < 0.001$), confirming that communes with larger cactus areas in 2014 experienced proportionally higher financial losses after the 2020 collapse (Fig.7.A). A complementary bar plot of gross economic losses by commune (Fig.7.B) highlights that the heaviest impacts occurred in communes such as Skhour Rhamna, Sidi Abdallah, Labrikiyne, while other communes with smaller initial areas reported lower losses. Error bars represent ±20% variation in yield and price assumptions, reflecting the sensitivity analysis described above.

### 3.2. Spatial Distribution and Extent of Cactus Plantations in 2014

The geometric analysis conducted allowed for an estimation of the approximate area covered by the cactus fields. Among the 1285 digitized polygons, the field sizes ranged from as small as 3 m² to as large as over 1000 ha, with the average size being 18 ha per cultivated field. This variation in field sizes is largely influenced by factors such as land ownership, the intended purpose of the plantation, and the nature of the agricultural practices employed. Based on the results of the geometric analysis, the total area dedicated to cactus cultivation was calculated, as summarized in Table 1, with a cumulative planted surface of 23,326 ha. This total area is further classified based on the degree of planting density, providing a clear view of the distribution and scale of cactus plantations across the region, we operationally defined cactus density classes based on the number of plants per hectare as observed during field surveys and high-resolution imagery interpretation. Low-density plantations were defined as lower than 100 plants/

ha, medium-density plantations as 100–300 plants/ha, and high-density plantations as higher than 300 plants/ha. These thresholds were established based on counts carried out in the field in plots.

### 3.3. Analysis of the Distribution of Cactus Fields in the Territorial Communes in 2014

By analyzing the geographical distribution of cactus plantation areas (Table 2), it is evident that certain communes stand out for their significant coverage. Specifically, the communes of Skhour Rhamna and Labrikiyne have recorded substantial plantation areas with medium density, amounting to 3,339 and 3,062 ha, respectively. In contrast, the commune of Sidi Abdallah stands out its high-density cactus plantations, covering a total area of 1129 ha. This distribution highlights the regional variability in plantation practices, with some areas exhibiting more intensive cultivation than others.

### 3.4. Spatial and Density Distribution of Cactus Stands in 2020

A detailed geospatial assessment based on 2020 satellite imagery, combined with a systematic grid of geo-referenced control points and meticulous vector-based digitization of cactus cultivation areas, allowed to produce updated cartographic outputs illustrating the residual spatial configuration of cactus stands post-infestation (Fig. 7). The analysis reveals a pronounced contraction in both the areal extent and spatial continuity of cactus plantations, underscoring the devastating impact of *D. opuntiae* on the regional cactus-based agroecosystem. The spatial distribution of surviving plantations is markedly discontinuous, with remnant stands predominantly composed of cochineal-resistant cactus genotypes, localized in fragmented, small-scale plots across a restricted set of territorial communes. In terms of density distribution, the mapping results indicate that the highest remaining

planting densities are concentrated in the central sector of the province, though confined to relatively limited surface areas. Medium-density fields persist in a scattered and irregular pattern throughout peripheral zones, suggesting differential resilience mechanisms and/or variable levels of agronomic intervention across sites. This spatial pattern reflects a significant ecological and structural shift in cactus cultivation dynamics, shaped by biotic stress pressure, underlying environmental heterogeneity, and potentially also by socio-technical disparities in pest management responses. The observed distribution typology provides critical insight into the spatial selectivity of resistance traits and highlights priority zones for future recovery and conservation strategies.

### 3.5. Spatial Distribution of Cactus Fields in 2020 in Terms of Their Planted Areas

Through the analysis of cactus plantation areas in 2020, we identified two distinct categories based on the density of plantations that survived the cochineal infestation. The medium-density cactus plantations covered a total surface area of 240 ha, while the high-density plantations were spread across a smaller area of 27 ha only (Table 3). This sharp decline from 23,326 ha in 2014 to only 267 ha in 2020 represents a 98.9% reduction in total cactus plant cover, underscoring the extreme

vulnerability of the ecosystem to cochineal infestation. Such a loss rate, quantified at commune level, provides the first spatially explicit benchmark for evaluating biological invasion severity in arid agricultural systems.

### 3.6. Distribution Area Analysis of the Cactus Fields in 2020 on Territorial Communes of the Rhamna Province

As shown in Table 4, cactus plantations are confined to only 10 territorial communes within the province. Among these, the commune of Sidi Abdallah stands out, with significant plantation areas of 88 ha for medium-density fields and 18 ha for high-density fields, distinguishing it from the other communes in terms of both scale and density.

### 3.7. Evolution of the Cactus Areas in the Period between 2014 and 2020

To address the first research objective, we quantified the spatial extent of cactus loss in Rhamna between 2014 and 2020, The cultivated areas were extensive and widely distributed across the province during the 2014 growing season, with a dense network of cactus fields occupying both central and peripheral zones. By 2020 (Fig. 8), a significant spatial contraction is observed, with only a limited number of fields persisting. These remaining plantations appear scattered and confined

**Table 4.** The distribution of cactus planted areas by territorial communes in 2020.

| Territorial Communes | Plantation Density | Area (ha) | % Total |
|---|---|---|---|
| Sidi Abdallah | Medium-density cactus plantation | 88 | 33.0 |
| Nzalat Laadam | Medium-density cactus plantation | 53 | 19.9 |
| Jbilate | Medium-density cactus plantation | 44 | 16.5 |
| Sidi Abdallah | High-density cactus plantation | 18 | 6.7 |
| Jaafra | Medium-density cactus plantation | 13 | 4.9 |
| Oulad Hassoune Hamri | Medium-density cactus plantation | 13 | 4.9 |
| Bourrous | Medium-density cactus plantation | 11 | 4.1 |
| Skoura Lhadra | Medium-density cactus plantation | 8 | 3.0 |
| Ait Hammou | Medium-density cactus plantation | 7 | 2.6 |
| Oulad Hassoune Hamri | High-density cactus plantation | 6 | 2.2 |
| Akarma | Medium-density cactus plantation | 3 | 1.1 |
| Skoura Lhadra | High-density cactus plantation | 2 | 0.7 |
| Sidi Ghanem | High-density cactus plantation | 1 | 0.4 |
| **Total Planted Areas** | | **267** | **100.0** |
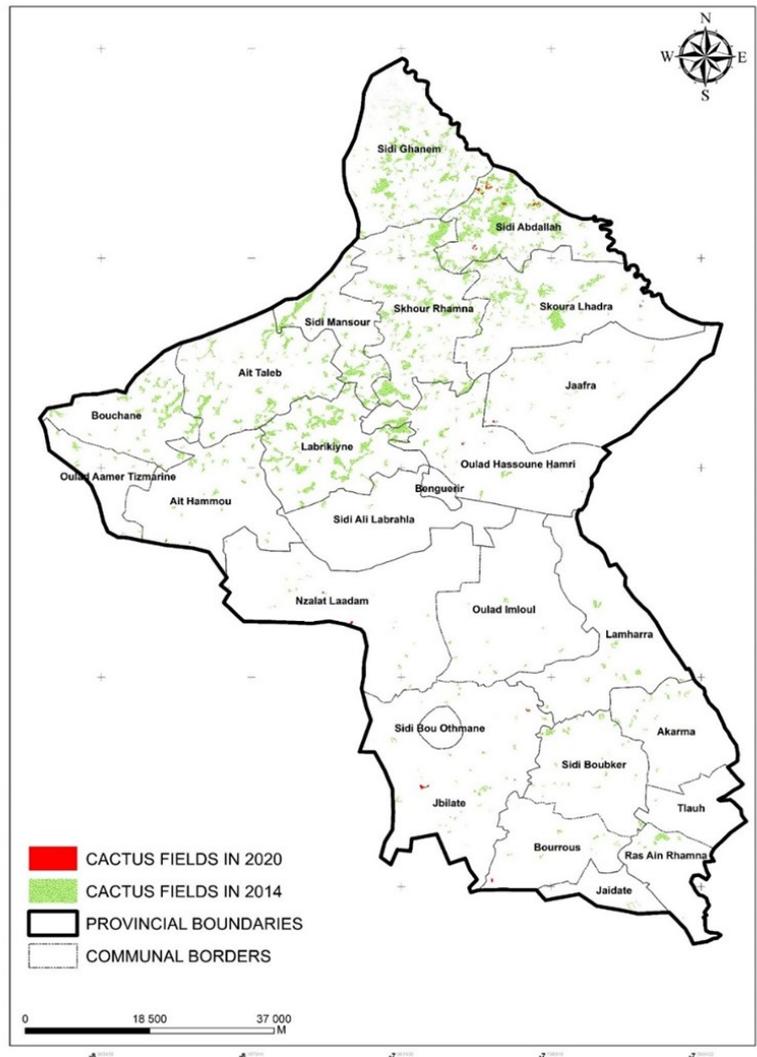
**Figure 9.** Evolution map of the cactus areas in the period between 2014 and 2020 in Rhamna Province-Morocco.

to small, localized zones that were not affected by the *D. opuntiae* infestation. The comparative histogram of cactus plantation areas across selected communes for the years 2014 and 2020 indicates a sharp decline in cultivated areas in nearly all communes (Fig. 9). In several cases, the reduction approaches complete disappearance, reflecting a severe decrease in the presence of *Opuntia* spp. within the administrative boundaries considered. Fig. 10 highlights the transformation of the landscape from widespread cactus cultivation in 2014 to a fragmented distribution pattern in 2020, with most of the original fields no longer visible in the 2020 dataset.

To answer the second objective concerning the spatial structure of collapse, we examined changes in density classes and the fragmentation of

plantations across commune, in 2014, cactus plantations covered 23 territorial communes (Fig. 11), with the largest areas found in the communes of Sidi Abdallah, Skhour Rhamna, and Labrikiyne, each exceeding 2,600 ha and reaching up to 3,800 ha. However, by 2020, the surviving cactus fields were confined to just over 10 communes, with significantly reduced surface areas. Among these, the commune of Nzalat Laadam recorded the highest proportion of undamaged cactus fields, followed by Jbilate and Bourrous, based on the percentage of surviving cactus compared to the area initially covered (Table 5).

In terms of cactus plantation density in 2014 (Fig. 9), high-density cactus fields were present in only nine territorial communes. The highest concentrations were observed in the communes of

Sidi Abdallah, Lamharra, and Skoura Lhadra, which collectively accounted for over 22.2% of the total cactus plantation area in the province. The remaining plantation areas were primarily characterized by medium-density cactus fields, with certain communes surpassing the 100% threshold of expected coverage. By 2020, the distribution of undamaged high-density cactus plantations was notably reduced, with surviving fields confined to a few communes, including Sidi Ghanem, followed

**Table 5.** Comparative cactus plantation areas across the main communes of the Rhamna region for the years 2014 and 2020.

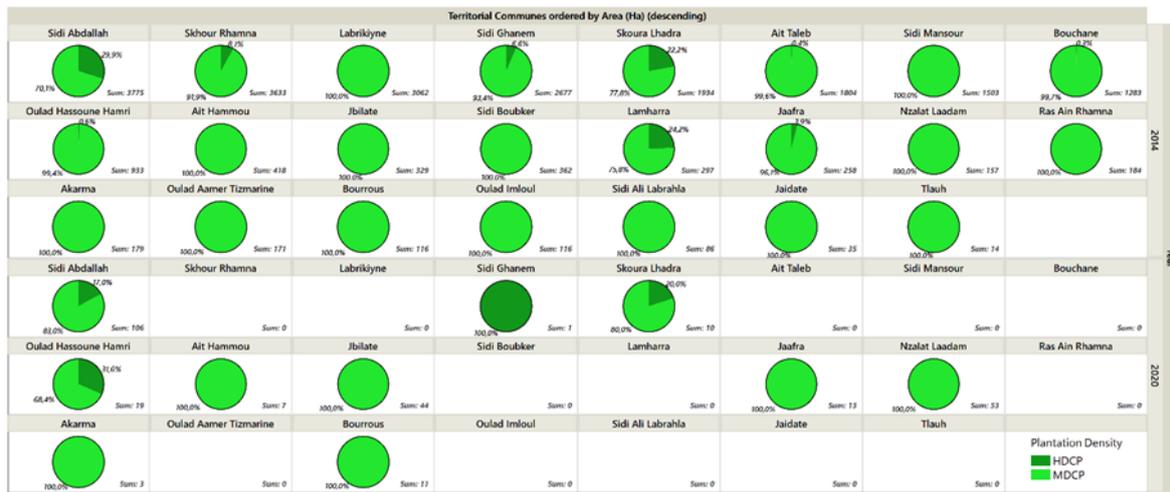| Territorial Communes | Cactus Area (ha) in 2014 | Cactus Area (ha) in 2020 | % Reduction |
|---|---|---|---|
| Ait Hammou | 418 | 7 | 98.0 |
| Ait Taleb | 1,797 | 0 | 100.0 |
| Ait Taleb | 7 | 0 | 100.0 |
| Akarma | 179 | 3 | 98.3 |
| Bouchane | 1,279 | 0 | 100.0 |
| Bouchane | 4 | 0 | 100.0 |
| Bourrous | 116 | 11 | 90.5 |
| Jaafra | 248 | 13 | 94.8 |
| Jaafra | 10 | 0 | 100.0 |
| Jaidate | 35 | 0 | 100.0 |
| Jbilate | 329 | 44 | 86.6 |
| Labrikiyne | 3,062 | 0 | 100.0 |
| Lamharra | 225 | 0 | 100.0 |
| Lamharra | 72 | 0 | 100.0 |
| Nzalat Laadam | 157 | 53 | 66.2 |
| Oulad Aamer Tizmarine | 171 | 0 | 100.0 |
| Oulad Hassoune Hamri | 927 | 13 | 98.6 |
| Oulad Hassoune Hamri | 6 | 6 | 0.0 |
| Oulad Imloul | 116 | 0 | 100.0 |
| Ras Ain Rhamna | 184 | 0 | 100.0 |
| Sidi Abdallah | 2,646 | 88 | 96.7 |
| Sidi Abdallah | 1,129 | 18 | 98.4 |
| Sidi Ali Labrahla | 86 | 0 | 100.0 |
| Sidi Boubker | 362 | 0 | 100.0 |
| Sidi Ghanem | 2,501 | 1 | 100.0 |
| Sidi Ghanem | 176 | 0 | 100.0 |
| Sidi Mansour | 1,503 | 0 | 100.0 |
| Skhour Rhamna | 3,339 | 0 | 100.0 |
| Skhour Rhamna | 294 | 0 | 100.0 |
| Skoura Lhadra | 1,504 | 8 | 99.5 |
| Skoura Lhadra | 430 | 2 | 99.5 |
| Tlauh | 14 | 0 | 100.0 |
| **Total Planted Areas** | **23,326** | **267** | **98.9** |

**Figure 10.** Percentage of cactus area cover densities during the year 2014 to 2020 by territorial communes.

by Oulad Hassoune Hamri, Skoura Lhadra, and Sidi Abdallah. The remaining areas were dominated by medium-density cactus plantations. Furthermore, 13 communes were entirely devoid of cactus fields, highlighting the significant decline in plantation density across the region because of the pest infestation. The drastic contraction of cactus plantations has led to significant socio-economic consequences for local communities. However, this study focuses primarily on the spatial quantification of vegetation degradation rather than on economic impact assessments.

In line with the third objective, we assessed the reliability of the visual interpretation approach using 3,305 ground control points, A correlation analysis was conducted to examine the relationship between the initial cactus plantation density in 2014 and the surviving surface area in 2020 (Fig. 10). The results indicated no significant correlation (r = 0.0096, p = 0.979), suggesting that the density of plantations did not influence their survival under the biological stress caused by the cochineal infestation. This finding implies that other factors, such as plant genotype or microclimatic conditions, soil conditions and crop management, may have played a more critical role in cactus resilience. The absence of a statistically significant relationship between initial density and surviving cactus area in 2020 should not be interpreted as evidence of no effect, but rather as the result of the near-total collapse of plantations across communes. Once infestation by *D. opuntiae* reached a critical threshold, losses occurred almost uniformly,

regardless of starting density. This pattern suggests that density alone was not a protective factor against collapse, and that other elements such as genotype susceptibility, microclimatic variation, and local management practices may better explain the residual heterogeneity observed.

To meet the fourth objective, we estimated the gross economic losses associated with cactus collapse at the commune level. The combined analysis of economic losses, fruit losses, and cladode (racket) losses across the territorial communes of the Rhamna Province reveals a highly uneven spatial distribution of the impacts caused by the cochineal (*D. opuntiae*) infestation. As shown in Fig. 11, the communes of Sidi Abdallah, Skhour Rhamna, and Labrikiyne experienced the most significant damage, with estimated economic losses exceeding 3 million USD per commune. These losses are directly correlated with the drastic reduction in cactus biomass and fruit yield, where cladode losses reached over 250,000 tons and fruit losses surpassed 60,000 tons in the most affected zones. The data underscore the disproportionate vulnerability of communes with historically dense *Opuntia* plantations, where the biological invasion led not only to ecological degradation but also to severe economic repercussions. This spatially explicit quantification provides critical evidence of the infestation's impact on both agricultural productivity and rural livelihoods, and further supports the relevance of high-resolution, commune-level monitoring frameworks for guiding targeted mitigation and restoration strategies in arid agro-

ecosystems.

The data summarized in Table 6 presents an analysis of cactus plantation distribution across each territorial commune between 2014 and 2020. This assessment highlights the widespread devastation experienced by all communes, with particularly severe losses in the communes of Sidi Abdallah, Skhour Rhamna, and Labrikiyne, which each suffered reductions in cactus plantation areas of 3669, 3633, and 3062 ha, respectively (Fig. 12). These reductions were quantified in terms of fruit and biomass losses, leading to an estimated total loss of approximately 261966,38 tons of fruit and 1457075 tons of biomass. The economic impact of these losses was further estimated by converting the affected areas into monetary terms, yielding an overall financial loss of approximately 230,590,000 MAD (or approximately 23,760,681 USD) annually. This substantial economic setback underscores the significant socio-economic implications of the cochineal infestation on cactus cultivation in the region. From a methodological perspective, the ability to quantify these drastic spatial regressions through visual interpretation and polygon-based geospatial modeling validates the effectiveness of the proposed approach. The grid-referenced manual mapping technique allowed a precise comparison over time, demonstrating its potential for replicability in other pest-affected arid zones.

In summary, cactus cover decreased by 98.9% between 2014 and 2020, leaving less than 270 ha. This collapse translated into an annual gross revenue loss of ≈230.6 M MAD (≈23.8 M USD). Notably, more than 80% of these losses were concentrated in only three communes. The correlation matrix presented in Fig. 13 provides valuable insights into the relationships between spatial, agronomic, and economic indicators associated with cochineal-induced degradation of *Opuntia* plantations. A strong positive correlation (r > 0.90) is observed between the total cactus area in 2014 and the subsequent fruit and cladode (racket) production losses, as well as the overall economic losses. This suggests that communes with larger initial cultivation areas suffered proportionally greater absolute losses. Similarly, a high correlation is observed between economic losses and both forms of agricultural loss (fruit and biomass), indicating that the economic impact is directly driven by production collapse. Conversely, the percentage of surface lost shows weak or negative correlations with all other variables, highlighting that relative losses do not necessarily scale with initial plantation size. Interestingly, the 2020 area shows a moderate correlation (r = 0.91) with economic and production losses, further supporting the notion that communes retaining larger residual areas were those initially most productive and hence most impacted. These findings underscore the importance of using absolute spatial data rather than percentages when assessing pest-driven
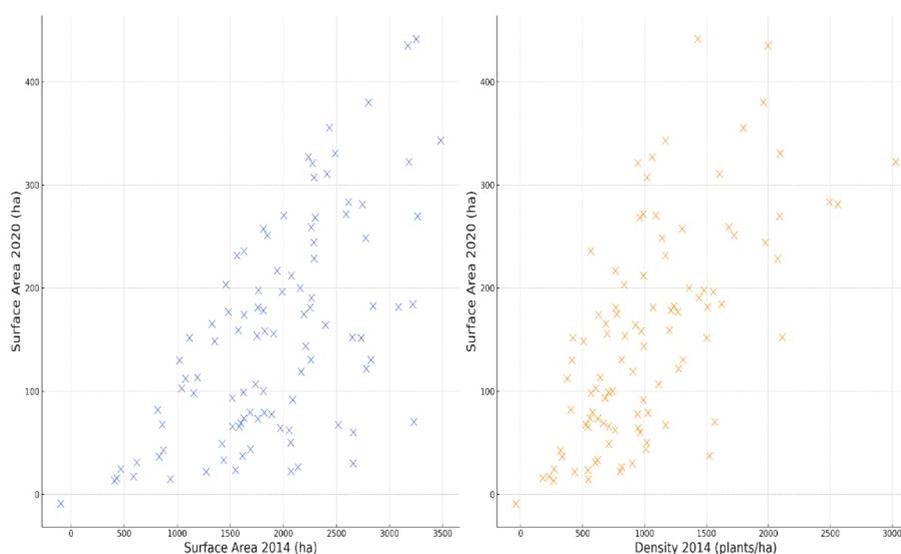


**Figure 11.** Correlation analysis between cactus plantation area and density from 2014 to 2020 in the Rhamna Province.
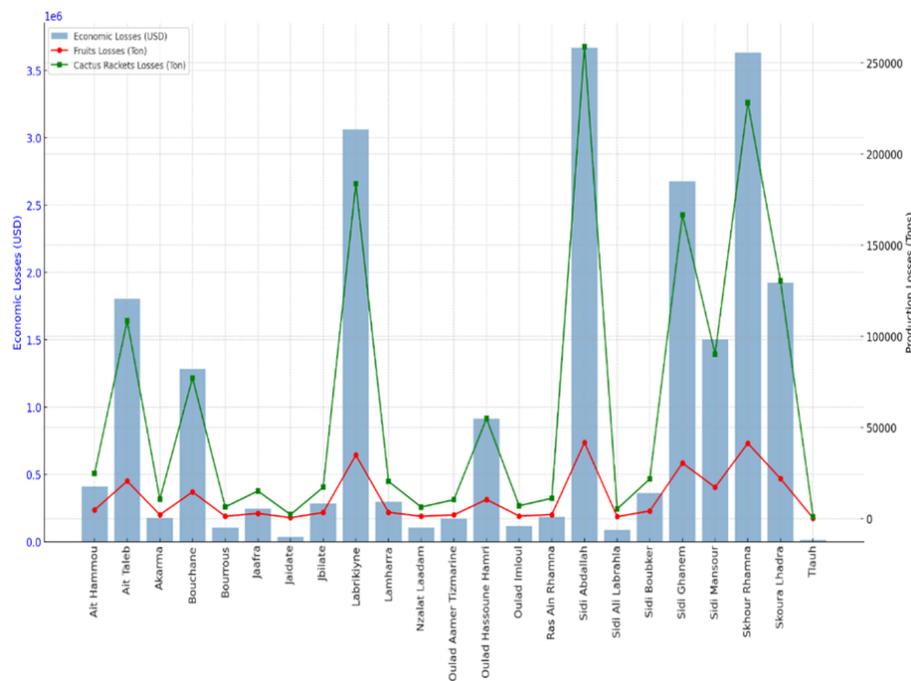
**Figure 12.** Economic and agricultural losses by territorial commune in 2020.

degradation in fragmented agro-ecosystems, and they validate the relevance of commune-level geospatial indicators in evaluating economic vulnerability. To illustrate the uneven spatial distribution of the economic impact, we plotted gross economic losses per commune (Fig. 13). The bar graph highlights that the highest losses were concentrated in communes such as Skhour Rhamna, Sidi Abdallah, and Labrikiyne, while smaller communes experienced comparatively lower losses. Error bars represent ±20% variation in yield and price assumptions, as derived from the sensitivity analysis.

### 3.8. Discussion

This study introduces and validates a novel geospatial methodology that combines high-resolution visual interpretation with rigorous field validation to assess vegetation loss caused by the cochineal pest (*D. opuntiae*). Unlike traditional automated classification systems or coarse NDVI analyses, this method enables fine-scale spatial quantification in fragmented agro-ecosystems, offering new insights into degradation dynamics in arid environments. This is particularly crucial in zones like Rhamna, where biological invasions are aggravated by recurring droughts and heterogeneous land-use patterns. The Rhamna region, historically recognized for its significant

role in cactus production and the development of associated products, has been central to Morocco's strategy for sustainable agriculture [27]. However, despite the sector's initial success, the arrival of *D. opuntiae* in 2014 delivered a major setback. The pest has inflicted severe damage on cactus plantations, effectively reversing years of investment in cactus as a resilient crop for ecological and economic development [28]. Using a robust geospatial approach grounded in over 3,300 control points, our analysis confirms a drastic decline in cactus plantations, which contextualizes the following discussion on regional vulnerability [29].

This discrepancy highlights the limitations of earlier national assessments likely based on coarse or incomplete data. By leveraging visual cues such as cactus morphology and field structure parameters typically overlooked in automated classification our method produces a more accurate and granular mapping of infestation impacts. Similar outcomes have been observed in other pest-damaged agro-ecosystems, such as Tuta absoluta-infested tomato fields in Tunisia [30],and locust-damaged millet crops in Niger [31], where manual spatial delineation significantly outperformed algorithmic approaches. At the national level, the surface area dedicated to cactus cultivation is estimated to exceed 150,000 ha, with an estimated fruit

**Table 6.** Analysis of the area distribution of cactus plantations, according to the types of production in each territorial commune during the period from 2014 to 2020.

| Territorial Communes | Area 2014 (ha) | Area 2020 (ha) | Difference (ha) | Percent Reduction (%) | Fruits Production Losses (tons) | Production Losses in Cactus Rackets (tons) | Economic Losses (MAD) |
|---|---|---|---|---|---|---|---|
| Ait Hammou | 418 | 7 | -411 | 98.33 | 4,669.25 | 24,660 | 4,110,000 |
| Ait Taleb | 1,804 | 0 | -1,804 | 100.0 | 20,494.70 | 108,485 | 18,040,000 |
| Akarma | 179 | 3 | -176 | 98.32 | 1,999.48 | 10,560 | 1,760,000 |
| Bouchane | 1,283 | 0 | -1,283 | 100.0 | 14,575.78 | 77,120 | 12,830,000 |
| Bourrous | 116 | 11 | -105 | 90.52 | 1,192.87 | 6,300 | 1,050,000 |
| Jaafra | 258 | 13 | -245 | 94.96 | 2,783.37 | 15,050 | 2,450,000 |
| Jaidate | 35 | 0 | -35 | 100.0 | 397.62 | 2,100 | 350,000 |
| Jbilate | 329 | 44 | -285 | 86.63 | 3,237.80 | 17,100 | 2,850,000 |
| Labrikiyne | 3,062 | 0 | -3,062 | 100.0 | 34,786.46 | 183,720 | 30,620,000 |
| Lamharra | 297 | 0 | -297 | 100.0 | 3,374.13 | 20,340 | 2,970,000 |
| Nzalat Laadam | 157 | 53 | -104 | 66.24 | 1,181.51 | 6,240 | 1,040,000 |
| Oulad Aamer Tizmarine | 171 | 0 | -171 | 100.0 | 1,942.68 | 10,260 | 1,710,000 |
| Oulad Hassoune Hamri | 933 | 19 | -914 | 97.96 | 10,383.68 | 54,840 | 9,140,000 |
| Oulad Imloul | 116 | 0 | -116 | 100.0 | 1,317.84 | 6,960 | 1,160,000 |
| Ras Ain Rhamna | 184 | 0 | -184 | 100.0 | 2,090.37 | 11,040 | 1,840,000 |
| Sidi Abdallah | 3,775 | 106 | -3,669 | 97.19 | 41,682.41 | 259,025 | 36,690,000 |
| Sidi Ali Labrahla | 86 | 0 | -86 | 100.0 | 977.02 | 5,160 | 860,000 |
| Sidi Boubker | 362 | 0 | -362 | 100.0 | 4,112.57 | 21,720 | 3,620,000 |
| Sidi Ghanem | 2,677 | 1 | -2,676 | 99.96 | 30,401.23 | 166,685 | 26,760,000 |
| Sidi Mansour | 1,503 | 0 | -1,503 | 100.0 | 17,075.13 | 90,180 | 15,030,000 |
| Skhour Rhamna | 3,633 | 0 | -3,633 | 100.0 | 41,273.42 | 228,270 | 36,330,000 |
| Skoura Lhadra | 1,934 | 10 | -1,924 | 99.48 | 21,857.99 | 130,420 | 19,240,000 |
| Tlauh | 14 | 0 | -14 | 100.0 | 159.05 | 840 | 140,000 |
| **Total General** | **23,326** | **267** | **-23,059** | **98.86** | **261,966.38** | **1,457,075** | **230,590,000** |

production exceeding 1,000,000 tons. In the Rhamna Province, prior to the impact of the cochineal pest, several studies reported varying estimates of cactus-covered areas. For instance, previous work [32][33], estimated the area at approximately 50,000 ha, while Zammar and Abdelbaki cited a slightly lower estimate of 40,000 ha [34]. However, according to official data from the Ministry of Agriculture and Maritime Fishing, a total of 26,000 ha were cultivated, predominantly in the communes of Sidi Abdallah, Jaafra, Skoura Lhadra, Skhour Rhamna, Sidi Ghanem, and Sidi Mansour [35]. These figures highlight the significant role of the Rhamna region in cactus cultivation, which has been severely impacted by the spread of the cochineal pest in recent years.

Despite the significance of cactus cultivation in Morocco, no scientifically robust studies have been conducted using precise area estimation methodologies to assess the extent of cactus fields or the damage caused by the cochineal insect. This study addresses this gap by employing a combination of remote sensing and GIS technologies to provide a more accurate and comprehensive analysis of the historical and diachronic distribution of cactus plantations [36][37]. The results of this study reveal that in 2014,

the actual planted area of cactus in the Rhamna province amounted to 23,326 ha, consisting of 21,199 ha of medium-density plantations and 2,127 ha of high-density plantations. This study covers a total of 23 territorial communes, with considerable variation in the planted area and plantation density.

These findings contrast with the official statistics reported by the the Ministry of Agriculture, Maritime Fisheries, Rural Development, and Water and Forests [7], which only considered cactus fields in six communes. The Ministry of Agriculture, Maritime Fisheries, Rural Development, and Water and Forests (MAPMDREF) data may be biased because they rely on aggregated sampling at coarse spatial resolution, which overlooks fragmented stands and underestimates residual cactus patches. In contrast, our approach based on remote sensing and GIS technologies provided more detailed spatial coverage. Nevertheless, visual interpretation also has limitations: distinguishing cactus from shrub vegetation can be challenging in areas with mixed land use, and observer judgment may introduce a degree of subjectivity. These caveats highlight the importance of combining visual interpretation with systematic field validation and, where feasible, UAV or higher-resolution imagery to strengthen reliability [38].
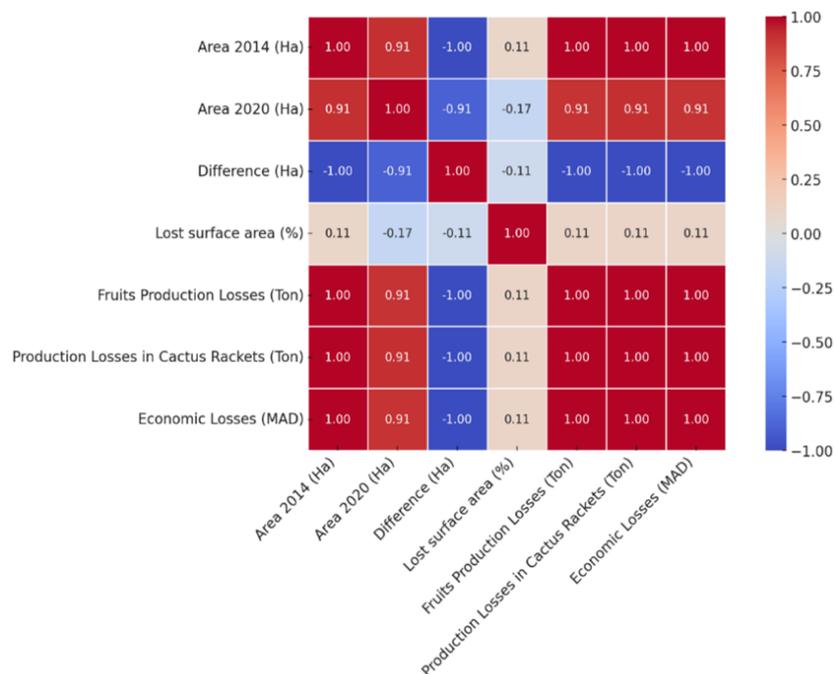


**Figure 13.** Heatmap of the correlation matrix between key variables related to cactus plantation degradation in the Rhamna region (2014–2020).

In absolute terms, communes such as Sidi Abdallah, Skhour Rhamna, and Labrikiyne incurred the heaviest losses, with estimated production reductions exceeding 250,000 tons of cladodes and 60,000 tons of fruits, and economic damages surpassing 3 million MAD per commune. These figures emphasize the scale of the damage, particularly in high-density plantation zones that were previously key contributors to the region's agro-economy. The findings of this study offer significant implications for the management and conservation of cactus plantations in Rhamna, providing a solid foundation for extending these advanced methodologies to other regions in Morocco. This research not only fills a critical gap in literature but also contributes valuable insights for the effective monitoring and preservation of cactus ecosystems, particularly in the face of ongoing threats like the cochineal pest.

For biomass production, yields depend strongly on planting density and management practices. In well-managed plots of Skhour Rhamna, annual cladode production was reported to reach about 95 tons/ha in high-density plantations (40 × 40 cm spacing, ≈625 plants/ha) and about 60 tons/ha in medium-density plantations (50 × 50 cm spacing, ≈400 plants/ha). Based on the distribution of density classes in 2014, the annual production of green biomass in Rhamna Province was estimated at approximately 1.47 million tons, of which 1.27 million tons came from medium-density plantations and about 0.20 million tons from high-density plantations. However, by 2020, following the reduction in cactus plantations, the total annual green biomass production was estimated at 2,565 tons for high-density fields and 14,400 tons for medium-density fields, representing a respective decrease of 199,595 tons and 1,257,480 tons compared to 2014. Furthermore, according to Lahbouki [3], when these figures are converted to dry mass, the total biomass production is estimated at 147,404 tons in 2014, with a significant reduction to 1,696.5 tons in 2020 [39].

In terms of forage units (FU) lost, the energy value of cactus cladodes is comparable to that of alfalfa, with an energy value of 0.12 FU/kg. Based on this, the estimated total cactus production in 2014 corresponded to approximately 176,884,800 FU. However, by 2020, the available production had dramatically decreased, with an estimated value of 2,035,800 FU, reflecting a loss of approximately 174,849,000 FU. As outlined by Chigr, the forage energy content in FU is determined by comparing the net energy of a sample to the net energy of 1 kilogram of feed barley, with the equivalence of 1 FU being equal to the energy content of 1 kilogram of feed barley [40]. This yields an estimated total loss in forage energy equivalent to 174,849,000 kg of feed barley [40][41].

From an economic perspective, cactus cultivation provides a substantial financial benefit, with each hectare of cactus yielding a profit exceeding 10,000 MAD, in stark contrast to the more modest returns of 1,500 MAD per hectare for cereal crops [42]. Consequently, based on these economic indicators, the total estimated revenue generated by cactus production in 2014 was approximately 233,260,000 MAD. However, by 2020, following the significant decline in cactus production, the estimated revenue had plummeted to a mere 2,670,000 MAD. This translates to an estimated economic loss of approximately 230,590,000 MAD (or 23,760,681 USD) annually, highlighting the severe financial impact of the cochineal pest infestation on the cactus sector [43]. Looking forward, adaptation strategies are critical. Conservation and propagation of resistant *Opuntia* cultivars, the introduction of safe biological control measures, and ecosystem restoration programs should be prioritized. The MAPMDREF national action plans, together with FAO-supported programs, provide key strategic frameworks for guiding these efforts. At the local scale, our commune-level indicators offer valuable tools for policymakers and stakeholders to prioritize interventions in areas where socio-economic returns are expected to be the highest.

## 4. CONCLUSIONS

Between 2014 and 2020, cactus plantations in the Rhamna Province collapsed by 98.9%, shrinking from 23,326 ha to less than 270 ha. This drastic reduction was accompanied by a sharp decline in density classes and a concentration of surviving stands into fewer than ten communes. The regression and accuracy assessments confirmed that communes with larger initial areas suffered

proportionally greater economic losses, amounting to an estimated 230.6 million MAD annually. These findings demonstrate not only the spatial extent of the devastation but also its ecological and agronomic consequences, including the loss of drought-resilient fodder, soil stabilization services, and biodiversity support. At the policy level, the results highlight priority areas for intervention and provide an empirical basis for restoring cactus plantations and strengthening local livelihoods. Looking ahead, research should focus on the conservation and propagation of resistant *Opuntia* genotypes, the testing of biological control measures, and the integration of high-resolution monitoring tools for early detection of pest outbreaks. This research provides a strong empirical foundation for restoring cactus plantations in the most severely affected areas. It also supports the development of policies aimed at long-term ecological and economic sustainability in arid regions of Morocco.

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### Conflicts of Interest

The authors declare no conflict of interest.

### DECLARATION OF GENERATIVE AI

Not applicable.

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