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Editorial

ABYA YALA | UNIVERSIDAD POLITÉCNICA SALESIANA

Dear reader:

Geospatial sciences have evolved greatly over the past few years, with geographic information systems (GIS), remote sensors on satellite and unmanned platforms or drones, as well as global navigation satellite systems (GNSS) among their top representatives. For this reason, this special edition of La Granja honors and presents these sciences with our number "Geospatial Sciences", which brings some research framed in these technologies.

In this way, we start this issue with the field of Geographic Information Systems (GIS), in which PhD. Lia Duarte and other researchers from the University of Porto in Portugal, present alternatives for comparing four different plugins to generate web maps using the QGIS tool, thus seeking new opportunities for the presentation of geospatial data results.

In the field of Geospatial Sciences in Latin American, PhD. Mauricio Perea-Ardilla and other researchers from the Pacific Oceanographic and Hydrographic Research Center in Tumaco, in collaboration with the University of Tolima in Colombia, carry out interesting research using remote satellite sensors to generate spectral characterization, and remote sensing mangrove forest monitoring in Colombia's Pacific coast, establishing an alternative of territorial planning in a sensitive ecosystem as mangrove.

PhD. Juan Gabriel Mollocana and his team from the Universidad Politécnica Salesiana also conduct fire simulation in Quito, Ecuador, using satellite images in Ecuador, thus proposing different options in managing the forest fires that affect the Ecuadorian capital, and inviting other cities with similar characteristics to begin to use it and take advantage of this geospatial information.

Returning to the general topics of La Granja, we present an article on the ecohydrology of the Ecuadorian paramo, in which the interactions of climatic variables with the development of plant species are analyzed; this study carried out by researchers of University of Cuenca, is led by PhD. Amanda Suqui. Additionally, we present a research on highly effective agricultural science technologies in specific action groups in the localities of Puebla, Mexico; it is a study conducted by PhD. José Regalado López, from the College of Postgraduates in Mexico.

Another research from Mexico, in the field of forestry, conducted by PhD. Alberto Santillán-Fernández and his multidisciplinary team from the College of Postgraduates of Campeche, the Higher Technological Institute Veracruzano, and the Center for Scientific Research of Yucatan, present their study of the sexual and asexual propagation of *Brosimum alicastrum Swartz*.

PhD. Nelino Florida Rofner, from the National Agrarian University of the Forest of Peru, in the field of pollutant analysis, presents a review of the maximum limits of cadmium in Cacao crops. While in the field of biotechnology, PhD. Ángel Hernández-Amasifuén and his team from the National University José Faustino Sánchez Carrión of Peru, present a study of the *in vitro* introduction of rocoto calluses. Finally, from the University of Research and Development in Bucaramanga, Colombia, PhD. Martha Castro-Castro and her team of researchers present an analysis of the economic sustainability of agricultural production units in peasant communities.

As members of La Granja, we present this new issue and are confident that it will be a compilation of useful research for the development of science in regional and global scientific work.

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Geospatial Science

Comparative analysis of four QGIS plugins for Web Maps creation

Análisis comparativo de cuatro plugins de QGIS para la creación de mapas web

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Abstract

QGIS is a free and open-source software that allows viewing, editing, and analyzing georeferenced data. It is a Geographic Information System (GIS) software composed by tools that allow to manipulate geographic information and consequently to create maps which help to get a better understanding and organization of geospatial data. Unfortunately, maps created directly in the GIS desktop software are not automatically transferred to a website. This research aimed to compare publishing capabilities in different QGIS plugins to create Web Maps. This study analyzes four QGIS plugins (QGIS2Web, QGIS Cloud, GIS Cloud Publisher and Mappia Publisher), performing a comparison between them, considering their advantages and disadvantages, the free and subscription plans, the tools offered by each plugin and other generic aspects. The four plugins were tested in a specific case study to automatically obtain different Web Maps. This study could help users to choose the most adequate tools to publish Web Maps under QGIS software.

Keywords: QGIS Cloud, QGIS 2 Web, GIS Cloud Publisher; Mappia Publisher, WebGIS, WebMap.

Resumen

QGIS es un software gratuito y de código abierto que permite visualizar, editar y analizar datos georreferenciados. Es un software de Sistema de Información Geográfica (SIG) compuesto por herramientas que permiten manipular la información geográfica y crear mapas que ayuden a obtener una mejor comprensión y organización de los datos geoespaciales. Desafortunadamente, los mapas que se crean directamente en el software de escritorio GIS no se pueden transferir automáticamente a un sitio web. Por lo tanto, esta investigación tuvo como objetivo comparar las capacidades de publicación en complementos de QGIS, y crear mapas web. El estudio analiza cuatro plugins de QGIS

(QGIS2Web, QGIS Cloud, GIS Cloud Publisher y Mappia Publisher), realizando una comparativa entre ellos, considerando sus ventajas y desventajas, los planes gratuitos y de suscripción, las herramientas que ofrece cada plugin y otros aspectos genéricos. Los cuatro complementos se probaron en un caso de estudio específico para obtener automáticamente los diferentes mapas web. Este estudio podría ayudar a los usuarios a elegir las herramientas más adecuadas para publicar mapas web en el software QGIS.

Palabras clave: QGIS Cloud, QGIS 2 Web, GIS Cloud Publisher; Mappia Publisher, WebSIG, WebMapas.

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1 Introduction

A Geographic Information Systems (GIS) is a framework for obtaining, managing and analyzing geospatial data, and could be defined as an aggregation of several components as hardware, software, data, methodologies and people (operators and users), that can make possible an analysis of geographical data, associating attribute information to the objects.

GIS maps could be easily shared and embedded in applications, and accessible virtually. A Web Map is not only cartography available via web, but a service by which the users can choose the characteristics of the map that will be shown (Parker et al., 2013). Therefore, a Web Map is not only a map but is also the related content (database) presented via web with an appropriate interface and optional functionality (for instance, for queries and reports). A Web Map application refers not only to the code that is created to define the web interface, but also to the elements and functions provided through the interface.

Web Maps are user interfaces for geospatial information and constitute the tools by which the users interact with and explore that information (Cartwright et al., 2001). In order to make the geographical information accessible to any user, there is a need to more simplistic interfaces environments. In order to satisfy this need and to support the cognitive usability principles of a user, the Web Maps should be composed by elements such as: navigation tools, zoom options, pan, move, changing the scale, among others (Cartwright et al., 2001). In the past few years, the number of users has increased due to the functionalities developed by the creators considering: easy access, diversity and more intelligent applications integrated, providing more collaborative environment (Veenendaal et al., 2017). Most of the GIS Web Maps are created using open-source software (QGIS or other) and proprietary (for instance, ArcGIS). One example is the most recently created ArcGIS Online (ArcGIS, 2021). Other platforms can also be used such as: CartoDB, MapBox, SimpleMappr, MangoMap, Click2Map, among others (https://digital-geography.com/create-maps-online-a-comparison-webmap-providers/). However, the referred platforms are not free to use, except for the SingleMappr, which only allows to upload information in a web map.

The workflow for developing a Web Map comprises four primary main steps: (i) collecting the data to be putted on the map; (ii) conceptualizing the map; (iii) planning the user experience and; (iv) producing the final web map.

Generally, there are two types of Web Maps: (i) the static map, where the map content is fixed and unchanged, however, these maps can be dynamically generated where the server runs software that generates a map image based on changing conditions or specific user request, and; (ii) interactive Web Maps, where users interact with the map. For representation of highly dynamic data, real-time maps can be created. However, these require complex, and custom programming. Hossain and Meyer (2018) investigated appropriate and stable solutions for representing the statistical data into map with some special features. This research also includes the comparison between different solutions for specific features. They found three solutions using three different technologies, one of them including QGIS.

Web Maps also present some challenges compared to desktop GIS software, such as: i) a static GIS Web Map is not flexible, an edition must be performed every time the information changed, so it is time-consuming; ii) higher hardware and software costs, requiring more powerful web servers and programs and; iii) internet connection. However, the powerful advantages exceed the disadvantages; hence, web maps are increasingly used worldwide.

QGIS is an open-source GIS that respects the Stallman four freedoms (Stallman, 2007), and is licensed under a GNU GPL license. One of the main advantages of QGIS relies on the easiness and quickness of developing new plugins, using python language (Teodoro and Duarte, 2013; Duarte et al., 2016, 2018a,b, 2019). There are several plugins available in QGIS for the Web Maps creation, for instance, QGIS Cloud (https://qgiscloud.com/); QGIS2Web (https://plugins.qgis.org/plugins/qgis2web/); Lizmap (https://www.lizmap.com/en/); GIS Cloud Publisher (https://www.giscloud.com/apps/gis-cloud-publisher-for-qgis/); GISQUICK (http://gisquick.org/); Mappia Publisher (https://plugins.qgis.org/plugins/mappia_ publisher/) and NextGIS (https://nextgis.com/). Sukic and Rančić (2011) have already discussed in 2011 the open-source plugins that have contributed to the GIS improvement and the way it is used. However, since then, several updates and improvements were done.

The integration of Web Map services has gained great notoriety in different areas of application. Chen and Nguyen (2017) develop a framework for the integration of Building Information Modeling (BIM) and Web Map service technologies for location and transportation analysis in green building certifications. With the aim of improving the traditional method of collecting road data and knowledge and management of the road network in Gharbi and Haddadi (2020) developed a GIS Mobile application using several solutions (PostgreSQL, PostGIS, QGIS, IntraMaps Roam, QGIS Cloud). Garnero and Vigna (2018) used QGIS2Web to support the activities of a forestry consortium (Canavese Forestry Consortium), which needs to plan its work in relation to the territory it manages. Bhatia et al. (2018) created a web GIS application using open-source tools, where Leaflet, Geoserver and PostgreSQL were used.

Four of these plugins were selected, specifically QGIS2Web, QGIS Cloud, GIS Cloud Publisher and Mappia Publisher, to perform a comparative analysis between them. The main objective of this study was to compare the referred plugins, which allows to create Web Maps through QGIS software, QGIS2Web, QGIS Cloud, GIS Cloud Publisher and Mappia Publisher, considering their advantages/disadvantages, main functionalities, subscription plans and their general functionalities. These plugins were considered since the QGIS2Web and QGIS Cloud plugins are the most downloaded plugins in QGIS official repository and the GIS Cloud Publisher and Mappia Publisher are more recent plugins, both created in February 2020. The results obtained provide a comparative analysis that can help the users understand the best plugin to use in a specific condition.

2 Materials and Methods

As already referred, this study analyzes four QGIS plugins (QGIS2Web, QGIS Cloud, GIS Cloud Publisher and Mappia Publisher), performing a comparison between them, considering their advantages and disadvantages, the free and subscription plans, the tools offered by each plugin and other generic aspects.

In the end of 2020, the QGIS repository was composed by 1302 plugins (https://plugins.qgis.org/plugins/).In this list, QGIS2Web have 649 717 downloads since the first version launched in June 2015. The QGIS Cloud Plugin have 290 423 downloads since the first version launched in August 2012. The GIS Cloud Publisher was recently created and have 4 462 downloads. Finally, the Mappia Publisher, also a recent created plugin has 10 692 downloads. These numbers are referred to 20 October 2020.

For all the 4 plugins referred, a base map was required in the Web Map composition. All the plugins have that functionality incorporated, except for QGIS2Web in which the plugin *QuickMapServices* (from QGIS software) was required to be installed before. The Open Street Map (OSM) and the satellite imagery from Google Earth were used as base maps. The data used in these four plugins to test the Web Maps include: i) two-point shapefiles; ii) two-line shapefiles; iii) two-polygon shapefiles and; iv) two-raster files. The processing time of each Web Map was also recorded.

2.1 Case Study

To compare the four plugins, a case study was considered in Alentejo, Portugal, in the Herdade da Contenda (HC) property (Figure 1). HC study area was chosen due to the set of geographical information available, vectorial and raster data, which can be used as input in the Web Maps. HC is a protected zone located in the municipality of Moura, Beja district, Portugal (Duarte et al., 2016).

Table 1 presents the information regarding the dataset used in the Web Maps created. This information includes the data type, the description of the data, the resolution/scale and the source.

All the information used was in European Terrestrial Reference System 1989 – Portugal Transverse Mercator 2006 (ETRS89 PTTM06; EPSG: 3763) coordinate system.

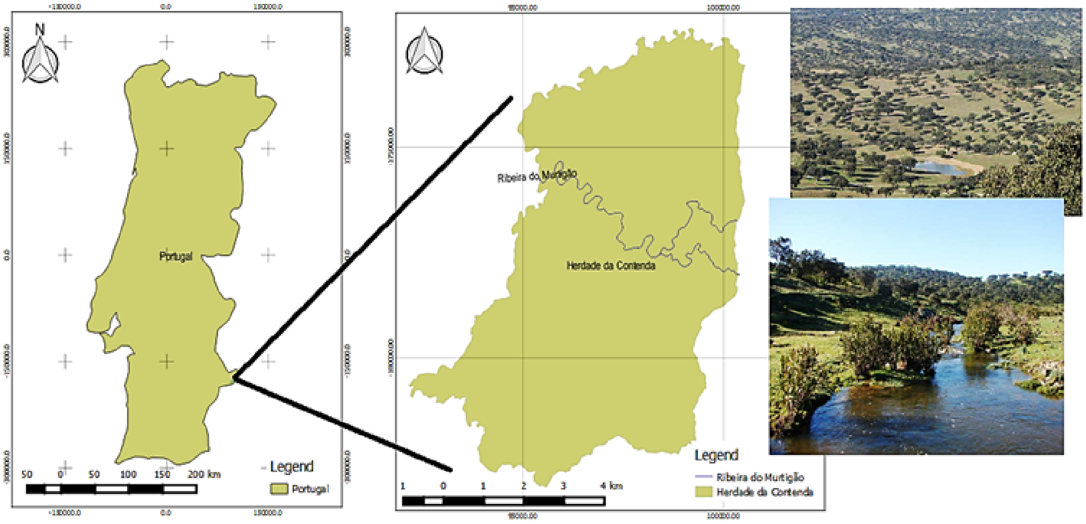

Figure 1. Study area (adapted from Duarte et al. (2016)).

Table 1. Dataset description of the study case.

Data type	Description	Resolution/Scale	Source
Vector – point	Carnivore in winter	-	Obtained in the field
Vector – point	Carnivore in summer	-	Obtained in the field
Vector – line	Contour lines	10 m equidistance	Generated from DEM
Vector – line	Rivers	1/100 000	DGT* (DGT - dgTerritório, 2015)
Vector – polygon	Land Cover map 2007	1/100 000	DGT* (DGT - dgTerritório, 2015)
Vector – polygon	Soil map	1/ 35 000	ICNF** (ICNF, 2015)
Raster	DEM	10 m	Obtained from flight
Raster	Slope	10 m	Generated from DEM

* DGT *(Direção Geral do Território).*
** ICNF *(Instituto da Conservação da Natureza e da Floresta)*

In order to introduce the data into the Web Maps, all the themes were projected to WGS84 (World Geodetic System 1984) in QGIS software. For each plugin were evaluated: i) the advantages (regarding for instance documentation, open source library, security, connectivity, among others); ii) disadvantages (regarding for instance the requirement of external programs, existence of subscription plans, among others); iii) a detailed comparison between the plugins considering if there have free plans or subscription plans considering also the limit for the data (when applicable); iv) the visualization and edition tools presented in each plugin (for instance, zoom in, zoom out, measure tools, pan, coordinates, creation of heat maps, data management tools, among others) and; v) a detailed comparison regarding the general functionalities such the existence of tutorials, the accessibility, the storage, the security, the cloud and the mobile application, among other functionalities.

2.2 QGIS2Web

QGIS2Web is the most popular plugin in QGIS to create Web Maps. QGIS2Web uses the open-source libraries *Leaflet*, *MapBox* and *OpenLayers* to store the created Web Maps.

The *Leaflet library* is a free and open-source *Javascript* library to build Web Maps. It was first launched in 2011, and supports mobile and desktop platforms with HTML5 and CSS3 support. *Leaflet* is the most popular library for interactive maps, and it is used along with *OpenLayers* and the *Google Maps Application Programming Interface* (API) in the known websites such as *FourSquare, Pinterest, Flickr,* among others (Leaflet, 2020). The *Leaflet* library allows users to display Web Maps in mosaics, hosted by a public server. It contains well-structured documentation with several tutorials. It supports the *GeoJSON* format. However, it has support for other formats such as CSV (Well-known Text), WKT (Well-known Text), TopoJSON, GPX (GPS eXchange Format; Geoapify (2020)).

The *OpenLayers* is a free and open source *Javascript* library for displaying map data in internet browsers such as mosaic and dynamic maps. It was first launched in 2006 and provides an API to build geographic maps on the internet similar to *Google Maps* and *Bing Maps* (Google Maps, 2020; Bing Maps, 2021). The *OpenLayers* library provides more features than *Leaflet* library such as the tools for map control. However, it requires complex knowledge to use projections and to define the coordinates (*LonLat* format; Leaflet (2020)). The documentation of *OpenLayers* contains *QuickStarts*, tutorials and many examples. It supports GeoRSS, Keyhole Markup Language (KML), Geography Markup Language (GML), *GeoJSON* and data from any source using Open Geospatial Consortium (OGC) standards such as Web Map Services (WMS) or Web Feature Service (WFS). The control and flexibility over the library are the main advantages of *OpenLayers*.

The *MapBox library* was created in 2010 by the same creators of *Leaflet*, and it allows to create personalized online maps for websites and applications such as *Foursquare, Lonely Planet, Facebook,* among others (MapBox, 2020). It significantly contributes to several open-source web mapping libraries and applications, including the *MapBox GL-JS Javascript* library, the *MBTiles* specification, the *TileMill mapping IDE*, among others. Data is obtained through open-source sources such as *OpenStreetMap* and *National Aeronautics and Space Administration* (NASA) and from private companies, such as *DigitalGlobe*.

This technology is based on *Node.js, Mapnik, Geospatial Data Abstraction Library* (GDAL) and *Leaflet* (MapBox, 2020). It contains a Software Development Kit (SDK), which is composed by a set of tools, allowing developers to create new applications. It is possible to find some similarities between *Mapbox* and *Leaflet* libraries. However, *MapBox* provides more features, data visualization options and higher quality in the vector maps creation.

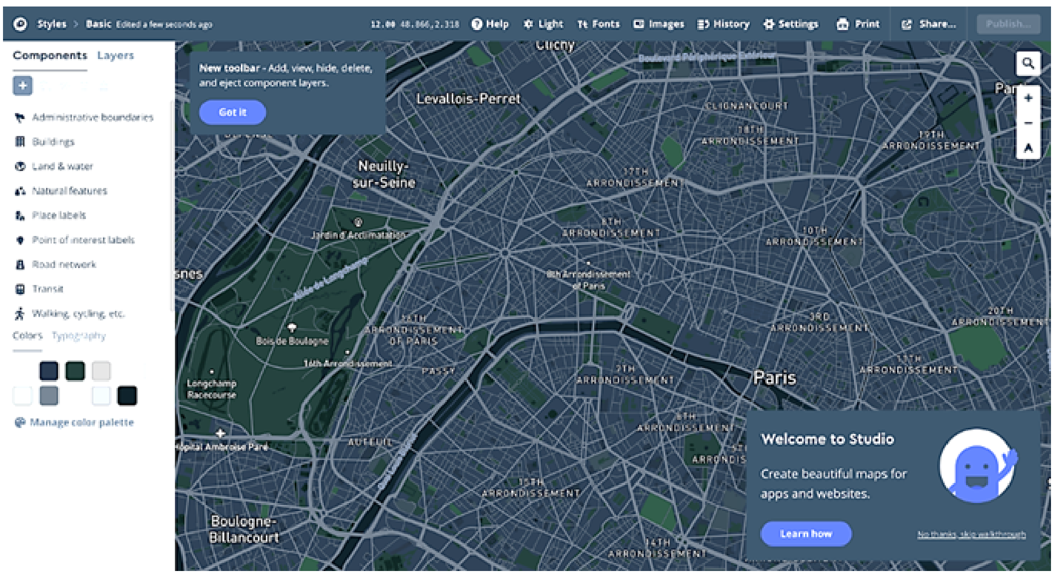

Figure 2. Web Map at official Mapbox website (source: https://www.mapbox.com/).

In this work, the QGIS2Web functionalities were defined in a Graphical User Interface (GUI) under QGIS software. Then the Web Map was exported in *GeoJSON* file. It can also be exported to a File Transfer Protocol (FTP) site, where it is possible to publish the Web Maps directly on the World Wide Web (WWW).

QGIS2Web exports the *HTML, CSS* and *Javascript* files required for the website creation to a local folder, allowing to open the Web Map in a personal browser. However, a server would be required to publish the map. The Web Map is only editable under QGIS software. QGIS2Web does not have extra features on the web page, such as the possibility of editing the map.

These functionalities are similar in the 3 libraries (*Leaflet, OpenLayers* and *MapBox*). However, the *MapBox* library contains a JS library that provides a web page to help the user to obtain extra tools for the Web Maps creation. This site allows the user to create Web Maps directly on it and transfer the file to the QGIS. Figure 2 presents an example of Web Map at official *Mapbox* website.

2.3 QGIS cloud

The QGIS Cloud is a powerful web GIS platform for publishing maps, data, and services on the internet. This plugin does not require a server or an infrastructure (QGIS Cloud, 2020). It provides a PostgreSQL 9 database extended with PostGIS 2. The user can modify the data storage by considering any compatible tool, such as *pgAdmin3*, the *QGIS browser* or the *QGIS DB-Manager*. It is also possible to share maps and data on the OGC compatible web page and display maps as WMS or download data as WFS. The users are free to edit the data directly on the web page or use the QGIS Cloud web GIS and the *Mobile Client* integrated into the QGIS Cloud with the Well-Formed Substring Table (WFS-T). There is also a functionality to provide high quality maps for printing as WMS. The data can also be stored in the PostgreSQL cloud. The access to the data is protected through a password and it is possible to access through Secure Shell (SSH). The QGIS Cloud provides two subscription plans: *QGIS Cloud Free*, where all the maps published on the internet can be freely accessed until 50 MB; and the *QGIS Cloud Pro*, where map access is limited.

The QGIS Cloud website requires the account creation and the free plan subscription. In the QGIS Cloud plugin (under QGIS environment) a database is created, and the data is uploaded to it. Finally, the map is published using the *Publish Map* button. A base map, *OSM, OpenTopoMap, OSM/ThunderForest, Wikipedia Maps or Bing Maps* can be also chosen from this GUI. The plugin provides 3 web publishing links and a customer support email: a link to the Web Map page, a Public WMS link to serve HTTP images, and finally a link to the map administrator, *Map Admin*. Therefore, the user can obtain a Web Map with public access through the QGIS Cloud website.

2.4 GIS Cloud Publisher

GIS Cloud Publisher is a QGIS plugin which allows to upload QGIS maps in Web Map form through the GIS Cloud website. It creates a data cloud for each user to save their Web Maps. This makes it much easier to transfer and publish GIS data from the personal computer to the cloud. This plugin has made a promising contribution to the GIS community by helping users who require a fast and accessible system to share larger maps or data sets with customers and make public that data. The map presented in QGIS is instantly replicated on a web page in the GIS Cloud account and easily shared via a link through a website (GIS Cloud, 2020).

The GIS Cloud editor allows the user to publish their maps and QGIS data to the GIS Cloud in just a few seconds, preserving the symbology and integrating the GIS data with the cloud. It is also possible to update all changes in the user's QGIS project and synchronize it with the maps published in the GIS cloud, as the project evolves.

It offers a wide variety of subscription plans for different types of functionality: free plans offering up to 100MB per account as well as viewing maps up to 1 smartphone and; extra QGIS plans if the user wants to create maps through the website (GIS Cloud, 2020). It is free for QGIS and ArcGIS.

It also requires a website account. Under QGIS software, the GUI is very intuitive since it provides step by step options. After publishing the map, GIS

Cloud Publisher provides two publishing options: (i) open the map in GIS Cloud; (ii) provide a link to another user.

This plugin provides several editing tools, such as for instance create, edit, add, share, export, duplicate, archive or update new maps by importing excel tables and adding bookmarks; edit, add, clone, and join shapefiles, apply a spatial filter; a buffer can be created, a point proximity relationship can be performed, or a heat map can be created.

2.5 Mappia Publisher

Mappia Publisher is an open-source web mapping platform that requires a free *GitHub* account to start creating the Web Maps. *GitHub* is a for-profit company that provides a hosting service for *Git* repositories (used for software development) based on a cloud (GitHub, 2020).

The plugin automatically configures the user's map for Web Map through *GitHub*. It is possible to customize the online interactions for Web Maps created through a friendly GUI. It also allows to use several Web Maps at the same time and does not require any server. It is possible to share Web Maps or combine maps from different sources, creating an interactive online platform. Through QGIS, Mappia Publisher creates tiles for display on the web page with a variety of zoom levels. *GitHub* helps to store files from QGIS, metadata, legends, and other information. The data stored on *GitHub* is completely under the control of the account's owner. It is possible to publish, delete and edit data without interference from Mappia Publisher (MappiaEarth, 2020).

The Mappia Publisher website provides a free online display map service (such as WMS or WTS) along with customization benefits. To display the maps, the Mappia Publisher platform loads the tiles and places them in the correct geographical position directly on *GitHub*, allowing it to work even without a private server. The user can share their source maps (*GitHub* has a 2GB map size limit), where it is controlled by the *Upload maps* parameter, and other users can download it directly from the Mappia Publisher platform.

Under QGIS software, the Web Map is created and exported to a public file linked to GitHub. After exporting, Mappia Publisher automatically opens a web page with the publication of the Web Map.

2.6 Recording times

The processing times (in seconds) of the creation of each Web Map were recorded. The procedures were performed in the computer CPU (Intel® Core™ i5-4278U CPU 2.60 GHz, with memory (8.00 GB RAM), and the operating system (Windows 10 Home v.1903). The times were processed under a connection to internet with the following configurations: 19 ms (Ping), 24.21 Mbps (Download) and 20.69 Mbps (Upload).

3 Results

The Web Maps were created based on each plugin investigated. The next sub-sections present the Web Maps obtained.

3.1 QGIS2Web

Under the QGIS2Web plugin, 3 Web Maps were created based on *Leaflet, OpenLayers* and *MapBox* libraries (Figure 3).

From Figure 3 was possible to verify that the 3 Web Map GUIs are very similar, composed by the same tools but with different interface widgets. The *Popups* in each Web Map have also different interfaces (Figure 4).

3.2 QGIS Cloud

The QGIS Cloud Web Map is presented in Figure 5. It contains the same functionalities as QGIS2Web but also offers the possibility to view and modify the map scale, the reference system and displayed map coordinates.

3.3 GIS Cloud Publisher

The GIS Cloud Publisher Web Map provides the functionalities similar to the other Web Maps, however, it provides menus and several editing tools (Figure 6).

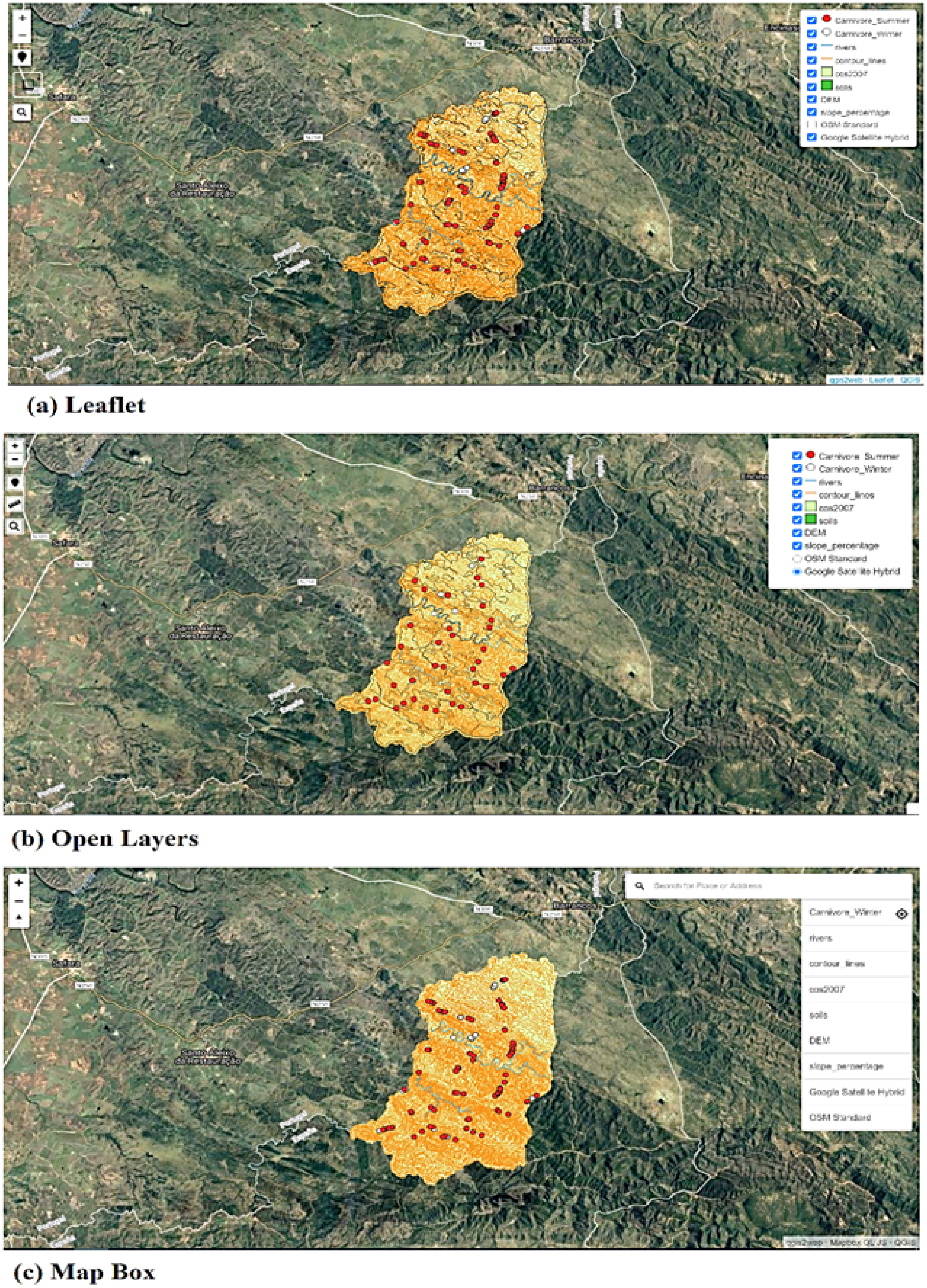

Figure 3. QGIS2Web web maps: a) *Leaflet*; b) *OpenLayers*; c) *MapBox*.

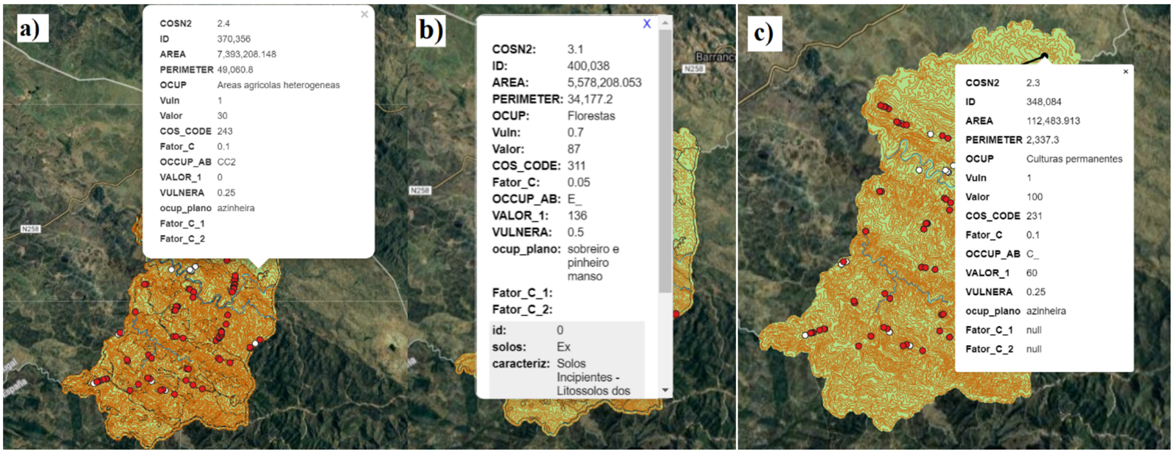

Figure 4. Popups: a) *Leaflet*, b) *OpenLayers* and c) *MapBox*.

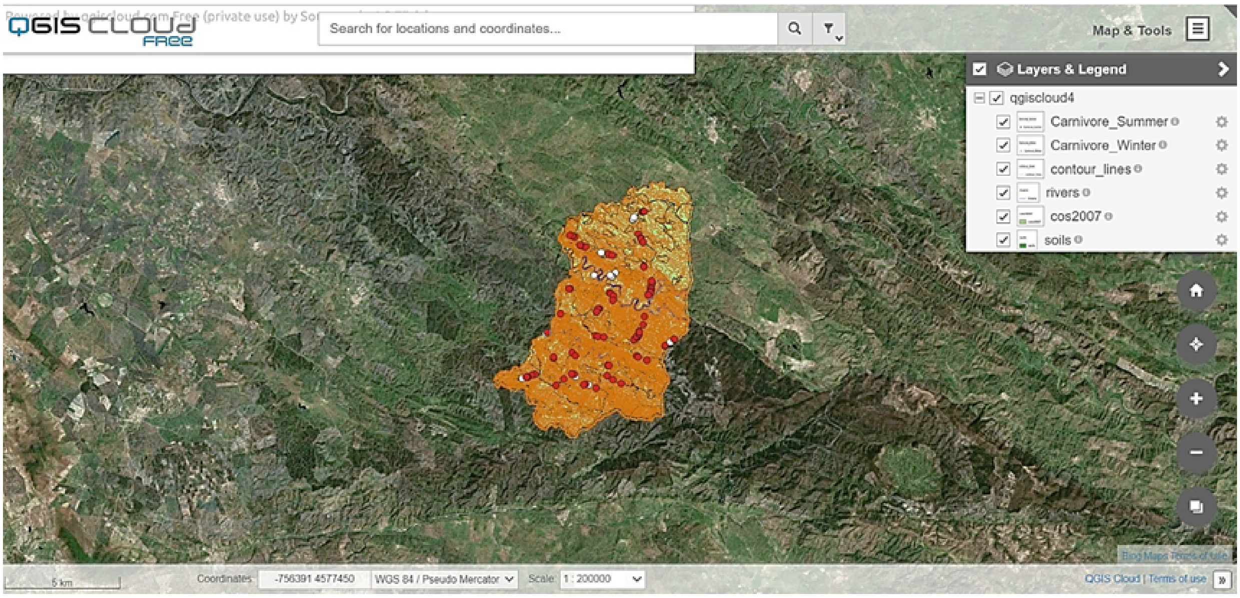

Figure 5. QGIS Cloud web map.

From Figure 6 it is possible to verify that beyond the visualization tools, it provides more editing tools (presented in Map, Layer, Analysis and Tools menus, Figure 7). In the map area, more tools are available such as: (i) *Info* button; (ii) *Select* tool; (iii) *Area Selection*; (iv) *Freehand Selection*; (v) *Show Google Street View*; (vi) *View Entire Map*; (vii) *Print*; (viii) *Scale*; and (ix) *Jump to Coordinates* (Figure 6).

3.4 Mappia Publisher

The Mappia Publisher Web Map offers similar visualization tools to the other Web Maps (Figure 8). However, it additionally provides: (i) user help tools; (ii) a tool for checking the information of an entity; (iii) a tool for visualizing metadata; (iv) enable and disable warning messages; (v) hide shapefile windows; and (vi) update new layers generated in QGIS.

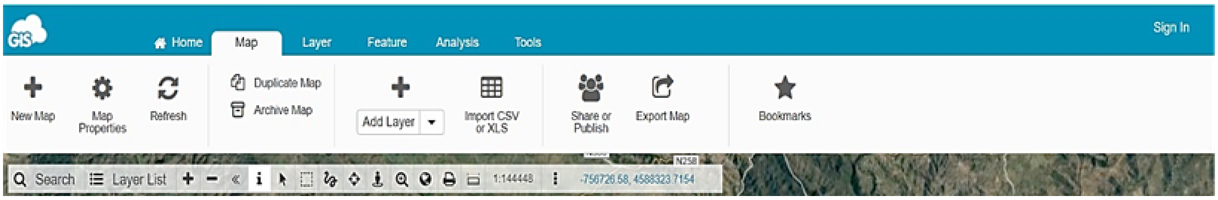

Figure 6. GIS Cloud Publisher web map functionalities.

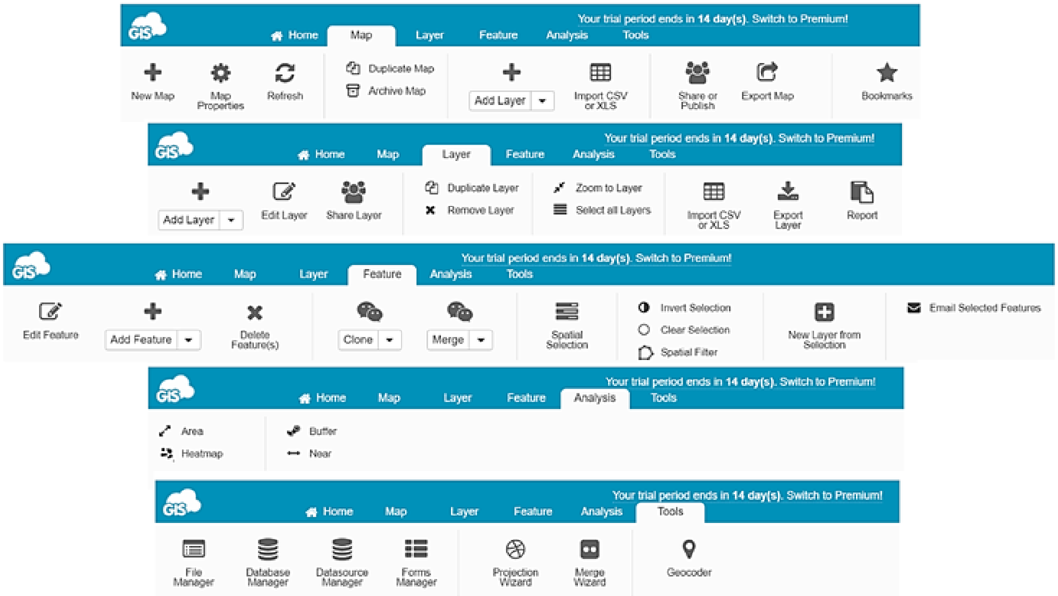

Figure 7. Detailed functionalities from GIS Cloud Publisher Web Map.

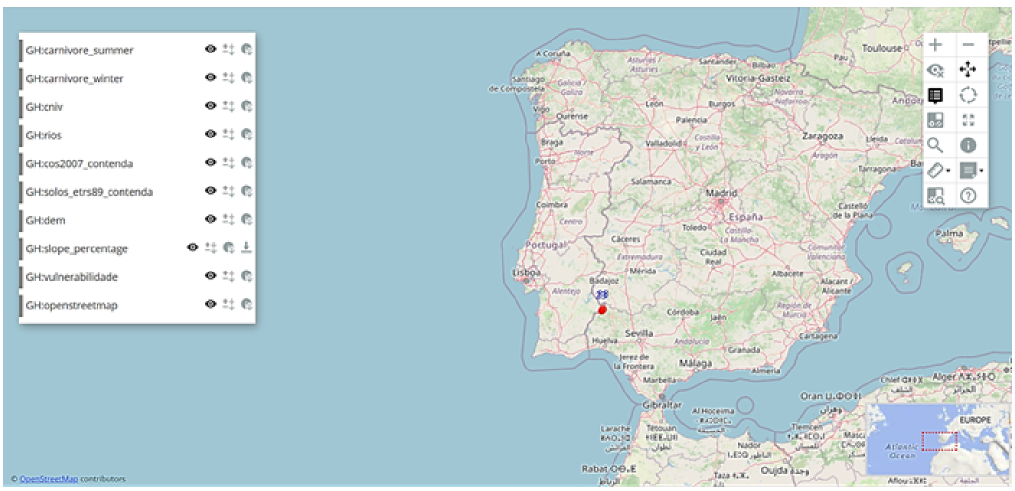

Figure 8. Mappia Publisher Web Map.

However, when zoomed in the case study zone, the Web Map does not correctly load the data (Figure 9), which can be a serious limitation to this plugin. Also, it was the Web Map with more time consumed in the creation.

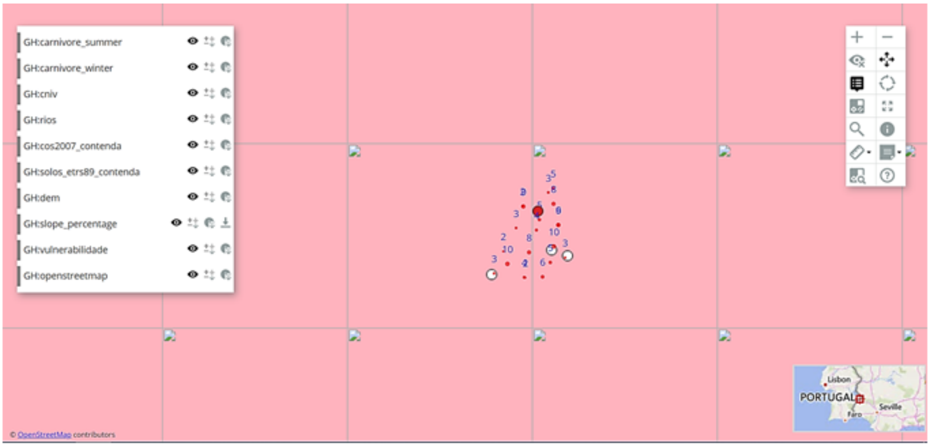

Figure 9. Zoom in to Mappia Publisher Web Map.

Table 2 presents the advantages and disadvantages regarding the most important features of each plugin. Table 3 provides a comparative analysis of the plans from each plugin, and Table 4 presents a comparative analysis of the visualization and editing tools associated to each plugin. Table 2 presented the advantages and disadvantages of each plugin, allowing to evaluate the compatibility with the user's needs. It was checked the type of programming language that each plugin uses, as well as the type of file it can export to. It is possible to visualize the tools embedded in the web pages for a better understanding of the Web Map. It also allows to evaluate the comparison of the storage for each plugin, as well as if it is protected by some type of security system on the website. It can also be checked if the plugin provides a web page that can be publicly accessed or if it requires external programs to perform this function.

From Table 3 it was concluded that the programs that offer full functionality over the plugin without requiring user subscription plans (open-source and free) are QGIS2Web and Mappia Publisher, where Mappia Publisher provides a Web Map preview page directly from the plugin and QGIS2Web provides the HTML code for the user to be able to publish on the internet. The plugins that offer an open-source plan, but with limit features, are defined in this work as partially free, as they can be used free of charge but with limitations in the use of some functionalities that are usually based on the storage, as such QGIS Cloud and GIS Cloud Publisher.

From Table 4 it was concluded that the GIS Cloud Publisher is the only plugin that provides edition tools. A summary of this comparative analysis is presented in Table 5.

From Table 5 it is possible to verify that GIS Cloud Publisher plugin contains almost all the evaluated elements, being the only plugin that allows to insert/use edition tools. However, it is not an open-free source, so it has costs to use. Table 5 allows to compare general characteristics between the four plugins evaluated.

3.5 Processing times

Table 6 presents the processing time regarding the four plugins analyzed. In terms of processing time, all plugins exported the Web Map almost instantly; however, the Mappia Publisher plugin took almost 2 hours to export it. The rest of the changes made after that export were almost instantaneous.

Table 2. Comparison of the four plugins regarding the advantages and disadvantages.

Plugins	Advantages	Disadvantages
QGIS2Web	- Open source library. - Supports HTML, CSS 3, GeoJSON, GeoRSS, KML, Node.js, Mapnik, GDAL. - Mobile application (MapBox library). - API documentation. - Simple for users with no experience in QGIS. - The most used plugin by the open source community.	- Requires external programs for the web map to be published. - Requires a base map. - Few web map editing tools on the web page.
QGIS Cloud	- No online infrastructure required. - PostgreSQ9 database extended with PostGIS2. - Possibility to share maps with OGC or via WMS and download via WFS. - Print high quality maps (WMS). - Security SSL. - Password protection. - No need for external programs for the web map to be public. - Simple for users with no experience in QGIS. - Mobile application.	- Momentary failures on the website server. - Only offers full functionality with subscription plan. - Does not work with the MacOS system. - Storage of free plan only 50MB.
GIS Cloud Publisher	- Cloud creation. - Possibility to transfer QGIS data (vectors, rasters, WMS, WFS) and their symbology. - Points, lines, polygons, categories and labels are supported. - Possibility to update changes on the map. - Share public maps (URL link). - Share private maps within the GIS cloud. - Connection with secure SSL. - No need for external programs for the web map to be public. - Simple for users with no experience in QGIS. - Compatibility with QGIS 3 and QGIS 2.	- Only offers full functionality with a subscription plan. - Storage of only 100MB for free plan.
Mappia Publisher	- Opensource. - GitHub account storage. - 2GB limit for data. - Do not require external programs to be public. - Offers a web page for the map display service (with WMS or WTS). - Simple for users with no experience in QGIS.	- The web map takes too long to create. - Some bugs.

Table 3. Comparison of the four plugins regarding the subscription plans.

Plugins	Free Plans	Subscription Plans
QGIS2Web	- Only free plans.	- Not applicable.
QGIS Cloud	- Free plan with 50MB cloud storage and a PostGIS 2.0 database.	- Offers web maps with restricted access, SSL support, PostGIS 2.0 databases with 500 MB/total, daily backups, web map editing tool on QGIS Cloud, domain names, logos and Custom CSS. -Additional plan to increase cloud storage and 10 additional databases.
GIS Cloud Publisher	- Offers a free plan with 100MB cloud storage and 10,000 vectors integrated within the vector files.	- The GIS Cloud Publisher Premium/Map Editor plan: private web maps, storage up to 1GB, 200,000 vectors integrated into vector files and premium support. - The Map Viewer plan: private web maps, personalized branding and access via the smartphone application. - The Map Portal plan: a domain and personalized branding and public access to 50,000 Map Views. - The Mobile Data Collection : the possibility to publish web maps in a smartphone application. - There is a plan to increase cloud storage for an addition of 500,000, 1,000,000, 2,500,000, 5,000,000, 7,500,000, 10,000,000, for vectors within the vector files. - A plan to increase storage for the addition of 10GB, 100GB and 1 TB, for rasters and storage of media files.
Mappia Publisher	- Only free plans.	- Not applicable.

Table 4. Visualization and edition tools for each plugin.

Plugins		QGIS2Web	QGIS Cloud	GIS Cloud Publisher	Mappia Publisher
Zoom in/out	Visualization Tools	✓	✓	✓	✓
Geolocation		✓	✓	✓	-
Distance Measure		✓	✓	✓	✓
Areas Measure		-	✓	✓	✓
Position Measure		-	✓	✓	-
GMS coodinates measure		-	✓	-	-
Search Bar		✓	✓	✓	✓
Reset bearing to north		✓	-	-	-
On/Off Layers		-	✓	✓	✓
On/Off Base Maps		-	✓	✓	-
Add/Remove Layer		-	-	✓	-
Update Layer		-	-	-	✓
Share Layer		-	-	-	✓
Duplicate Layer		-	-	-	✓
Export Layer		-	-	-	✓
Zoom to Layer		-	✓	✓	✓
Popups		✓	✓	✓	-
Hide Popups		-	-	-	✓
Zoom Selection by area		-	-	✓	✓
Modify Map Scale		-	✓	-	-
Projection Information		-	✓	✓	-
Google Street Map Viewer		-	-	✓	-
Print		-	-	✓	-
Help Tool		-	-	✓	✓
Web map Legend		-	✓	-	✓
Metadata		-	-	-	✓
On/Off Map Interactions		-	-	-	✓
Save web map	Edition Tools	-	-	✓	-
Add Selected Layers		-	-	✓	-
Remove Layer		-	-	✓	-
Join Layers		-	-	✓	-
Spatial Selection/Invert		-	-	✓	-
Spatial Filter		-	-	✓	-
Import Excel tables		-	-	✓	-
Add Bookmarks		-	-	✓	-
Email Selected Layers		-	-	✓	-
Analyse Areas		-	-	✓	-
Analyse Buffers		-	-	✓	-
Point Proximity Relation		-	-	✓	-
Heat Maps		-	-	✓	-
Files Managemnt		-	-	✓	-
Database		-	-	✓	-
Data Source		-	-	✓	-
Forms Management		-	-	✓	-
Projection and Join Assistent		-	-	✓	-
Geocoder		-	-	✓	-

Table 5. General functionalities of each plugin.

General funcionalities	QGIS2Web	QGIS Cloud	GIS Cloud Publisher	Mappia Publisher
Opensource/ Completely Free	✓	-	-	✓
Opensource/Partially Free	-	✓	✓	-
Tutorials	✓	✓	✓	✓
Acessibility	✓	✓	✓	✓
Storage	✓	✓	✓	✓
Independency	-	✓	✓	✓
Competition	-	✓	✓	-
Visualization Tools	✓	✓	✓	✓
Edition Tools	-	-	✓	-
Extra Web Page	-	✓	✓	✓
SSL Security	-	✓	✓	-
Cloud	-	✓	✓	-
Mobile Application	-	✓	✓	-

Table 6. Processing times (in seconds) for each Web Map.

Plugins	QGIS2Web			QGIS Cloud	GIS Cloud Publisher	Mappia Publisher
	Leaflet	*OpenLayers*	*MapBox*			
Processing Time (s)	5	5	5	25	52	7800

4 Discussion

Tables 2 to 5 present the comparison between the four plugins at several aspects: advantages/ disadvantages; plans; visualization and edition tools; and general functionalities. The information presented in these tables will help to support the user decision when the objective is to create a Web Map using QGIS software. In general, the four plugins have several advantages in terms of accessibility by supplying tutorials and online support, and providing a set of visualization tools. Some of these plugins provide accessibility for users with no experience in QGIS. This feature is undoubtedly an advantage for a user who is new in this environment. The four plugins provide tutorials and help videos. All the plugins provide visualization tools. However, only the GIS Cloud Publisher provides viewing and editing tools within the Web Map. In terms of storage, each plugin provides a variety of storage according to each one's functionality. QGIS2Web provides more storage than the others. Mappia Publisher provides 2GB of web storage. GIS Cloud Publisher provides up to 100MB storage in the user's free account cloud and can reach up to 1GB if the user subscribes the plan. The QGIS Cloud plugin provides 50MB of cloud storage on the user's free account and can reach up to 1GB if the user subscribes the plan. In terms of data security, QGIS Cloud and GIS Cloud Publisher use secure SSL connection. These plugins offer the user extra security so that no one can access their Web Maps without their permission. Mappia Publisher uses the security provided by the *GitHub* page and QGIS2Web is not composed by any type of security plan.

The four plugins work within QGIS software, however there are some plugins that use web pages to provide extra functionality such as QGIS Cloud, GIS Cloud Publisher and Mappia Publisher. Unfortunately, QGIS2Web does not have a web page, so it requires a different program to publish the Web Map on the internet. This type of plugins facilitates the connection between the internet and QGIS software, as well as provide an opportunity for new GIS users. The plugins attract a new audience for QGIS and offer an overview for all users.

Although the QGIS plugins to create Web Maps cannot compete with proprietary platforms, such as ArcGIS Online, one of the most used platforms, they can provide an extremely quick and effective way of collaborative mapping and it can be a good first step for many GIS users. The ArcGIS Online, part of the Esri Geospatial Cloud (ArcGIS, 2021), is a proprietary platform and it allows to connect people, locations, and data through interactive maps.

According to the information collected and presented in the Tables 2 to 5, some future recommendations can be considered: i) create the possibility to add edition tools in QGIS2Web, QGIS Cloud and Mappia Publisher; ii) add a mobile application to the plugins since it is crucial to give access to the Web Map through mobile devices; iii) the Mappia Publisher plugin requires more time to process the data and this should be minimized, so the optimization of the code to process the data is also crucial and; iv) the plugins that require external programs are more difficult to use, so these programs should be integrated in the plugins.

Currently, Web Maps are created and shared with everyone, so it is important to learn how to create Web Maps or even how to use them. The four plugins tested in this study are composed by several tutorials and support to work with them. Thus, any beginner or advanced user can be prepared to use these plugins. The open-source concept implies that a code can be updated at any time by anyone, being a great advantage to applications developed under open-source software and related with the creation of Web Maps, as part of a collaborative project.

5 Conclusions

This paper presented a comparison between four QGIS plugins considering their advantages, disadvantages, functionalities, subscription plans and the accessibility to create Web Maps. The existence of plugins under GIS open-source software provides the possibility to automatize procedures without requiring programming language. The plugins chosen to test and compare allows to create Web Maps and it can be very useful to users without experience in programming language to create from scratch a simple Web Map. As QGIS provides several plugins to perform that steps, four of them, QGIS2Web, QGIS Cloud, GIS Cloud Publisher and Mappia Publisher were tested and compared. It was concluded that all the four plugins provide visualization tools, however the GIS Cloud Publisher provide more visualization tools than the others and also provides edition tools. In terms of subscription plans, only the QGIS2Web is completely free, however host the Web Maps in local server. From all the advantages and disadvantages, even with the subscription plan, the GIS Cloud Publisher proved to be a more robust plugin providing a set of visualization and edition tools to support the creation of a Web Map.

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References

ArcGIS (2021). Arcgis. Accessed 9 january 2021. Online: https://bit.ly/2PTjeLH.

Bhatia, T., Singh, H., Litoria, P., and Pateriya, B. (2018). Web gis development using open source leaflet and geoserver toolkit. *Int. J. Comput. Sci. Technol*, 9(3. Online: https://bit.ly/3ej0Wgq).

Bing Maps (2021). Bing maps. Accessed 25 september 2020. Online: https://binged.it/3h52216.

Cartwright, W., Crampton, J., Gartner, G., Miller, S., Mitchell, K., Siekierska, E., and Wood, J. (2001). Geospatial information visualization user interface issues. *Cartography and Geographic Information Science*, 28(1):45–60. Online: https://bit.ly/3xJa5qh.

Chen, P. and Nguyen, T. C. (2017). Integrating web map service and building information modeling for location and transportation analysis in green building certification process. *Automation in Construction*, 77:52–66. Online: https://bit.ly/3nPi8NL.

DGT - dgTerritório (2015). Direão-geral do território. Accessed on 22 April 2015. Online: https://bit.ly/3xOsp1d.

Duarte, L., Espinha, J., and Teodoro, A. (2019). An open source gis-based application for the assessment of groundwater vulnerability to pollution. *Environments*, 6(7):86. Online: https://bit.ly/3xPTdxU.

Duarte, L., Silva, P., and Teodoro, A. (2018a). Development of a qgis plugin to obtain parameters and elements of plantation trees and vineyards with aerial photographs. *ISPRS International Journal of Geo-Information*, 7(3):109. Online: https://bit.ly/3toihZq.

Duarte, L., Teodoro, A., Gonçalves, J., Soares, D., and Cunha, M. (2016). Assessing soil erosion risk using rusle through a gis open source desktop and web application. *Environmental monitoring and assessment*, 188(6):351. Online: https://bit.ly/33jGHJi.

Duarte, L., Teodoro, A., Monteiro, A., Cunha, M., and Gonçalves, H. (2018b). Qphenometrics: An open source software application to assess vegetation phenology metrics. *Computers and Electronics in Agriculture*, 148:82–94. Online: https://bit.ly/3thbKQo.

Garnero, G. and Vigna, I. (2018). Gis instruments in support of the forestry activities: A case study. *Journal of Agricultural Science and Technology B*, 8:388–395. Online: https://bit.ly/2PTN179.

Geoapify (2020). Leaflet vs openlayers. what to choose? Accessed 25 september 2020. Online: https://bit.ly/3uot33n.

Gharbi, A. and Haddadi, S. (2020). Application of the mobile gis for the improvement of the knowledge and the management of the road network. *Applied Geomatics*, 12(1):23–39. Online: https://bit.ly/33mlH4x.

GIS Cloud (2020). Real-time mapping. Accessed 25 september 2020. Online: https://bit.ly/3vNColk.

GitHub (2020). Where the world builds software. Accessed 25 september 2020. Online: https://bit.ly/3eiDuzL.

Google Maps (2020). Google maps. Accessed 25 september 2020. Online: https://bit.ly/3nPGlDz.

Hossain, M. and Meyer, H. (2018). Concepts and methods of embedding statistical data into maps. *International Journal of Scientific and Research Publications (IJSRP)*, 8(5):2250–3153. Online: https://bit.ly/3nSRcfK.

ICNF (2015). Instituto da conservaçãda natureza e das florestas. Accessed on 22 April 2015. Online: https://bit.ly/3b4FTfE.

Leaflet (2020). Leaflet, an open-source javascript library for mobile-friendly interactive maps. Accessed 25 september 2020. Online: https://bit.ly/3b8nsX8.

MapBox (2020). Maps and location for developers. Accessed 25 september 2020. Online: https://bit.ly/3f0hTeq.

MappiaEarth (2020). Mappiaearth. Accessed 25 september 2020. Online: https://bit.ly/3ejluW2.

Parker, C., May, A., and Mitchell, V. (2013). The role of vgi and pgi in supporting outdoor activities. *Applied ergonomics*, 44(6):886–894. Online: https://bit.ly/3h3CxwW.

QGIS Cloud (2020). Qgis cloud. Accessed 25 september 2020. Online: https://bit.ly/3h68PYc.

Stallman, P. (2007). Why 'open source' misses the point of free software, gnu operating system. Accessed February 2011. Online: https://bit.ly/3ti9Oap.

Sukic, E. and Rančić, D. (2011). Fos gis solutions in web mapping. *Technics Technologies Education Management*, 6(4):1083–1088. Online: https://bit.ly/3enhIuU.

Teodoro, A. and Duarte, L. (2013). Forest fire risk maps: a gis open source application–a case study in norwest of portugal. *International Journal of Geographical Information Science*, 27(4):699–720. Online: https://bit.ly/3nYoRF1.

Veenendaal, B., Brovelli, M., and Li, S. (2017). Review of web mapping: Eras, trends and directions. *ISPRS International Journal of Geo-Information*, 6(10):317. Online: https://bit.ly/3xSKN91.

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Spectral characterization and monitoring of mangrove forests with remote sensing in the Colombian Pacific Coast: Bajo Baudó, Chocó

Caracterización espectral y monitoreo de bosques de manglar con Teledetección en el litoral Pacífico colombiano: Bajo Baudó, Chocó

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Abstract

The Colombian Pacific has extensive areas in mangrove forests (MF), which is a strategic ecosystem of great environmental and socioeconomic for climate change mitigation. This work aimed to perform spectral characterization and monitoring of 66.59 km2 for four MF densities in Bajo Baudó (Colombia), using three Landsat images (1998, 2014 and 2017), combinations of spectral bands and three vegetation indices (VI) (Normalized Difference Vegetation Index-NDVI, Soil Adjusted Vegetation Index-SAVI and the Combined Mangrove Recognition Index-CMRI). The results showed that the best combination of spectral bands for visual identification of MF corresponded to infrared color (NIR, Red, Green) and false-color composite 1 (NIR, SWIR, Red). The spectral sign of MFs had different behaviors in four densities under the conditions of high tide and low tide. During the 19 years analyzed, there was a difference of up to 17.9% in the average reflectance value in MF. Similarly, the values of VI were proportional to the densities of MF, but their value was reduced by tidal effects at the time of capturing the images; the largest increases in VI were recorded over the coastal area of land-water transition, where there is a strong interaction with the tidal condition. This research contributes to the spatial characterization and monitoring of MF with remote sensors and the spectral study of this important ecosystem in Colombia.

Keywords: Tide, spectral signature, vegetation indexes, Landsat, reflectance.

Resumen

El Pacífico colombiano posee extensas zonas en bosques de manglar (BM), que es un ecosistema estratégico de gran importancia ambiental y socioeconómica para la mitigación del cambio climático. Este trabajo tuvo por objetivo realizar la caracterización espectral y monitoreo de 66,59 km2 para cuatro densidades de BM en el Bajo Baudó (Colombia), empleando tres imágenes Landsat (1998, 2014 y 2017), combinaciones de bandas espectrales y tres índices de vegetación (IV) (Índice de Vegetación de Diferencia Normalizada-NDVI, Índice de Vegetación Ajustado al Suelo-SAVI y el Índice combinado de reconocimiento de manglares-CMRI). Los resultados demostraron que la mejor combinación de bandas espectrales para la identificación visual de los BM correspondió a infrarrojo color (NIR, Rojo, Verde) y falso color compuesto 1 (NIR, SWIR, Rojo). La firma espectral de los BM tuvo diferentes comportamientos para las cuatro densidades bajo las condiciones de pleamar y bajamar. Durante los 19 años analizados, se registró una diferencia de hasta el 17,9 % en el valor promedio de la reflectancia en los BM. De igual manera, los valores de IV fueron proporcionales a las densidades de BM, pero su valor se notó reducido por efectos de la marea al momento de la captura de las imágenes; los mayores aumentos de IV se registraron sobre la zona costera de transición tierra-agua donde existe una fuerte interacción con la condición mareal. Esta investigación aporta a la caracterización y monitoreo espacial de BM con sensores remotos y el estudio espectral de este importante ecosistema en Colombia.

Palabras clave: Marea, firma espectral, índices de vegetación, Landsat, reflectancia.

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1 Introduction

Mangrove forests (MF) are ecosystems that are very important for coastal zones of tropical and subtropical countries; they are relevant for the preservation as they host a large number of species of flora and fauna, and are vital and represent an economic source for rural communities (FAO, 2007; Monirul et al., 2018). Mangroves are key to the carbon cycle and climate change mitigation actions (Kuenzer et al., 2011; Giri, 2016; Pham et al., 2019). Despite the multiple benefits, worldwide MF are strongly degraded, mainly due to agricultural activities, urban expansion, coastal development and induced phenomena such as sea-level rise (Rhyma et al., 2020); therefore, regular monitoring in the MF is necessary to contribute to the ecosystem and to serve as a planning tool for the preservation of ecosystem services for future generations (FAO, 2007).

MFs are located in intertidal areas that are difficult to access and with varying environmental conditions that largely limit logistical aspects to conduct periodic monitoring in the field (Zhang et al., 2017; Jia et al., 2019). In this regard, Remote Sensing is a valuable tool for monitoring these ecosystems, as it allows monitoring of the MF at regional and local scales (Giri, 2016; Muhsoni et al., 2018). MFs are easily identifiable in the infrared bands due to the amount of moisture in the vegetation (Purwanto and Asriningrum, 2019). These spectral characteristics also determine the measurement of photosynthetic activity of the MF by using vegetation indices (IV) (Bannari et al., 1995; Rhyma et al., 2020).

The Normalized Difference Vegetation Index (NDVI) proposed by Rouse et al. (1974) is one of the most used for the study of vegetation worldwide (Chuvieco, 2010); this IV has as its main characteristic in the relationship between infrared and red bands, which efficiently determines the differences in the absorption of light from plants (Asner, 1998). NDVI has been widely used for monitoring MF and has an easy interpretation since it has a measuring range of -1 to +1, where positive values reflect areas with vegetation (Rhyma et al., 2020).

On the other hand, The Soil-Adjusted Vegetation Index (SAVI) (Huete, 1988) was developed to eliminate the influence of soil on reflectance absorption by vegetation, this includes the L parameter which can obtain values between 0 and 1 to eliminate the effect of the soil, i.e., is an improved NDVI (Bannari et al., 1995). The Combined Mangrove Recognition Index (CMRI) was developed by Gupta et al. (2018) to uniquely identify MF; its main characteristic is the subtraction between the NDVI and the NNormalized Difference Water Index (NDWI), facilitating the recognition of the BM since it incorporates the moisture content of the vegetation. The CMRI has a measurement range between -2 and +2, where positive values represent areas with MF. The use of spectral parameters and the specific development of IVs has allowed great advances in obtaining the quantitative and qualitative information necessary for the characterization of MF in different zones (Conti et al., 2016).

Different studies worldwide have incorporated the use of remote sensor images and remote sensing techniques for mangrove monitoring; this is the case with Rebelo-Mochel and Ponzoni (2007), who used Landsat 5 TM images and field data to characterize four species in MF in Turiau Bay, northeastern Brazil. Omar et al. (2018) used Landsat images for spectral signature characterization and implemented the use of IV to monitor changes in Malaysia's MF for three dates (1990, 2000 and 2017). Similarly, Ávila et al. (2020) determined the spatial-temporal variation of MF in Cuba using Landsat data for 35 years (1984 - 2019) and implemented two IVs (NDVI and EVI) in their monitoring for conservation purposes. Umroh and Sari (2016) used false color combinations in Landsat and NDVI images to monitor the different densities of MF on Pongok Island in Indonesia. Additionally, Rhyma et al. (2020) used NDVI and different L parameter setting values in the SAVI index for MF monitoring, using medium spatial resolution images at the Matang reserve in Malaysia. For his part, Chen (2020) implemented the use of CMRI and NDVI for monitoring MF in Dongzhaigang (China) with medium-resolution satellite images.

At the regional level, Galeano et al. (2017) used images from high-resolution remote sensors incorporating NDVI and climate factors in MF monitoring in the Rosario Islands in the Colombian Caribbean. Perea-Ardila et al. (2019) mapped dense MF in the municipality of Buenaventura, central zone of the Colombian Pacific, and detailed some basic spectral signatures of this ecosystem using Sentinel

2 images. The studies mentioned above highlight the importance of the use of remote sensing for the characterization of MF, monitoring at different scales and with different methodological approaches.

Colombia, along the Pacific coast, has approximately 2094,03 km^2 mangrove forests (Rodríguez-Rodríguez et al., 2016), an area that can correspond to 70 and 80% of the country's total MF (Wilkie and Fortuna, 2003). This ecosystem requires constant monitoring, as it provides multiple ecosystem services in terms of conservation and is considered to be an ecosystem highly threatened by climate change (Chow, 2017). The aim of this paper is to use remote sensing techniques and three vegetation indices (NDVI, SAVI, CMRI) to characterize spectrally and monitor four densities of MF using three-year Landsat images (1998, 2014 and 2017) in different tidal states in Lower Baudó – Chocoano. With the results obtained in this research, progress will be made in the spectral study and spatial monitoring of MF with Landsat images in strategic coastal ecosystems of Colombia.

2 Materials and methods

2.1 Study area

The study area was located in the north of the Colombian Pacific, on the coastal area of the municipality of Bajo Baudó, Chocó (Figure 1). According to the classification of life zones established by Holdridge (1978), the area corresponds to a Tropical Very Humid Forest (bmhT). Annual precipitation ranges from 4000 to 7000 mm of rain and has an average annual temperature of more than 24°C (Blanco et al., 2014). Land geoforms and climatic conditions in the area lead MF to be mostly on the coast, with heights above 40 m (Rodríguez-Rodríguez et al., 2016).

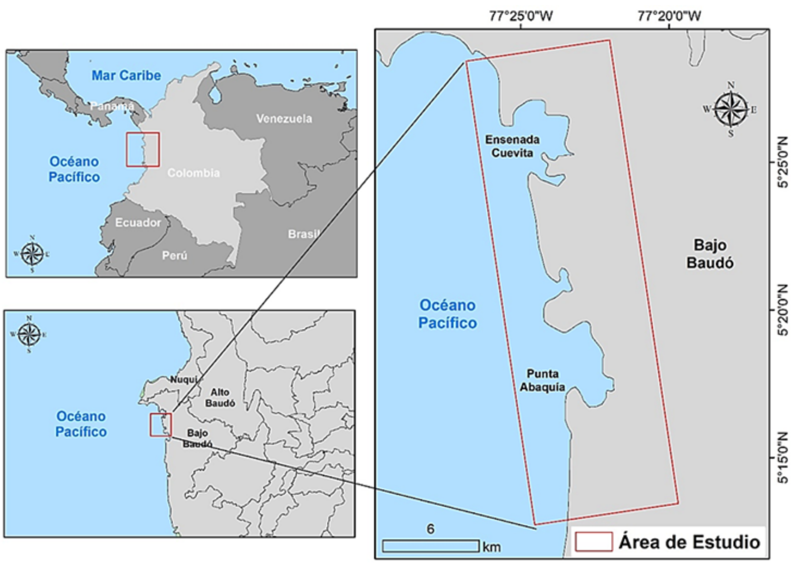


Figure 1. Location of the study area.

The flow diagram used in this research is presented in Figure 2. It was observed in the processes used (i) the digital processing of Landsat images, (ii) spectral signature analysis of mangrove forests by spectral sign and (iii) calculation of vegetation indices for different mangrove densities. Similarly, geospatial data management and analysis of Landsat images was performed using ArcGIS 10.3 software (ESRI, 2014).

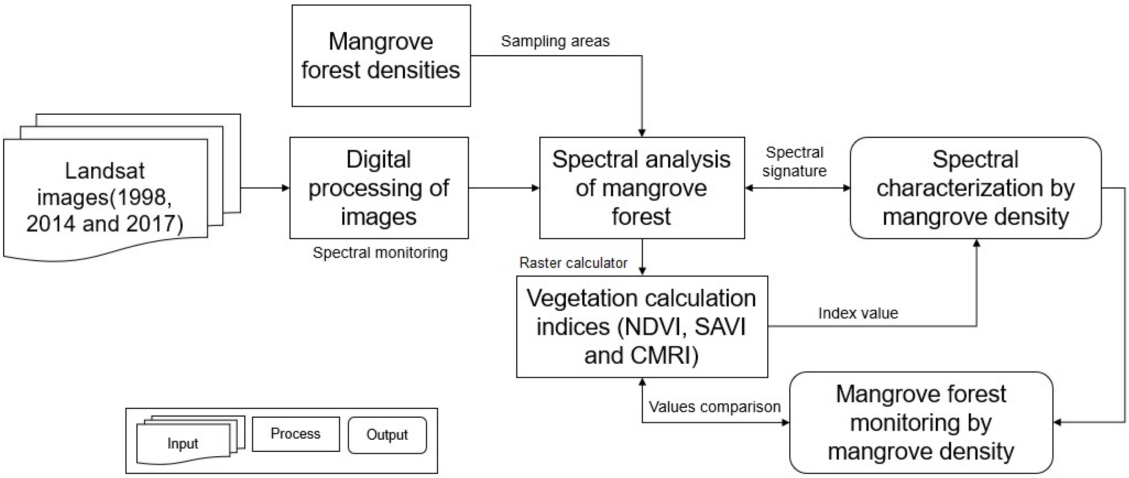


Figure 2. Flow diagram used.

2.2 Remote sensor images

Three Landsat images with 30 m spatial resolution for the years 1998, 2014 and 2017 ((USGS, 1998, 2014, 2017) were freely downloaded through the official website of the U.S. Geological Survey (USGS) https://earthexplorer.usgs.gov/ (USGS, 2020). The selection of the images corresponded to products that did not present cloud affectation, since this area presents high cloudiness during most of the year (Table 1).

Information on marine conditions was identified on the basis of data from the RedMPOMM (Ocean Parameters and Marine Meteorology Monitoring Network) of Colombia, of the Maritime General Office (https://geohub-dimar.opendata.arcgis.com/) (Dirección General Marítima., 2020). In this step, the date and time of the Landsat image was identified and validated with respect to the tide conditions recorded for that time.

2.3 Pre-processing of satellite images

Images underwent pre-processing; their digital levels (DL) were transformed to physical units (full-time reflectance at the Top of Atmosphere-ToA) using the parameters for reflectance normalization established by Ariza (2013); USGS (2018b) for Landsat 8 and Chander and Markham (2003); USGS (2018a) for Landsat 5 and 7, respectively (Table 2). Similarly, the images were cut out according to the study area, then the band fusion was carried out for their respective analysis.

2.4 Definition of mangrove forest densities

Vectorized 2019 data for the 1:2000 scale MF density developed by the Pacific Oceanographic and Hydrographic Research Center (CCCP) (DIMAR-CCCP, 2013) were used. This mapping was performed under visual image interpretation techniques using very high spatial resolution orthophotos and Light Detection and Ranging (LIDAR), which have the spatial characterization of the different MF in relation to their density and height, allowing to establish four density categories corresponding to: High Dense Mangroves (MDA), High Open Mangrove (MAA), Low Dense Mangrove (MDB) and Low Open Mangrove (MAB). A mask was made with this layer, where the limits of mangrove coverage were defined in Landsat images and their corresponding densities were determined.

2.5 Spectral analysis of mangrove forests

To observe the behavior of MF at different wavelengths, 4 combinations of bands described by Horning (2014); Franco (2017) were used, which were: True color (Red, Green, Blue), Infrared color (NIR, Red, Green) and composite false color 1 (NIR, SWIR, Red) and composite false color 2 (SWIR, NIR,

Table 1. Characteristics of the Landsat images used.

Characteristics	Landsat 5 TM	Landsat 8 OLI	Landsat 7 ETM+
ID Product	LT50100561998003CPE00	LC80100562014239LGN01	LE70100562017111EDC00
Capture date	03/01/98	27/08/14	21/05/17
Column/Row		010 - 056	
Cloud cover	16.00 %	18.53 %	21.00 %
Solar angle	46.62°	63.51°	64.39°
Fubmetric resolution	8 Bits	12 Bits	8 Bits
	Band 1 - Blue (0.45-0.52)	Band 2 - Blue (0.45-0.51)	Band 1 - Blue (0.45-0.52)
	Band 2 - Green (0.52-0.60)	Band 3 - Green (0.53-0.59)	Band 2 - Green (0.52-0.60)
Wavelength	Band 3 - Red (0.63-0.69)	Band 4 - Red (0.64-0.67)	Band 3 - Roja (0.63-0.69)
	Band 4 - NIR (0.77-0.90)	Band 5 - NIR (0.85-0.88)	Band 4 - NIR (0.77-0.90)
	Band 5 - SWIR1 (1.55-1.75)	Band 6 - SWIR1 (1.57-1.65)	Band 5 - SWIR1 (1.55-1.75)
Tide state	Unknown	High tide	Low tide
Projection		UTM zone 18	

Based on the metadata of the images and tidal records of the RedMPOMM.

Red). Polygons for cloud masking were digitized for each image to avoid the influence of clouds and shadows in spectral analysis of MF (Zhu and Woodcock, 2014; Pimple et al., 2018). In accordance with Congalton's statistical sampling recommendations for spectral analysis (Congalton, 1991), a random set of 200 sampling points distributed equally among the different MF densities (50 for each established density) was established, the average ToA reflectance values were established for each image, and the corresponding spectral signs were recorded in the evaluated time period.

2.6 Calculation of Vegetation Indices

To monitor MFs in the selected time period, the IV indices described in Table 3 were used.

2.7 Mangrove forest monitoring with vegetation indices

A comparison was made between IV values, taking into account MF densities for 1998-2014, 2014-2017 and 1998-2017 as a reference and identifying the variation in the IV value for each density. Graphical comparisons were made between the IV value and the MF density, where the behavior was determined for each period of time studied.

3 Results

3.1 Pre-processing of satellite images

NDs of the images were transformed to ToA reflectance values (Table 4), this process allowed to obtain a radiometric improvement by largely eliminating the atmospheric effects present in the original products. Images were also clipped to the study area and the clouds present in the study area were masked.

3.2 Mangrove forest density

According to the digital information described in DIMAR-CCCP (2013), the analysis of spatial distribution and MF density was carried out in the area of study; a total extension of MF was found of 66.59 km^2. The density of High Dense Mangrove (MDA) was the most predominant in the area, while Low Open Mangrove (MAB) presented the least extent in the study site (Table 5).

Table 2. Calibration Parameters of Landsat 8 images.

Sensor	Equation
Landsat 5 TM Landsat 7 ETM+	$L_\lambda = \left(\frac{LMAX_\lambda - LMIN_\lambda}{Qcalmax - Qcalmin}\right)(Q_{cal} - Q_{calmin}) + LMIN_\lambda$ $\rho_\lambda = \frac{\pi L_\lambda d^2}{ESUN_\lambda cos\theta_s}$ With: L_λ: Spectral radiation at the sensor opening $[W/(m^2 sr\mu m)]$. $Qcal$: Calibrated pixel quantified value $[DN]$. $Qcalmin$: The minimum quantified value of the calibrated pixel $[DN]$. $Qcalmax$: The maximum quantified value of the calibrated pixel $[DN]$. $LMIN_\lambda$: Spectral radiance at the sensor that scales to Qcalmin $[W/(m^2 sr\ \mu m)]$. $LMAX_\lambda$: Spectral radiance on the sensor that scales to Qcalmax $[W/(m^2 sr\ \mu m)]$. ρ_λ: Planetary reflectance of the ToA. d: Earth-Sun distance [astronomical units]. $ESUN_\lambda$: Exoatmospheric mean solar irradiance $[W/(m^2)]$. θ_s: Solar zenithal angle.
Landsat 8 OLI	$\rho'_\lambda = \frac{M_p Q_{cal} + A_p}{sen\theta_{se}}$ With: ρ'_λ: Planetary reflectance or on top of the atmosphere-ToA. M_p: Specific scaling multiplicative factor. Q_{cal}: Calibrated pixel quantified value. A_p: Specific scaling additive factor. θ_{se}: Solar elevation angle of the center of the scene.

3.3 Spectral analysis of mangrove forests

Four spectral combinations were obtained for satellite products, and MF could be visually distinguished from other plant coverages (Table 6). The true color combination showed that the vegetation of MF showed dark green tones and a low brightness for the image of 1998 and 2014, and slightly lighter green tone for the image of 2014 that is not influenced by tide. For the infrared color combination, MF showed dark red tones and low brightness; the 2014 image in high tide showed a much lower brightness, highlighting the large moisture content of the vegetation compared to other plant coverings that presented reddish to pinkish tones. Similarly, for the composite false color 1 combination, MF showed a brown color with a dark tone for the image of 1998 and 2014, showing large moisture content in the vegetation and great contrast against other coverages. The composite false color combination 2 revealed a moderately dark green coloring, allowing easy recognition of coverage; however, differences in tones with respect to the tidal state were observed

Table 3. Description of the vegetation indices and water index used in this study.

Index	Equation	Reference
Normalized Difference Vegetation Index (NDVI)	$\frac{NIR - Red}{NIR + Red}$	Rouse et al. (1974)
Soil-Adjusted Vegetation Index (SAVI)	$\frac{NIR - Red}{NIR + Red + L}(1+L)$	Huete (1988)
Normalized Difference Water Index (NDWI)*	$\frac{Green - NIR}{Green + NIR}$	Gao (1996)
Combined Mangrove Recognition Index (CMRI)	NDVI-NDWI	Gupta et al. (2018)

With: L=0.5. *NDWI was only used to determine CMRI.

Table 4. Statistical summary of reflectance values obtained from Landsat images.

Parameters	Landsat image used														
	Landsat TM (1998)					Landsat OLI (2014)					Landsat ETM+ (2017)				
	B1	B2	B3	B4	B5	B2	B3	B4	B5	B6	B1	B2	B3	B4	B5
Min	0.00	0.00	0.00	0.01	0.00	0.07	0.04	0.02	0.00	0.00	0.01	0.01	0.01	0.03	0.00
Max	0.44	0.89	0.76	0.95	0.63	0.75	0.75	0.79	0.90	0.59	0.34	0.38	0.35	0.80	0.50
Av	0.03	0.05	0.03	0.17	0.07	0.10	0.08	0.06	0.20	0.09	0.03	0.04	0.03	0.32	0.13
Std	0.03	0.05	0.03	0.14	0.05	0.04	0.04	0.05	0.15	0.06	0.03	0.03	0.03	0.19	0.07

With B1 (Band 1), B2 (Band 2), B3 (Band 3), B4 (Band 4), B5 (Band 5), Minimum (Min), Maximum (Max), Average (Av) and Standard deviation (Std).

3.4 Mangrove forest spectral sign

The spectral sign for ToA reflectance was calculated for all three images (Figure 3). It was found that the average reflectance for NIR band of 2017 image with respect to the NIR reflectance of 2014 and 1998 showed a difference of 12.6% and 17.9%, respectively.

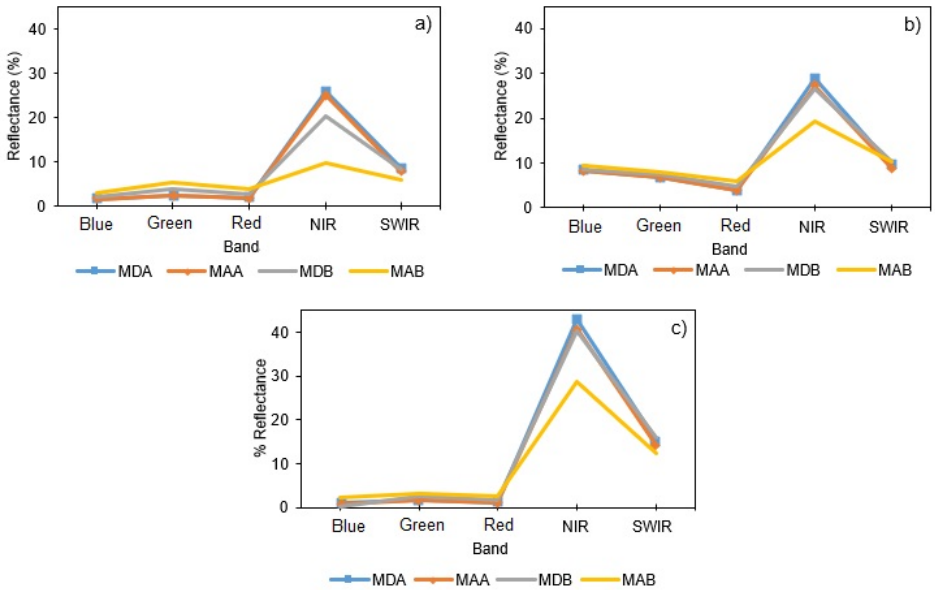


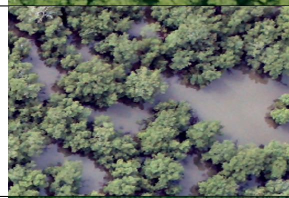
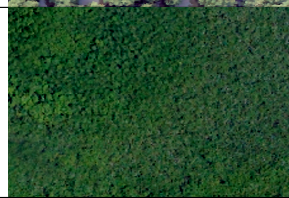
Figure 3. Spectral sign estimated for MF in Landsat products (a) 1998, (b) 2014 and (c) 2017. Where: High Dense Mangrove (MDA), High Open Mangrove (MAA), Low Dense Mangrove (MDB), Low Open Mangrove (MAB).

In all the cases presented, MF in their different densities (MDA, MAA, MDB, and MAB) showed higher reflectance values in the near infrared, being consistent with the average spectral sign of vegetation. In this sense, the minimum, maximum and average reflectance values recorded for each MF density are shown in Table 7.

3.5 Vegetation index

It was observed that values for MAB density in the three IVs in 1998 were the lowest with 0.28, 021 and 0.41 for NDVI, SAVI and CMRI, respectively (Figure 4). It was found that IV values tend to decrease slightly according to density, and it was also observed that high tide conditions in the 2014 image tend to have lower IV values than 2017 image. Ta-

Table 5. Density of mangrove forests present in the study area.

Mangrove density	**Description**	**Area (km^2)**	**Extension (%)**	**Detail**
High Density Mangrove (MDA)	Mangroves with heights above 15 m cwhose density represents more than 70 % coverage in their unit.	53.60	80.49	
High Open Mangrove (MAA)	Mangroves with heights above 15 m whose density represents between 30 and 70 % coverage in their unit.	9.8	13.94	
Low Density Mangrove (MDB)	Mangroves with heights lower than 15 m whose density represents more than 70 % coverage in their unit.	3.18	4.78	
Low Open Mangrove (MAB)	Mangrove with heights below 15 m whose density represents between 30 and 70 % coverage in their unit.	0.53	0.8	
TOTAL		66.59	100.00 %	

ble 8 shows the minimum, maximum and average values of IVs recorded for each year at the different MF densities present in the study area.

3.6 Mangrove forest monitoring

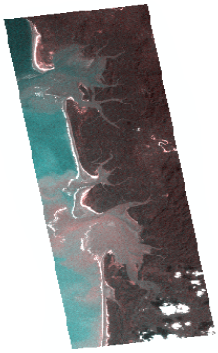
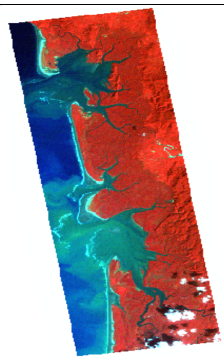
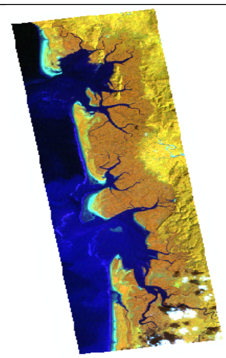
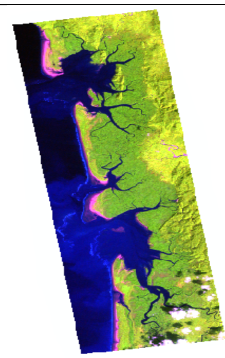
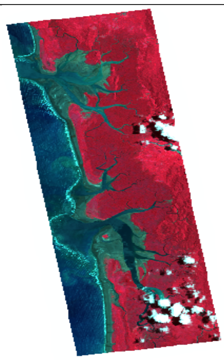
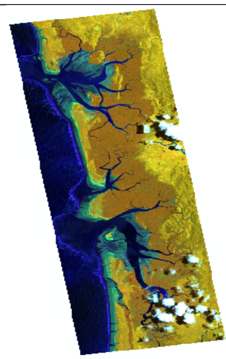
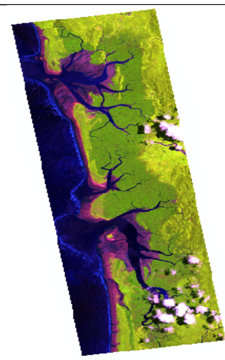
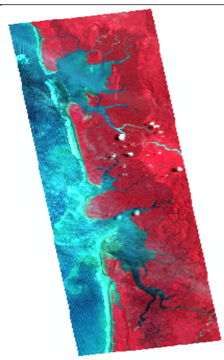
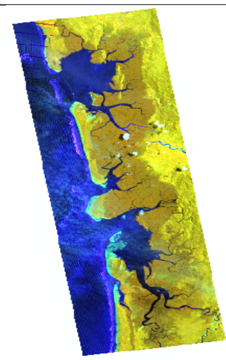
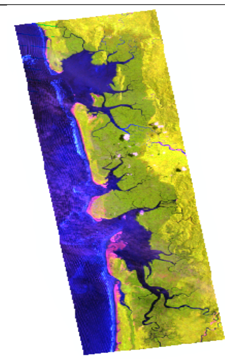
An average increase in the value of NDVI and CMRI for MAB of 0.19 and 0.42 was observed between 1998-2014 (Figure 5). Increases were observed over coastal areas that are constantly interacting with the tide.

For its part, the period 2014-2017 recorded an increase for SAVI values of more than 0.5 in all densities. The period 1998-2017 recorded an average increase in NDVI and CMRI values of 0.09 and 0.35 for MDB and 0.31 and 0.95 for the MAB, respectively; Likewise, SAVI presented increases in value higher than 0.2 for all densities (Figure 6).

4 Discussion

The combination of spectral bands is a visual analysis technique that allows identifying different types of coverage through its spectral characteristics ((Chuvieco, 1995; Pérez and De la Riva, 1998; Horning, 2014; Mohamed, 2017). Its application to the MF is valid to the extent that combinations that highlight this coverage are used, such as the infra-

Table 6. Combinations of bands used in the research.

Combinations of bands			
True color	**Infrared color**	**False composite 1**	**False composite 2**
Landsat 5 - 1998			
			
Landsat 8 - 2014			
			
Landsat 7 - 2017			
			

red color (NIR, Red, Green) and the false composite color 1 (NIR, SWIR, Red) in accordance with what is mentioned by Pagkalinawan (2014). However, an important aspect to consider when performing spectral analysis on MF is the presence of clouds and shadows, since this region has a large volume of precipitation (Blanco et al., 2014), which can greatly affect MF reflectance values and can be a limiting factor in performing multi-temporal analysis and primary changes as expressed by Pimple et al. (2018) and (Wang et al., 2019). While this study found low cloud coverage, masking removed a portion of the mangrove in the southern zone, causing uncertainty about the reflectance values for the removed area.

Table 7. Estimated average reflectance values for mangrove forest densities.

Band	Landsat 5 - 1998											
	MDA			MAA			MDB			MAB		
	Min	Max	Av	Min	Max	Av	Min	Max	Av	Min	Max	Av
Blue	0.8	2.8	1.5	0.8	2.5	1.5	1.2	4.3	2.1	1.0	6.7	3.0
Green	1.0	5.0	2.4	1.0	4.5	2.4	1.9	8.1	3.7	1.4	13.1	5.4
Red	0.9	2.9	1.8	0.9	2.6	1.7	0.9	6.3	2.7	1.6	8.3	3.8
NIR	16.5	32.8	26.0	13.3	30.5	25.0	2.1	31.0	20.3	1.6	32.8	9.8
SWIR	5.4	14.5	8.5	5.2	10.0	7.8	1.4	15.0	8.3	1.2	18.0	5.8
	Landsat 8 - 2014											
Blue	7.9	14.2	8.3	7.6	10.6	8.2	8.1	11.1	8.6	8.3	11.2	9.5
Green	6.2	12.8	7.0	5.4	9.1	6.8	6.1	9.6	7.5	6.8	9.8	8.1
Red	3.3	10.5	4.0	3.0	6.7	3.9	3.7	9.0	4.7	4.0	8.8	6.0
NIR	20.1	34.7	28.9	12.2	36.5	27.3	14.1	33.8	26.6	9.2	31.1	19.3
SWIR	7.1	15.7	9.6	3.8	11.3	8.9	5.7	13.0	10.4	7.0	16.2	10.4
	Landsat 7 - 2017											
Blue	0.3	2.7	1.0	0.0	2.3	0.7	1.2	3.2	0.3	0.5	4.7	2.2
Green	0.6	3.1	1.8	0.8	3.5	1.6	1.5	3.9	2.5	1.2	4.9	3.1
Red	0.5	2.4	1.2	0.5	2.8	1.0	0.9	3.4	1.8	1.1	4.7	2.7
NIR	28.2	51.2	43.0	1.8	48.9	40.8	16.1	48.9	40.2	12.0	47.2	28.7
SWIR	10.0	19.2	15.2	8.9	17.2	14.2	7.2	20.5	15.9	4.7	24.4	12.3

Where: Minimum (Min), Maximum (Max) and Average (Av).

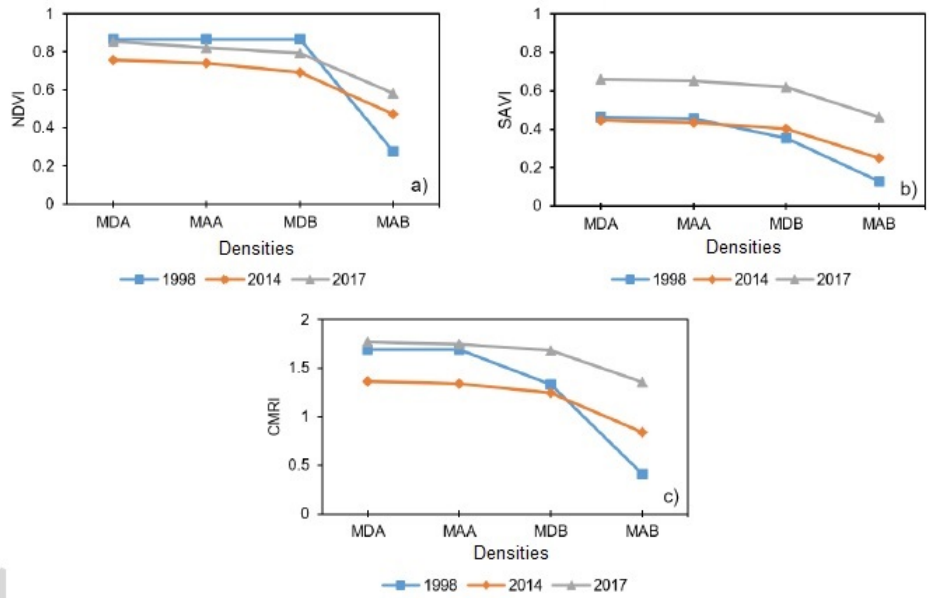


Figure 4. Estimated values for vegetation indices according to mangrove forest densities and analyzed season (a) NDVI (b) SAVI and (c) CMRI. Where: High Dense Mangrove (MDA), High Open Mangrove (MAA), Low Dense Mangrove (MDB), Low Open Mangrove (MAB).

The reflectance of the infrared band of 1998 and 2014 varied from that of 2017, between 12.6 and 17.9%, respectively; however, these values are within the range reported by authors such as Mondal et al. (2018) and Perea-Ardila et al. (2019). Moreover, MAB for 1998 had an average reflectance in the infrared band of 9%, which is close to that reported by Vaghela et al. (2018) for open mangroves in India. Low values in infrared reflectance can be caused by the high moisture content in mangroves by

Table 8. Values of vegetation indices for each mangroves density.

Index	Landsat 5 - 1998											
	MDA			**MAA**			**MDB**			**MAB**		
	Min	Max	Av	Min	Max	Av	Min	Max	Av	Min	Max	Av
NDVI	-0.6	0.96	0.87	-0.2	0.95	0.87	-0.6	0.96	0.87	-0.62	0.92	0.28
SAVI	-0.1	0.62	0.46	-0.03	0.58	0.45	-0.1	0.56	0.36	-0.1	0.62	0.13
CMRI	-1.3	1.93	1.69	-0.5	1.92	1.69	-0.9	1.86	1.34	-1.34	1.8	0.41
	Landsat 8 - 2014											
NDVI	-0.1	0.84	0.76	0.07	0.83	0.74	0.18	0.83	0.69	0.18	0.83	0.69
SAVI	0.03	0.63	0.45	0.02	0.58	0.43	0.07	0.62	0.4	12	0.57	0.25
CMRI	-0.4	1.56	1.37	-0.1	1.53	1.34	0.3	1.53	1.25	-0.01	1.5	0.84
	Landsat 7 - 2017											
NDVI	0.26	1.32	0.86	0.21	1.21	0.82	0.24	1.22	0.79	0.16	0.16	0.58
SAVI	0.29	0.83	0.66	0.15	0.79	0.65	0.26	0.78	0.62	115	0.74	0.46
CMRI	1.01	2.26	1.77	0.64	2.13	1.75	0.98	2.1	1.68	0.51	1.98	1.36

Where: Minimum (Min), Maximum (Max) and Average (Av).

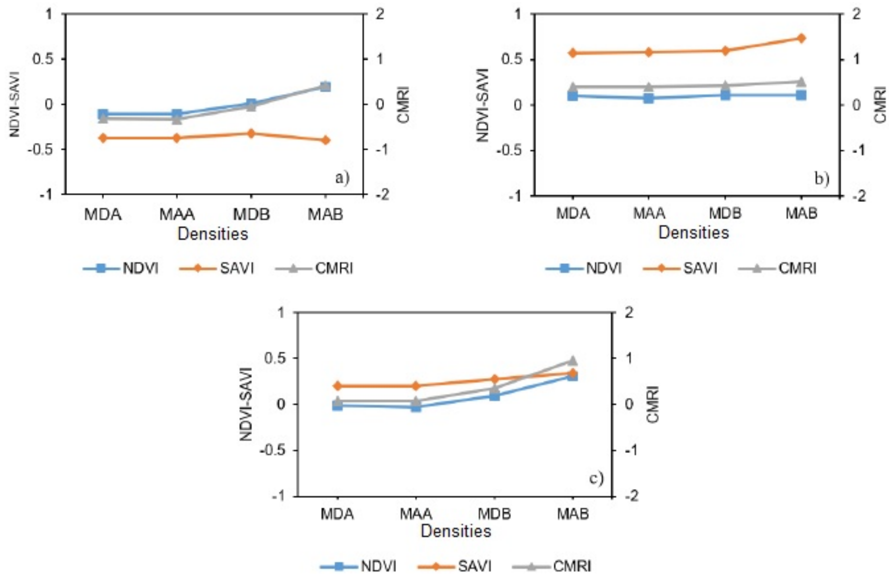


Figure 5. Behavior of vegetation indices for different mangrove densities a) 1998-2014, b) 2014-2017 and c) 1998-2017.

the increase in tides (Winarso and Purwanto, 2017; Gupta et al., 2018); on the contrary, reflectivity in the infrared band reported for 2017 showed high values (greater than 40 %) for three of the MF densities (MDA, MAA and MDB), while MAB obtained average values above 28 % in low tide conditions, results that agree with those reported by Zhang et al. (2017) and Xia et al. (2018).

The spectral sign of MF may vary due to the effects of the tide; therefore, it is affected due to the amount of water under MF at the moment of obtaining the image. Because of the latter, different spectral responses can be obtained for MF at different dates and densities. It usually tends to underestimate the mangrove surface with images that only consider a single tidal state. The latter aspect is very important for remote sensing research in mangroves Zhang and Tian (2013). The behavior of the IV values of the years 2014 and 2017 was similar to that described for infrared reflectance, but with a decrease in the value of the image in high tide, also, the value of the IVs decreased as the density of MF decreased (NDVI and CMRI better showed this situation).

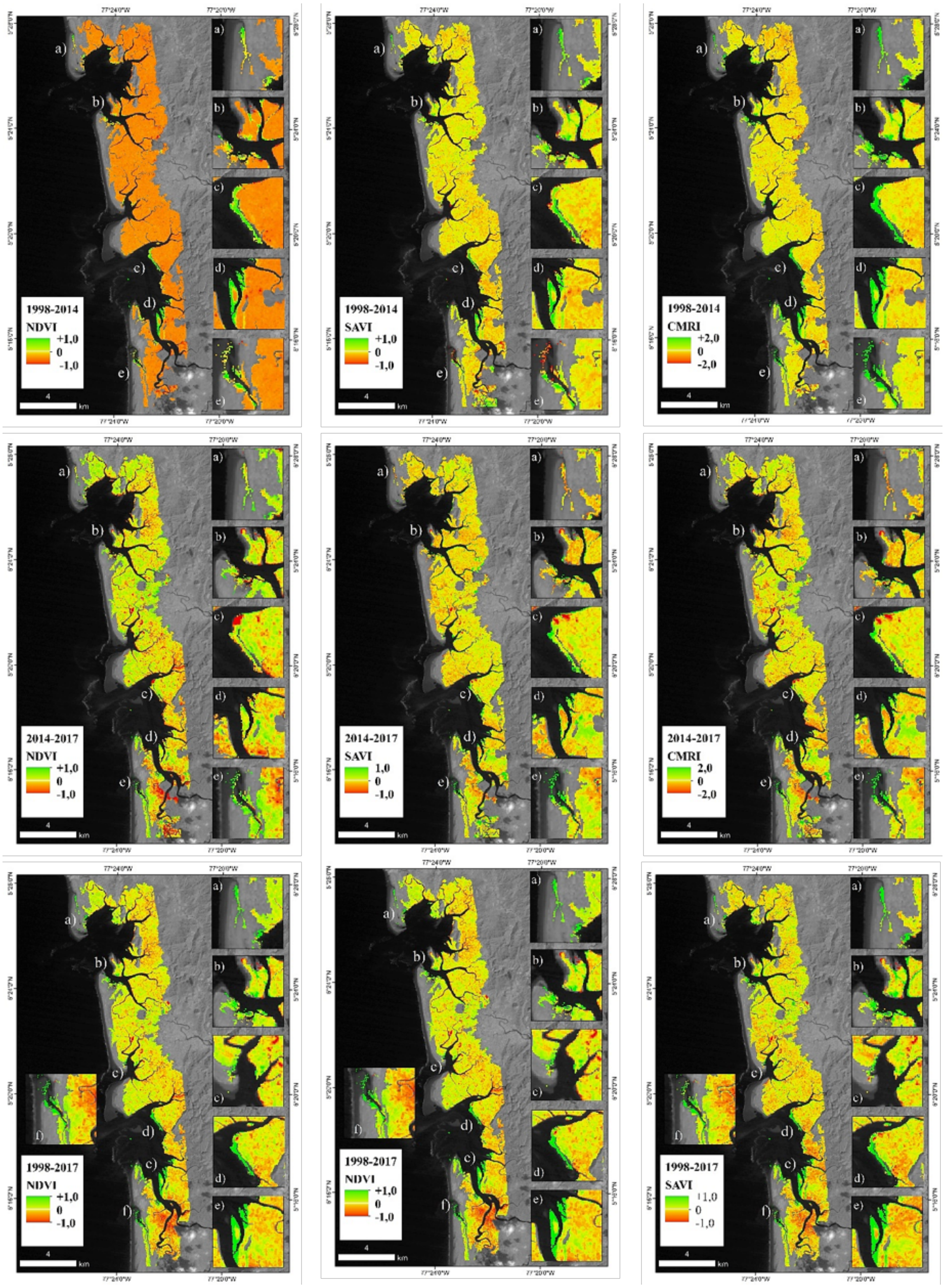


Figure 6. Vegetation indices for monitoring mangrove forests. (a), (b), (c), (d), (e), (f).

The spatial-temporal evaluation of IVs (1998-2014, 2014-2017 and 1998-2017) showed that changes in these indices occurred in the period 1998-2014, where there was an increase in the mean MAB value of 19 % in NDVI. For the period 1998-2017, the positive variation in the mean value was 31 % for NDVI, however, these variations in the IV were recorded in respect of MF located mainly in the land-sea strip, where there is a strong interaction of tide, and mangroves may be submerged periodically, generating a difference between the IV values (Jia et al., 2019; Xia et al., 2020). Similarly, when the 2014-2017 comparison was made, the mean values of NDVI and CMRI remained with a constant positive trend close to zero (0), this being the comparison of images in high tide and low tide.

The lowest SAVI value was +0.13 for MAB in the 1998 image, values that are similar to those reported by Rhyma et al. (2020) for mangroves in Malaysia using SPOT images; however, in the 1998-2014 comparison, it was observed that the average values tended to negative changes (reductions that may exceed 30 %), whereas for 2014-2017 the mean values of SAVI were greater than 50 % for all densities. This variation may be related to the findings of Rhyma et al. (2020) who noted that different values for the adjustment L factor of SAVI index should be tested at the different mangrove densities, as their value should be adjusted according to the soil moisture conditions due to the tide at each site. Similarly, Xia et al. (2020) indicated that NDVI and SAVI yield better in mangroves when analyses are performed with images captured at low tide, as IV cannot efficiently detect submerged mangroves, making characterization and monitoring difficult.

CMRI proposal is recent, but has been applied in different mangrove monitoring studies worldwide (Ahmad et al., 2019; Chen, 2020; Diniz et al., 2019; Ghosh et al., 2020). This study showed a first application of CMRI for mangrove monitoring in Colombia. The results shown indicated that MF were in constant photosynthetic production over 19 years and that the indices value demonstrated that MF in that particular site was in very good physiological condition. This IV could yield better results for images with different tidal conditions by eliminating the effect of moisture content on soil by using NDWI (Baloloy et al., 2020).

5 Conclusions

Landsat images are an important resource for mangrove monitoring, as they allow their identification through the spectral response of MF and the possibility of space-time analysis over a long period of time. Visual identification of MF in Landsat products should be done using combinations of bands, using NIR such as infrared color (NIR, Red, Green) and composite false color 1 (NIR, SWIR, Red). In this sense, the spectral response of MF is affected by the humidity conditions caused by the fluctuation of tidal conditions. The use of IVs allowed to recognize that the coastal area showed constant changes in its values. Mainly influenced by the tidal state; this aspect needs to be taken into account when analyzing IVs in MF as it is essential for the implementation of other more detailed analysis and classification processes, in order to obtain the least uncertainty possible. This study used CMRI, which is an IV developed specifically for MF studies, and in this case, it showed good yields. This research is a reference for future research in the spectral characterization and monitoring of MF with Landsat images on the northern coast of the Colombian Pacific.

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References

Ahmad, Z., Luqman, M., Suharni, M., Noor, S., Taib, A., and Shaheed, M. (2019). Impact of coastal development on mangrove distribution in c6ytherating estuary, pahang, malaysia. *Malaysian Journal of Fundamental and Applied Sciences*, 15(3):456–461. Online:https://bit.ly/36OYYje.

Ariza, A. (2013). Descripción y corrección de productos landsat 8 ldcm (landsat data continuity mission) versión 1.0. Technical report, Centro de

Investigación y Desarrollo – CIAF, Instituto Geográfico Agustín Codazzi, Bogotá.

Asner, G. (1998). Biophysical and biochemical sources of variability in canopy reflectance. *Remote sensing of Environment*, 64(3):234–253. Online:https://bit.ly/3hVvgzg.

Ávila, D., Curbelo, E., Madrigal, L., and Pérez, R. (2020). Variación espacio-temporal de la respuesta espectral en manglares de la habana, cuba, evaluada con sensores remotos. *Revista de Biología Tropical*, 68(1):321–335. Online:https://bit.ly/3kF9SQM.

Baloloy, A., Blanco, A., Raymund, A., and Nadaoka, K. (2020). Development and application of a new mangrove vegetation index (mvi) for rapid and accurate mangrove mapping. *ISPRS Journal of Photogrammetry and Remote Sensing*, 166:95–117. Online:https://bit.ly/2Tw2dcq.

Bannari, A., Morin, D., Bonn, F., and Huete, A. (1995). A review of vegetation indices. *Remote sensing reviews*, 13(1-2):95–120. Online:https://bit.ly/3Bw8ENw.

Blanco, J. F., Escobar-Sierra, C., and Carvajal-Quintero, J. D. (2014). Gorgona, baudó y darién (chocó biogeográfico, colombia): ecorregiones modelo para los estudios ecológicos de comunidades de quebradas costeras. *Revista de Biología Tropical*, 62(1):43–64. Online:https://bit.ly/2UQYl6z.

Chander, G. and Markham, B. (2003). Revised landsat-5 tm radiometric calibration procedures and postcalibration dynamic ranges. *IEEE Transactions on geoscience and remote sensing*, 41(11):2674–2677. Online:https://n9.cl/wygmu.

Chen, N. (2020). Mapping mangrove in dongzhaigang, china using sentinel-2 imagery. *Journal of Applied Remote Sensing*, 14(1):1–11. Online:https://bit.ly/3hY0I06.

Chow, J. (2017). Mangrove management for climate change adaptation and sustainable development in coastal zones. *Journal of Sustainable Forestry*, 37(2):139–156. Online:https://bit.ly/36UsrbI.

Chuvieco, E. (1995). *Fundamentos de teledetección espacial*. Ediciones RIALP S.A., Madrid, 2nd ed. edition.

Chuvieco, E. (2010). *Teledetección Ambiental*. Ariel Editorial, Barcelona, 3rd ed edition.

Congalton, R. (1991). A review of assessing the accuracy of classifications of remotely sensed data. *Remote Sensing of Environment*, 37(1):35–46. Online:https://bit.ly/3kUfMgX.

Conti, L., Sampaio, C., and Cunha, M. (2016). Spatial database modeling for mangrove forests mapping; example of two estuarine systems in brazil. *Modeling Earth Systems and Environment*, 2(73):1–12. Online:https://bit.ly/3kPkInf.

DIMAR-CCCP (2013). Zonificación fisiográfica del litoral pacífico colombiano. fase i. Technical report, Dirección General Marítima-Centro de Investigaciones Oceanográficas e Hidrográficas del Pacífico, Dirección General Marítima: San Andrés de Tumaco.

Diniz, C., Cortinhas, L., Nerino, G., Rodrigues, J., Sadeck, L., Adami, M., and Souza, P. (2019). Brazilian mangrove status: Three decades of satellite data analysis. *Remote Sensing*, 11(7):1–19. Online:https://bit.ly/3y78oCI.

Dirección General Marítima., editor (2020). *Red de Medición de Parámetros Oceanográficos y de Meteorología Marina (REDMPOMM). Infraestructura de Datos Espaciales Marítima, Fluvial y Costera de Colombia*.

ESRI (2014). *ArcGIS Desktop 10.3., Environmental Systems Research Institute*. Redlands, USA.

FAO (2007). *The world's mangroves 1980-2005*. Food and Agriculture Organization of the United Nations.

Franco, R. (2017). *Composiciones Landsat en ARCGIS. Guía Básica*, MIXDYR. Online: https://bit.ly/3iXYcWX edition.

Galeano, A., Urrego, L., Botero, V., and Bernal, G. (2017). Mangrove resilience to climate extreme events in a colombian caribbean island. *Wetlands ecology and management*, 25(6):743–760. Online:https://bit.ly/36UD5PJ.

Gao, B. (1996). Ndwi a normalized difference water index for remote sensing of vegetation liquid water from space. *Remote Sensing of Environment*, (358):257–266. Online:https://bit.ly/3x1kps2.

Ghosh, S., Bakshi, M., Gupta, K., Mahanty, S., Bhattacharyya, S., and Chaudhuri, P. (2020). A preliminary study on upstream migration of mangroves in response to changing environment along river hooghly, india. *Marine pollution bulletin*, 151:1–14. Online:https://bit.ly/3iFWKYT.

Giri, C. (2016). Observation and monitoring of mangrove forests using remote sensing: Opportunities and challenges. *Marine pollution bulletin*, 8(9):1–8. Online:https://bit.ly/3iCgAV0.

Gupta, K., Mukhopadhyay, A., Giri, S., Chanda, A., Majumdar, S., Samanta, S., Mitra, D., Samal, R., Pattnaik, A., and Hazra, S. (2018). An index for discrimination of mangroves from non-mangroves using landsat 8 oli imagery. *MethodsX*, 5:1129–1139. Online:https://bit.ly/2UzJIEz.

Holdridge, L. (1978). *Ecología basada en zonas de vida*. Centro Interamericano de Documentación e Información Agrícola-IICA.

Horning, N. (2014). Selecting the appropriate band combination for an rgb image using landsat imagery version 1.0.

Huete, A. (1988). A soil-adjusted vegetation index (savi). *Remote sensing of environment*, 25(3):295–309. Online:https://bit.ly/3zuX8jY.

Jia, M., Wang, Z., Wang, C., Mao, D., and Zhang, Y. (2019). New vegetation index to detect periodically submerged mangrove forest using single-tide sentinel-2 imagery. *Remote Sensing*, 11:1–17.Online: https://bit.ly/3iToERo.

Kuenzer, C., Bluemel, A., Gebhardt, S., Quoc, T., and Dech, S. (2011). Remote sensing of mangrove ecosystems: A review. *Remote Sensing*, 3(5):878–928. Online:https://bit.ly/2UHovII.

Mohamed, E. (2017). Consideration of landsat-8 spectral band combination in typical mediterranean forest classification in halkidiki, greece. *Open Geosciences*, 9(1):468–479. Online:https://bit.ly/36Zo7Yt.

Mondal, P., Trzaska, S., and De Sherbinin, A. (2018). Landsat-derived estimates of mangrove extents in the sierra leone coastal landscape complex during 1990–2016. *Sensors*, 18(12):1–15. Online:https://bit.ly/3BxOpiF.

Monirul, I., Helena, B., and Lalit, K. (2018). Monitoring mangrove forest land cover changes in the coastline of bangladesh from 1976 to 2015. *Geocarto International*, 31(13):1458–1476. Online:https://bit.ly/2VbEcI1.

Muhsoni, F., Sambah, A., Mahmudi, M., and Wiadnya, D. (2018). Comparison of different vegetation indices for assessing mangrove density using sentinel-2 imagery. *Int. J. Geomate*, 14:42–51. Online:https://bit.ly/3eMwOcT.

Omar, H., Misman, M., and Linggok, V. (2018). Characterizing and monitoring of mangroves in malaysia using landsat-based spatial-spectral variability. In *IOP Conference Series: Earth and Environmental Science*, volume 169, pages 24–25. Online:https://bit.ly/3hWSAwK.

Pagkalinawan, E. (2014). Mangrove forest mapping using landsat 8 images. *State of the mangrove summit: Northwestern Luzon Proceedings*, pages 60–64. Online:https://bit.ly/2TxBOLj.

Perea-Ardila, M., Oviedo-Barrero, F., and Leal-Villamil, J. (2019). Cartografía de bosques de manglar mediante imágenes de sensores remotos: estudio de caso: Buenaventura, colombia. *Revista de Teledetección*, 53(1):73–86. Online:https://bit.ly/3ygOWU8.

Pérez, F. and De la Riva, J. (1998). El empleo de imágenes landsat tm para la detección y cartografía de áreas incendiadas en el prepirineo occidental oscense. *Geographicalia*, (36):131–145. Online:https://bit.ly/36XtEij.

Pham, T., Yokoya, N., Bui, D., Yoshino, K., and Friess, D. (2019). Remote sensing approaches for monitoring mangrove species, structure, and biomass: Opportunities and challenges. *Remote Sensing*, 11(3):1–24. Online:https://bit.ly/3rFlMf2.

Pimple, U., Simonetti, D., Sitthi, A., Pungkul, S., Leadprathom, K., Skupek, H., Som, J., Gond, V., and Towprayoon, S. (2018). Google earth engine based three decadal landsat imagery analysis for mapping of mangrove forests and its surroundings in the trat province of thailand. *Journal of Computer and Communications*, 6:246–264. Online:https://bit.ly/3BBa7SU.

Purwanto, A. and Asriningrum, W. (2019). Identification of mangrove forests using multispectral satellite imageries. *International Journal of Remote Sensing and Earth Sciences (IJReSES)*, 16(1):63–86. Online:https://bit.ly/36YbtJn.

Rebelo-Mochel, F. and Ponzoni, F. (2007). Spectral characterization of mangrove leaves in the brazilian amazonian coast: Turiaçu bay, maranhão state. *Anais da Academia Brasileira de Ciências*, 79(4):683–692. Online:https://bit.ly/3rEKZGj.

Rhyma, P., Norizah, K., Hamdan, O., Faridah, I., and Zulfa, A. (2020). Integration of normalised different vegetation index and soil-adjusted vegetation index for mangrove vegetation delineation. *Remote Sensing Applications: Society and Environment*, 17:1–70. Online:https://bit.ly/3y2s4ru.

Rodríguez-Rodríguez, J., Sierra-Correa, P., Gómez-Cubillos, M., and Villanueva, L. (2016). *The Wetland Book*, chapter Mangroves of Colombia. Springer Netherlands, Dordrecht.

Rouse, J., Haas, R. Shell, J., and Deering, D. (1974). *Monitoring vegetation systems in the Great Plains with ERTS*. Goddard Space Flight Center.

Umroh, A. and Sari, S. (2016). Detection of mangrove distribution in pongok island. *Procedia Environmental Sciences*, 33:253–257. Online:https://n9.cl/w48d.

USGS (1998). Usgs eros archive - landsat archives - landsat 4-5 thematic mapper (tm) level-1 data products. In *Landsat 4-5 TM Collection 1*, Landsat Scene ID LT50100561998003CPE00. U.S Geological Survey. Online:https://bit.ly/3b7KDjI.

USGS (2014). Usgs eros archive - landsat archives - landsat 8 oli level-1 data products. In *Landsat 8 Operational Land Imager (OLI) Collection 1*, Landsat Scene ID LC80100562014239LGN01. U.S Geological Survey. Online:https://bit.ly/3b7KDjI.

USGS (2017). Usgs eros archive - landsat archives - landsat 7 etm+ level-1 data products. In *Landsat 7 Enhanced Thematic Mapper Plus (ETM+) Collection 1*, Landsat Scene ID LE70100562017111EDC00. U.S Geological Survey. Online:https://bit.ly/3b7KDjI.

USGS (2018a). Landsat 7 data users handbook. version 2.0. Technical report, U.S Geological Survey.

USGS (2018b). Landsat 8 data users handbook - versión 3.0. Technical report, U.S Geological Survey.

USGS (2020). Earthexplorer. software, U.S Geological Survey.

Vaghela, B., Parmar, M., Solanki, H., Kansara, B., Prajapati, S., and Kalubarme, M. (2018). Multi criteria decision making (mcdm) approach for mangrove health assessment using geo-informatics technology. *International Journal of Environment and Geoinformatics*, 5(2):114–131. Online:https://bit.ly/3rx4Zuo.

Wang, L., Jia, M., Yin, D., and Tian, J. (2019). A review of remote sensing for mangrove forests: 1956-2018. *Remote Sensing of Environment*, 231:1–150. Online:https://bit.ly/2WcAxdr.

Wilkie, M. and Fortuna, S. (2003). *Status and trends in mangrove area extent worldwide*. Food and Agriculture Organization of the United Nations.

Winarso, G. and Purwanto, A. (2017). Evaluation of mangrove damage level based on landsat 8 image. *International Journal of Remote Sensing and Earth Sciences*, 11(2):105–116. Online:https://bit.ly/3rutwjS.

Xia, Q., Qin, C., Li, H., Huang, C., and Su, F. (2018). Mapping mangrove forests based on multi-tidal high-resolution satellite imagery. *Remote Sensing*, 10(1343):2–20. Online:https://bit.ly/3l6iPD5.

Xia, Q., Qin, C., Li, H., Huang, C., Su, F., and Jia, M. (2020). Evaluation of submerged mangrove recognition index using multi-tidal remote sensing data. *Ecological Indicators*, 113:1–140. Online:https://bit.ly/3kRKpDH.

Zhang, X. and Tian, Q. (2013). A mangrove recognition index for remote sensing of mangrove forest from space. *Current Science*, 105(8):1149–1155. Online:https://bit.ly/3i0V11a.

Zhang, X., Treitz, P., Chen, D., Quan, C., Shi, L., and Li, X. (2017). Mapping mangrove forests using multi-tidal remotely-sensed data and a decision-tree-based procedure. *International journal of applied earth observation and geoinformation*, 62:201–214. Online:https://bit.ly/3i0jVOr.

Zhu, Z. and Woodcock, C. (2014). Automated cloud, cloud shadow, and snow detection in multitemporal landsat data: An algorithm designed specifically for monitoring land cover change. *Remote Sensing of Environment*, 152:217–234. Online:https://bit.ly/3ByuHDD.

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Geospatial Science

Assessment of fuel related data in the Metropolitan District of Quito for modeling and simulation of wildfires, case study: Atacazo Hill wildfire

Evaluación de información relacionada con combustibles en el Distrito Metropolitano de Quito para el modelado y simulación de incendios forestales, caso de estudio: Incendio del cerro Atacazo

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Abstract

The Metropolitan District of Quito (DMQ) does not have all the information needed to design wildfire management strategies based on models and simulations. This work evaluated the use of information related to wildfires in the DMQ obtained from governmental and free sources, using the case study of the Atacazo Hill wildfire (09/29/2018). Topographic, meteorological and fuel data from different sources were processed. The topographic information was obtained from the topographic sheets of the Military Geographical Institute; the meteorological information was obtained from Guamaní station of the Metropolitan Network of Atmospheric Monitoring of Quito, and the fuel and vegetation cover information was estimated based on vegetation and alteration level categories of the coverage and land use map of the Thematic Cartography at Scale 1:25000 of Ecuador Project, executed by the Ministry of Agriculture, Livestock, Aquaculture, and Fisheries. The major paths and the fire arrival times were simulated on FlamMap for two different cases. In Case 1, the simulation included fire barriers based on OpenStreetMap data. Additional information gathered during field visits was included in Case 2. Satellite imagery was used to compare the real wildfire extent with the simulated extent using Sorensen and Cohen's kappa coefficients, obtaining 0.81 and 0.85 for Case 1, and 0.78 and 0.81 for Case 2, respectively. These results showed great similarity between the behavior of the model and the real wildfire. After the model was validated, it was applied to estimate the wildfire behavior in various scenarios of interest; it was found that the design of fire barriers based on simulations has great potential to reduce the affected area of a wildfire

Keywords: FlamMap, wildfires simulation, wildfires modeling, remote sensing.

Resumen

El Distrito Metropolitano de Quito (DMQ) no cuenta con toda la información necesaria para diseñar estrategias de gestión de incendios forestales basadas en modelos y simulaciones. Este trabajo evaluó el uso de información relacionada con incendios forestales del DMQ obtenida de fuentes gubernamentales y libres, tomando como caso de estudio el incendio del cerro Atacazo (29/09/2018). Se procesó información topográfica, meteorológica y de combustibles; las hojas topográficas se obtuvieron del portal del Instituto Geográfico Militar, la información meteorológica de la estación Guamaní de la Red Metropolitana de Monitoreo Atmosférico de Quito, y la información de combustibles y cobertura vegetal se estimó en base a las categorías de vegetación y nivel de alteración del mapa de cobertura y uso de la tierra del proyecto Cartografía Temática a Escala 1:25000 del Ecuador ejecutado por el Ministerio de Agricultura, Ganadería, Acuacultura y Pesca. Se realizaron simulaciones en FlamMap de los trayectos principales y tiempos de arribo del incendio para dos casos: el Caso 1 contempla barreras de fuego construidas con los datos de *OpenStreetMap*; y el Caso 2 complementa esta información con observaciones en campo. Se utilizó imágenes satelitales para comparar la extensión del incendio real con las simulaciones usando los coeficientes de Sorensen y kappa de Cohen; obteniendo 0,81 y 0,85 (Caso 1), y 0,78 y 0,81 (Caso 2), respectivamente. Estos resultados mostraron una gran similitud entre el comportamiento del modelo y el incendio real. Una vez validado el modelo, se lo aplicó para estimar el comportamiento del incendio en varios escenarios de interés; se comprobó que el diseño de barreras de fuego en base a simulaciones tiene gran potencial para disminuir el área de afectación de un incendio.

Palabras clave: FlamMap, simulación incendios forestales, modelado incendios forestales, sensores remotos.

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1 Introduction

Large wildfires have been reported in recent years in the Metropolitan District of Quito (DMQ). There were 285 wildfires during July 2019 – September 2019, which consumed almost 2500 ha of plant cover. Wildfires are one of the most recurring natural and anthropic threats in DMQ; they are considered catastrophic events due to their high environmental impact (Secretaría de Seguridad DMQ, 2015). Impacts of a wildfires that can affect ecosystems and nearby communities in the short or long term include loss of ecosystem services, threat to endangered species, simplification of forest structure and biological composition, entry of invasive species, and generation of dry climate conditions by greenhouse gas emissions (Moore et al., 2003; Barkhordarian et al., 2019).

The application of models and simulations for wildfire management, prevention and response covers various approaches (DeMagalhães et al., 2017; Srivastava et al., 2018; Botequim et al., 2019; Jahdi et al., 2019; Palaiologou et al., 2020; Xofis et al., 2020). For example, the Canadian Forest Service (CFS) develops various models and software applications for predicting a fire. These tools include the Canadian predicting fire spread Model (CanFIRE), used to predict short-term fire behavior, and the Probabilistic Fire Analysis System (PFAS), used to predict long-term effects. These tools assess the intervention need to suppress a fire when it is likely not to be extinguished naturally, saving hundreds of millions of dollars annually in fire suppression costs (Fitch et al., 2018; Government of Canada, 2020).

Traditionally, wildfire modeling includes prediction of fire spread, intensity, and length of flame. Part of easy-to-measure variables are related to fuel type, terrain topography and surface climatic conditions. Fuel types are often classified into different categories depending on their quantity, apparent density, heat content and extinction humidity. The characteristics of these fuel categories serve as inputs to semi-empirical fire behavior models implemented in software such as FlamMap and FIRESITE (Bakhshaii and Johnson, 2019; Zigner et al., 2020).

FlamMap is fire modeling and simulation software developed by the U.S. Fire, Fuel, and Smoke Science Program (FFS) widely applied today (Hernández et al., 2007; Jahdi et al., 2016; Botequim et al., 2017; Conver et al., 2018; Rios et al., 2019). This program implements several semi-empirical models to estimate the behavior, growth and spread of a fire. Simulations in each area using this software require meteorological, topographic and fuel information. This program can generate different outputs based on the results of fire behavior simulations, Minimum Travel Time (MTT) and Treatment Optimization Model (TOM) (Finney, 2006; Stratton, 2009).

Semi-empirical wildfire models are the most used today, however, they have several limitations, such as their focus on the representation of fire behavior, but not on combustion and heat transfer mechanisms. In addition, they carry out several simplifications in order to provide methods of easy execution through statistical assumptions and geometric approximations in two dimensions of three-dimensional processes. On the other hand, the new generation of atmospheric wildfire models includes the application of Computational Fluid Dynamics (CFD) to numerically solve three-dimensional physical models of combustion, heat transfer, aerodynamics and turbulence. In addition, these models include Numerical Weather Prediction (NWP) methods that allow to simulate the interaction of the fire with the nearby atmosphere. In this way, the dynamics of complex three-dimensional processes that can occur during a fire can be represented, such as plume-driven fires, fire whirls, horizontal rolling vortices, fire combining with mountain winds, chimney fire, and fire storms. The main disadvantage of these models is the large number of computational resources required, so their applicability is focused on research (e.g., FIRETEC) (Bakhshaii and Johnson, 2019).

The main drawback for the simulation of wildfires with FlamMap in DMQ is that there is no database with fuel characteristics and vegetation percentages for wildfire management in DMQ. However, there are maps of vegetation type and land use generated by the Ministry of Agriculture, Livestock, Aquaculture and Fisheries (MAGAP) and the Ministry of Environment and Water of Ecuador (MAAE) with information that may be related to the type of fuel in an area. These data, in combination with OpenStreetMap maps and satellite imagery, may be potential sources of fuel information for fire simulation (MAAE, 2020; MAGAP, 2015). In addition, wildfire remote sensing tools such as the National Aeronautics and Space Administration (NASA) FIRMS system can be used to identify fires that serve as case studies in the DMQ; National Aeronautics and Space Administration) (NASA, 2021) or implement algorithms based on neural networks and multispectral satellite images (Govil et al., 2020; Mujtaba and Wani, 2018; Govil et al., 2020).

The aim of this paper is to evaluate the information available in the DMQ to model and simulate wildfires using FlamMap software and estimate the properties of fuels with free access information and government agencies, taking the fire of Atacazo Hill as a case study, which occurred in September 2018 (DMQ Fire Department, 2018). To validate the results of the simulations, the actual and simulated extent of fire will be compared using Sorensen and Cohen's kappa coefficients (Banko, 1998). Finally, the application of the model for the simulation of scenarios will be evaluated, these are: fire behavior in extreme weather conditions, fire behavior in the face of strategically designed fire barriers, and fire behavior in the face of a fire barrier failure.

2 Materials and Methods

The case study of this investigation is the wildfire of Atacazo Hill that occurred on September 29, 2018; four phases were considered to model and validate this fire: data collection, data processing, simulation and validation (Figure 1). In the first phase, meteorological information was collected from the Guamani weather station of the Metropolitan Atmospheric Monitoring Network of Quito (REMMAQ.), and topographic information was obtained from the topographic chart of Amaguaña parish of the DMQ created by the Military Geographic Institute (GGI), and an estimate of canopy cover and fuel type was made from the land coverage and use map of the MAGAP 1:25000 Thematic Mapping Project. This map has categories that classify the land according to the type of vegetation (herbaceous, shrub and forest) and alteration levels (low, medium and high). In addition, OpenStreetMap's natural road and cover data were used to supplement fuel information, because trails, secondary roads, water bodies and rocky areas may behave as barriers to natural or unintentional fires (Rigolot et al., 2004). In the second phase, an LCP file was created containing slope, elevation, aspect, fuel models and plant cover data; a WXS file with meteorological data; and two maps with fire barriers for case 1 and case 2. The extent of the fire on Atacazo Hill was estimated based on Sentinel-2 satellite images. In phase three, the fire extension simulation was performed using the calculation of the MTT in FlamMap. Finally, the precision of the simulation was calculated with the Sorensen coefficient and the Cohen's kappa coefficient.

2.1 Case Study

Atacazo Hill is in Ecuador, Pichincha province, on the southern border of the DMQ with Mejía canton (Figure 2). It is located at $0°21'15.8''$S $78°37'14.3''$W at a height of 4463 meters above sea level. Atacazo Hill is a stratovolcano that is part of the Western Cordillera, its average temperature is 11.9 °C, it has a humid tropical climate, and its vegetation is mainly paramo with herbaceous vegetation. The fire on Atacazo Hill began on September 29, 2018, lasted four days and consumed more than 1200 ha of DMQ and Canton Mejía (Figure 3). According to reports from the DMQ Fire Department, the fire was reported at 14h50 hours on September 29, 2018, was controlled at 7h06 on October 2, 2018, and was monitored for two more days. The duration of the fire, from its report to its control time, was 2 days, 16 hours and 16 minutes (3856 minutes in total). It is worth mentioning that there are telecommunication antenna installations on the top of Atacazo Hill. For this reason, there are second-order tracks that can be traveled in vehicles with dual transmissions that get very close to the rock cover of the top. This information is important because a road, wide enough to be traveled by a car, can behave as a fire barrier in a fire, as well as rocks and sand near the top of a volcano are surfaces where fire does not spread.

2.2 wildfire Modeling

Rothermel's semi-empirical surface fire propagation model is one of the most widely used models to describe the behavior of a wildfire. This model is generally applied in conjunction with other models of flame intensity, flame length, crown fire, fire attempts, fire propagation speed, fire front growth, among others, for fire and fuel handling. The final equation of Rothermel surface fire propagation model is detailed below (Andrews, 2018):

Equation 1

$$R = \frac{I_R \xi (1 + \phi_W + \phi_S)}{\rho_B \varepsilon Q_{ig}} \quad (1)$$

Where:

R is the propagation speed measured in $\frac{m}{min}$.
I_R is the reaction intensity measured in $\frac{J}{m^2 min}$.
ξ is the flow propagation reason.
ϕ_W is a factor related to the effect of wind on fire propagation.
ϕ_S is a factor related to the effect of the slope of the ground on the fire spread.
ρ_B is the apparent fuel density measured in $\frac{kg}{m^3}$.
ε is the effective heating number
Q_{ig} is the amount of heat needed to ignite a pound of fuel measured in $\frac{J}{kg}$.

Although this model has existed since 1972, it is still implemented as part of more complex models and simulators widely used today such as FlamMap and FIRESITE. FlamMap is a wildfire simulator that implements different patterns of fire behavior, these are:

- Rothermel model (1972) for surface fire propagation.
- Van Wagner model (1977) for the initiation of crown fire.
- Rothermel model (1991) for the propagation of crown fire.
- Albini model (1979) for fire attempts.
- Finney's (1998) or Scott and Reinhardt's (2001) crown fire calculation method.
- Nelson's Dead Fuel Moisture Model (2000).

The input geospatial information for FlamMap is described by several raster combined into a Landscape file with LCP extension; weather information can be processed by the WindNinja tool and entered in WSX format. In addition, other data such as fire barriers and trigger points can be defined by maps with vector-type information.

2.3 Data processing

2.3.1 Landscape File

To generate the Landscape file for FlamMap, five rasters must be created: elevation or height, slope, aspect, plant coverage, and fuel models. For this, it is important that all rasters have the same cell or pixel size (in this case 20×20 m), that their pixels match exactly, and cover the same study area. In addition, it is necessary to indicate the projection used through a file with PRJ extension, in this case, WGS84 zone 17S.

2.3.2 Creating Height, Slope, and Aspect Rasters

Height, Slope, and Aspect Rasters are obtained from the level curves of the Amaguaña topographic sheet. This was done using the ArcGIS software and the procedure described in Figure 4. The result of this process is shown in Figure 5.

2.3.3 Creation of Fuel and Plant Cover Model Rasters

The MAGAP 1:25000 Thematic Mapping Project's land use and coverage map was used to generate the plant cover rasters and fuel models. This map is in vector format with attribute "coverage" that contains 25 categories of land coverage and use of Atacazo Hill area. The vegetation types indicated in these categories are related to Scott-Burgan fuel models for generating the FlamMap fuel raster (Scott and Burgan, 2005). On the other hand, ground alteration levels are related to ranges of plant coverage percentages to generate the coverage raster. In addition, guidelines from the National Wildfire Coordination Group (NWCG) fuel selection guide were considered. With this information, the database in Table 1 was created, where the attributes "fuel value" and "cc class" were used to create fuel model and plant cover rasters, respectively (Figure 6). In this table, each category of the "coverage" attribute is assigned a fuel model ("fuel type") with its respective numeric code ("fuel value") and a plant coverage class ("cc class"). In the plant coverage class, 0 corresponds to 0% coverage, 1 from 1 to 25% coverage, 2 from 26 to 50% coverage, 3 from 51 to 75%

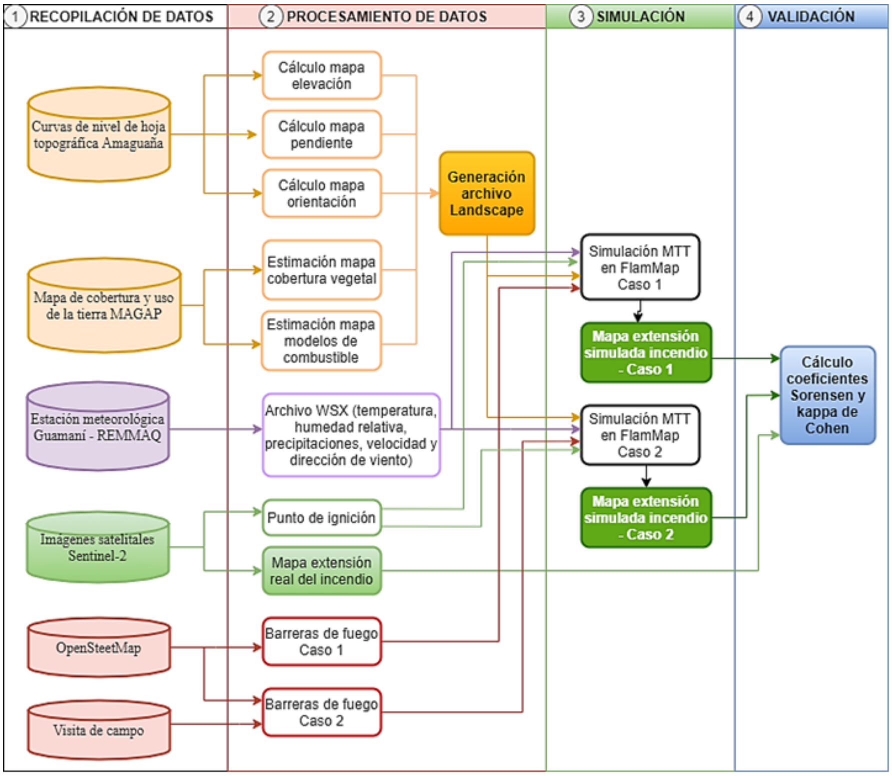

Figure 1. Methodology diagram (own elaboration)

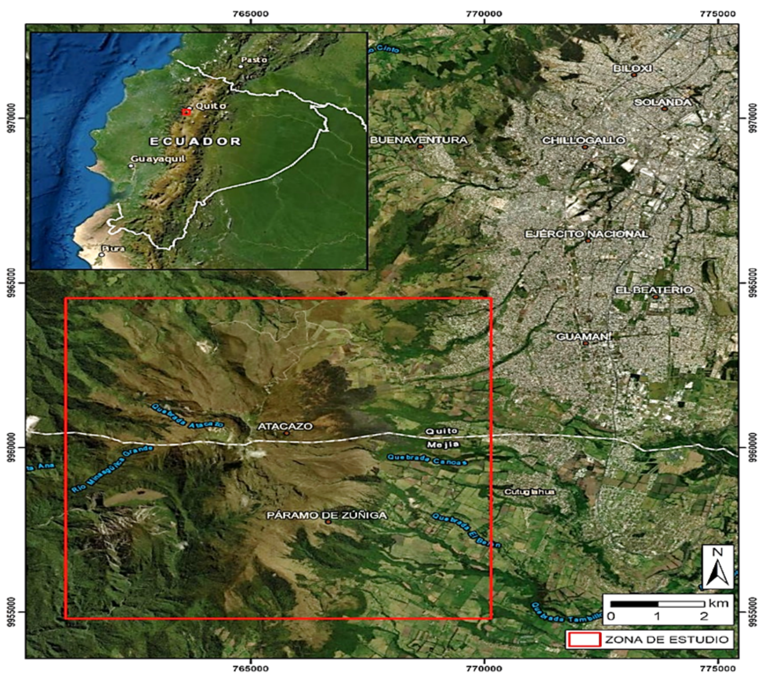

Figure 2. Location of Atacazo Hill (own elaboration)

coverage, and 4 from 76 to 99% coverage. It should be mentioned that the information corresponds to

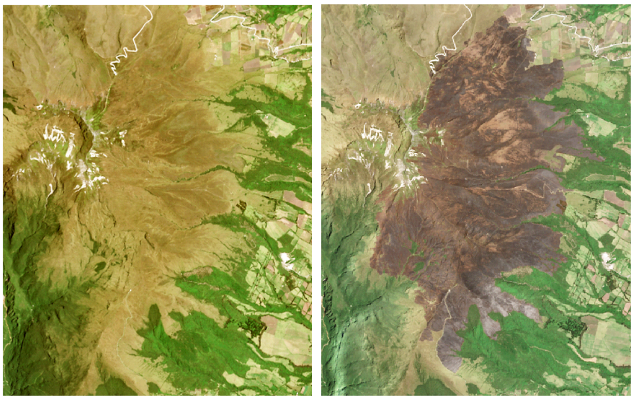

Figure 3. Sentinel-2 images, Atacazo Hill. Before the fire – 09/29/2018 (left) and after the fire – 10/24/2018 (right)

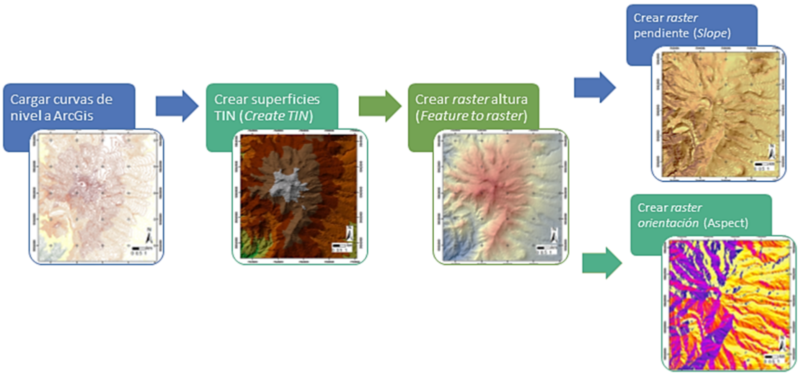

Figure 4. Steps for creating the height, slope and aspect rasters (own elaboration)

the year 2015 and is the most current and with the best resolution found.

2.3.4 Wxs file creation with weather conditions

The meteorological variables are temperature, relative humidity, cloud cover, precipitation, wind speed and wind direction. All these variables, except for cloud, are available at the REMMAQ's Guamani station between September 29 and October 5, 2018. With this data, a file with a WXS extension will be generated containing the input weather information for the dead fuel humidity calculations performed by FlamMap.

Table 2. WXS file meteorological variables and their mean value (own elaboration)

Variable	Units	Mean value
Temperature	Celsius Degrees	14
Relative humidity	Percentage	59
Precipitations	hundreths millimeters	0
Wind speed	Kilometers per hour	6
Wind direction	Grades	181
Nubosity	Percentage	0

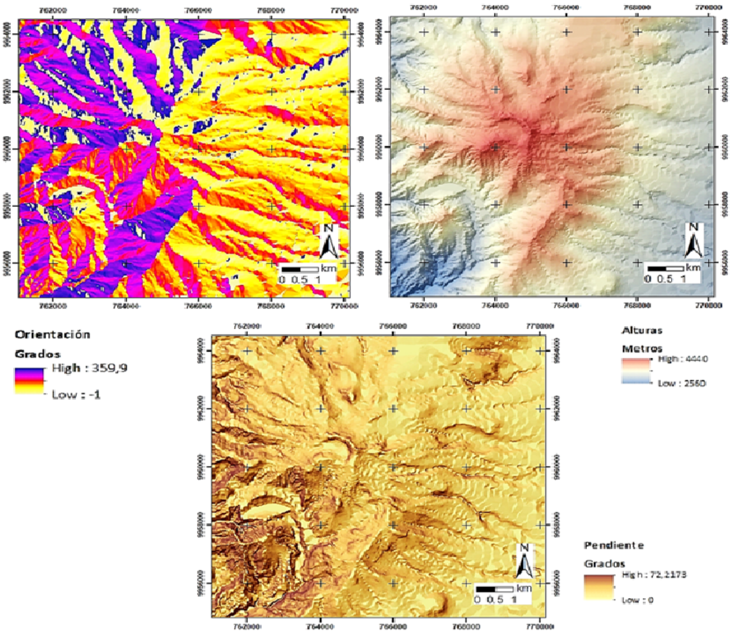

Figure 5. Rasters of height, slope and aspect of the study area (own elaboration)

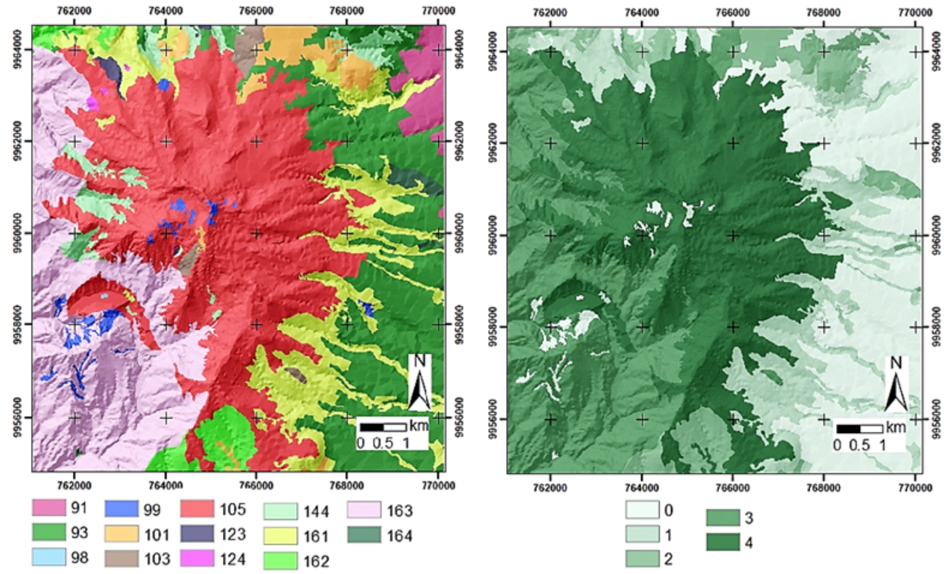

Figure 6. Raster of fuel models and plant cover of the study area (own elaboration)

2.3.5 Point of ignition

One of the advantages of the case study is that a satellite image Sentinel-2 is available with little cloud shortly after its first report. The fire developed on the south of Hill Atacazo and was reported at 14h50 on September 29, 2018. In addition, one of the theories of its creation is that it was caused by an uncontrolled agricultural burning. For these reasons, the black area near the planting shown in Figure 7 was considered as an ignition point. A shapefile interpreted on the satellite image was created in the shape of this area to be used for MTT simulations in FlamMap.

Table 1. Coverage database, fuel models, numerical code of fuel models, and vegetation cover (own elaboration)

Cover	fuel_type	fuel_value	cc_class
AREA IN THE PROCESS OF URBANIZATION	NB1	91	0
POPULATED AREA	NB1	91	0
URBAN	NB1	91	0
MISCELANEO SHORT CYCLE	NB3	93	0
MISCELANEO FORESTRY	NB3	93	0
POTATO	NB3	93	0
CULTIVATED GRASS	NB3	93	0
LAKE/LAGOON	NB8	98	0
EROSION PROCESS AREA	NB9	99	0
QUARRY	NB9	99	0
MINE	NB9	99	0
VERY DISTURBED HUMID HERBACEOUS VEGETATION	GR1	101	4
DISTURBED HUMID HERBACEOUS VEGETATION	GR5	105	4
MEDIANLY DISTURBED HERBACEOUS PARAMO	GR3	103	3
MEDIANLY DISTURBED SHRUBBY PARAMO	GS4	124	2
LITTLE DISTURBED HERBACEOUS PARAMO	GR5	105	4
VERY DISTURBED HUMID SHRUB	TU1	161	1
VERY DISTURBED HERBACEOUS PARAMO	GR1	101	2
POORLY DISTURBED WET SCRUB	GH4	144	3
DIRTURBED SHRUBBY PARAMO	GS3	123	1
MODERATELY DISTURBED WET SCRUB	SH4	144	2
MODERATELY DISTURBED HUMID FOREST	TU2	162	2
PINE	TU2	162	2
SLIGHTLY DISTURBED HUMID FOREST	TU3	163	3
EUCALIPTUS	TU4	164	2

2.3.6 Fire Barriers According to OpenStreetMap Map

Vehicle walkways could be identified by means of an area recognition. The width of these roads and the low height of the surrounding herbaceous vegetation make it possible for them to behave like fire barriers. On the other hand, water bodies and rocky areas on the top are surfaces where fire does not spread. With these observations and information from the OpenStreetMap platform, two sets of fire barriers were generated. Case 1 includes fire barriers built only with OpenStreetMap data, while case 2 complements this information with field observations (Figure 8).

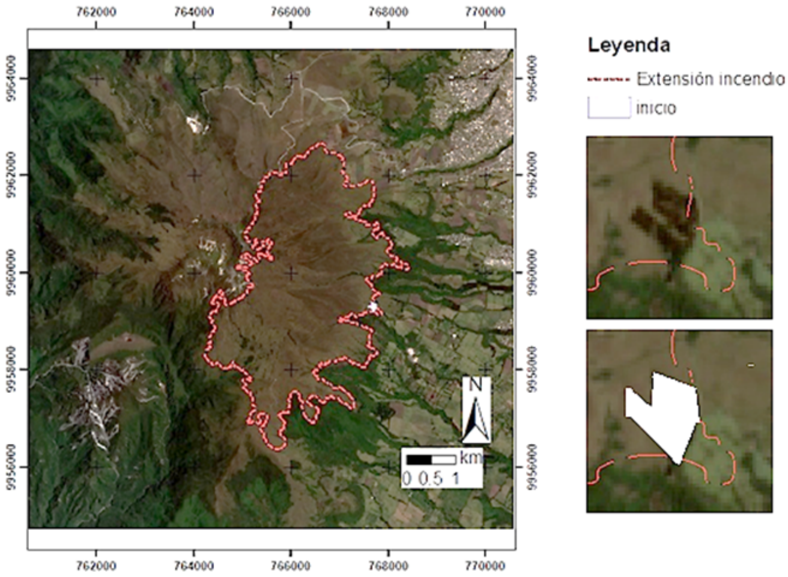

Figure 7. Probable ignition point of the fire at Atacazo Hill (own elaboration).

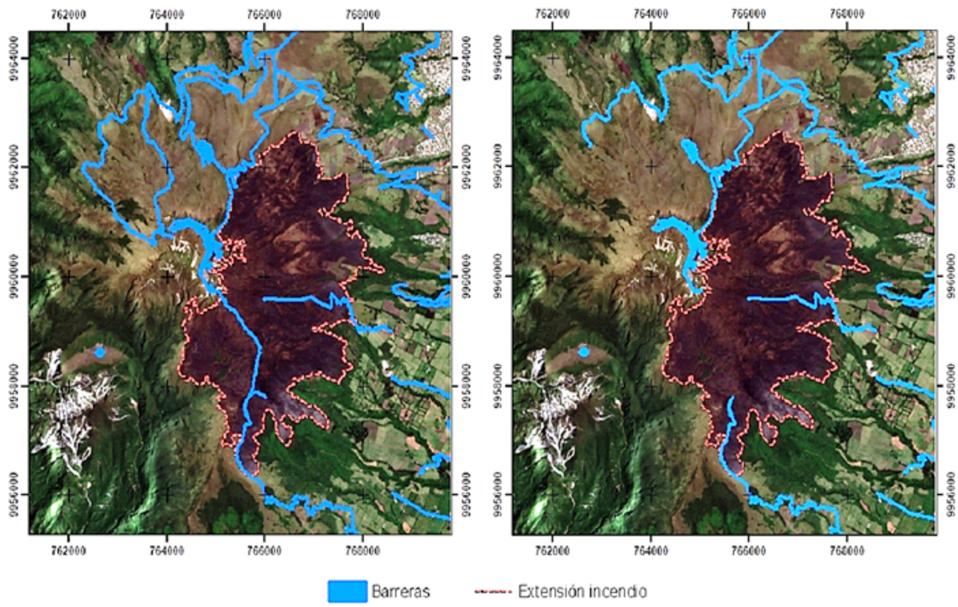

Figure 8. Fire barriers: Case 1 (left), case 2 (right) (own elaboration).

2.4 Error measures

2.4.1 Sorensen's coefficient

This coefficient aims to compare the similarity of two samples with information on the existence or non-existence of a finished characteristic. In the context of wildfire simulation, the burned or unburned areas of the real fire can be compared with the simulations. The formula for calculating this coefficient is as follows:

Equation 2

$$SC = \frac{2a}{2a+b+c} \quad (2)$$

Where:

SC is the Sorensen coefficient.
a is the number of cells burned in the simulation and actual fire.
b is the number of cells burned in the simulation and not burned in the actual fire.
c is the number of cells not burned in the simulation and burned in the real fire.

2.4.2 Cohen's kappa coefficient

Cohen kappa coefficient is a measure of error that can be derived from an error matrix or confusion matrix. This coefficient evaluates the overall adjustment of the error matrix, considering the elements outside its diagonal. In the context of a wildfire, it can be calculated using the following formula:

Equation 3

$$KC = \frac{N\sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r}(x_{i+}x_{+i})}{N^2 - \sum_{i=1}^{r}(x_{i+}x_{+i})} \quad (3)$$

Where:

KC is Cohen's kappa coefficient.
r is the number of rows in the error array.
N is the total number of observations.
x_{ii} is the number of observations in row i and column i of the error matrix
x_{i+} is the marginal total of row i.
x_{+i} is the marginal total of column i.

3 Results

3.1 Simulation of major paths and arrival time

MTT-based simulations were run in both cases to obtain the major paths and arrival time map (Figure 9). The main routes make it easy to identify fuel treatment areas, while the arrival time map allows to visualize the extent of the fire. In case 1, the extent of the fire is limited to the north, south and west by the fire barriers considered, while the change in vegetation type is limited to the east. This type of vegetation is classified as highly altered wet scrub and corresponds to fuel model TU1 (mixture of forest and understory of grass and shrubs) with a plant coverage percentage between 1 and 25%. In case 2, the extent of the fire is limited to the north and northwest by the fire barriers considered, while the change in vegetation type is limited to the southwest, east and south. Vegetation to the east is classified as highly altered wet scrub and corresponds to fuel model TU1 (forest with low grass and shrub load) with a plant coverage percentage between 1 and 25%. Vegetation to the south is classified as a moderately altered humid forest and corresponds to fuel model TU2 (forest with moderate load of grass and shrubs) with a plant coverage percentage between 25 and 50%. Vegetation to the southwest is classified as poorly altered wet forest and corresponds to fuel model TU3 (forest with moderate load of grass and shrubs) with a plant coverage percentage between 51 and 75%. It is worth mentioning that the fire begins to spread through this last type of vegetation at the end of the simulation.

3.2 Model Validation

To compare the simulated and actual extent of the fire, Sorensen and Cohen kappa coefficients are calculated. For this, it is necessary to create rasters that classify each pixel into "burned" and "unburned" cells to calculate the a, b, and c parameters of equation 2 (Figure 10) and generate the error matrices of equation 3 (Table 3 and table 4). Sorensen's coefficient values obtained are 0.81 and 0.85 for case 1 and 2, respectively. Cohen's kappa coefficient values are 0.78 and 0.81 for case 1 and case 2, respectively. Hence, the simulation where OpenStreetMap information was supplemented with field observations has better results.

3.3 Simulation of scenarios

Different simulations of scenes of interest can be generated with the validated model; in this research three scenarios were used. The first scenario considers extreme weather conditions with zero rainfall. It can be observed that the fire spreads to the southwest through vegetation categorized as little disturbed wet forest, reaching an area of high slopes (Figure 11); causing the fire to spread over a large area beyond the study area. The second scenario simulates the fire's behavior in the event of a fire barrier to the north. It can be seen how the fire spreads to a large area to the west of Atacazo Hill (Figure 11). The third scenario considers two fuel treatments; the first treatment is to place a fire barrier that cuts off the major paths leading the fire to the southwest in the first scenario; the second treatment extends a road near the top, creating a barrier that begins at the agrarian border, at the bottom of the hill, and ends at its top (Figure 12).

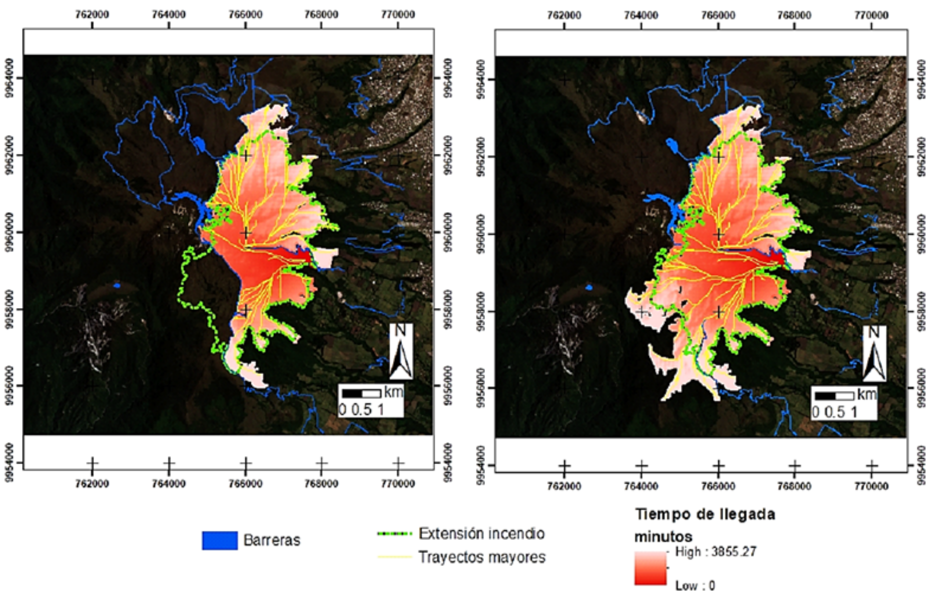

Figure 9. Simulation of major paths and arrival time for case 1 (left) and case 2 (right) (self-elaboration).

Table 3. Error matrix simulation case 1 (own elaboration).

	Burned Cell (Simulation)	Unburned Cell (Simulation)	Total
Burned Cell (Real)	25920	6732	32652
Unburned Cell (Real)	5190	183743	188933
Total	31110	190475	221585

4 Discussion

Although Cohen's Sorensen and kappa coefficients show great similarity between simulations and the

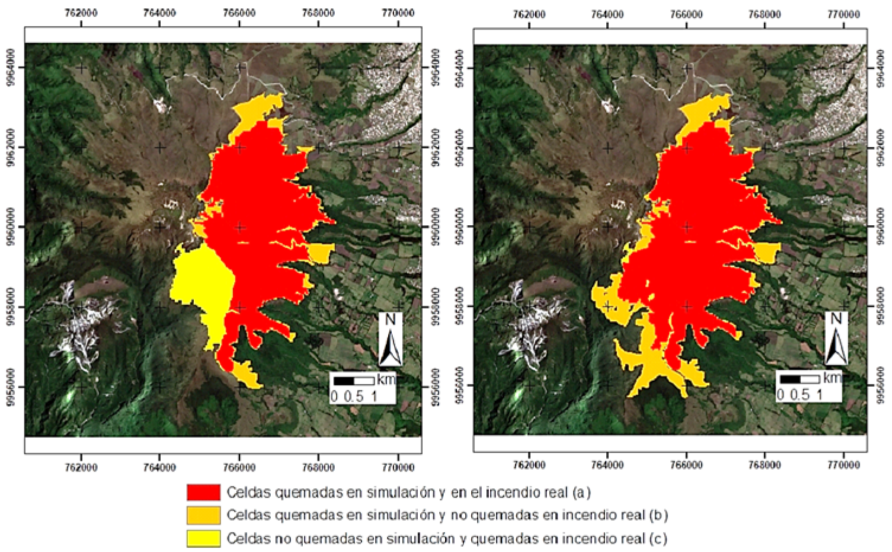

Figure 10. Parameters for calculating Sorensen and Cohen kappa coefficients for case 1 (left) and case 2 (right) (own elaboration).

Table 4. Simulation error matrix Case 2 (own elaboration).

	Burned Cell (Simulation)	**Unburned Cell (Simulation)**	**Total**
Burned Cell (Real)	31771	881	32652
Unburned Cell (Real)	10772	178161	188933
Total	42543	179042	221585

real fire, and their values are consistent with similar studies (Jahdi et al., 2016), it should be mentioned that this is due to the homogeneity of the vegetation in the area, among other reasons. The reliability of the proposed methodology can be increased by calibrating the model with several fires before applying it for simulation scenarios, and it is recommended to do so with at least three fires (Stratton, 2009). It is recommended to calibrate fuel model humidity and fire barriers; this can be done by combining simulations with field observations, experimental measurements or satellite images.

On the other hand, there are several sources of error that were not considered because of the difficulty in estimating or because of lack of information, for example: the effect of firefighting actions by fire fighters is not considered (nor is there any information available); the fuel models used correspond to ecosystem vegetation present in the United States, which excludes ecosystems typical of the Andes. Therefore, it is important to develop fuel models belonging to the study area (Elia et al., 2015); much information used was not raised for the purpose of simulating fires, for this it is possible to raise from scratch the data of fuels and vegetation using laser object detection and measurement techniques (LIDAR; Laser Imaging Detection and Ranging) (Jakubowksi et al., 2013; Stefanidou et al., 2020), Stratified random sampling, multispectral satellite images, supervised classification, or some combination of these techniques. On the other hand, the weather conditions were taken from a station located more than one kilometer away from Atacazo hill and the calculation of Cohen's Sorensen and kappa coefficients was carried out with the final ex-

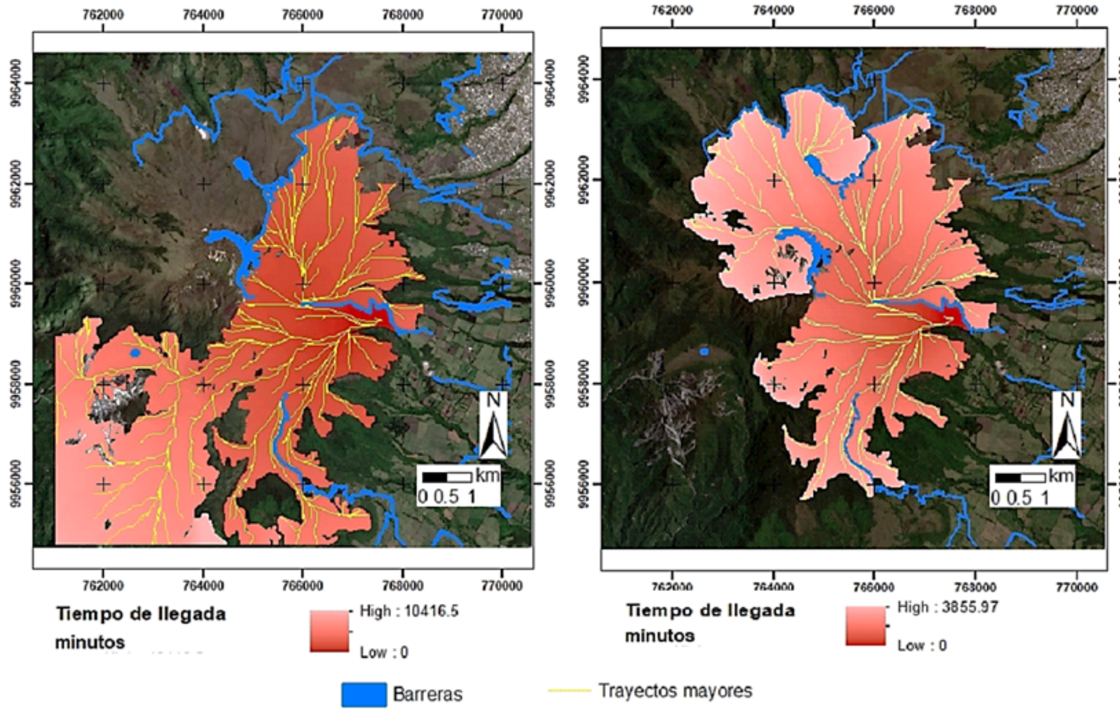

Figure 11. Simulation of major paths and arrival time for the first (left) and second (right) scenario (own elaboration).

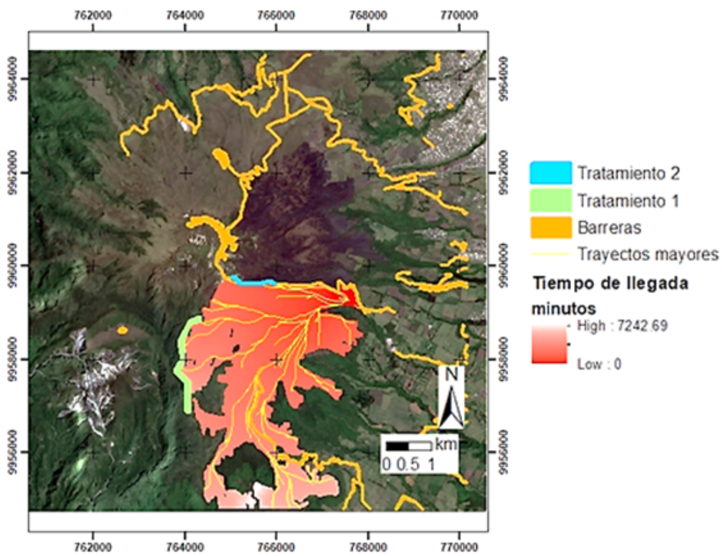

Figure 12. Simulation of major paths and arrival time for the third scenario (own elaboration).

tension of the fire, therefore, there is no information on the accuracy of the model to represent its time evolution (Stratton, 2009).

It can be seen, both in the simulations and in the real fire, that the areas classified as a poorly disturbed herbaceous paramo possess high fire propagation; the fire barriers and the change of vegetation are the limits in the final extension of the fire. The identification of these limitations is important because Atacazo hill has a large amount of vegetation of this type to the west of its top, through which a fire can spread if the fire barriers fail to contain it.

On the other hand, simulation by calculating fuel moisture based on the changing weather conditions of the WSX file allows the results to be much closer to the actual fire behavior (Finney, 2006). A simulation with fixed weather conditions would mean skipping the increase in humidity and the decrease in temperature in the evenings and early mornings; it may cause fire to spread through areas with poorly disturbed humid forest or very disturbed humid scrub. In a real scenario, this would correspond to a fire that takes place in an unusual dry summer and extremely unfavorable weather conditions (little rain and strong winds).

It is important to mention the effectiveness in controlling a fire showed by the implementation of strategically located fire barriers (Figure 12), becoming decisive elements in the expansion of a fire in large areas. Moreover, its implementation is common in other countries (Rigolot et al., 2004) and is quite convenient because of the existence of several paths and roads commonly used by tourists and workers. However, the ecological impact of its implementation is still under discussion (Shinneman et al., 2019). It should be mentioned that a properly designed fire barrier can serve a dual purpose, first, it will prevent the spread of fire, and then it will facilitate access by fire personnel to the site.

5 Conclusions

This paper studied Atacazo Hill, which began to evaluate on September 29, 2018, the use of the information available in the DMQ in the modeling and simulation of wildfires using FlamMap software. In the DMQ, there is no raised information specifically aimed at modeling and simulating these emergencies. Data are needed on the type of fuel and percentage of plant cover in the territory. As mentioned before, the data used to estimate fuel models and plant cover percentages were not collected for the purpose of being used in the modeling and simulation of wildfires. For this reason, there are many ways to improve the reliability of simulation results based on improved generation of fuel model rasters and vegetation percentages. Some options are:

- Generate DMQ-specific fuel models: Scott-Burgan models are developed for the types of vegetation present in the United States; so, using them in DMQ implies an approach that can be improved by generating own models for the high mountain ecosystems of the Andean Mountain range of DMQ (Elia et al., 2015).
- Generate fuel and plant cover maps from scratch: the approximations made by collecting the data from the plant cover and land maps used in this work may involve major changes in the simulation of a fire. For example, a small, poorly classified area can cause the fire to expand into very large areas in a simulation. In addition, an area with a certain type of fuel may contain areas with a different percentage of coverage, which implies the fire to spread differently.

References

Andrews, P. (2018). The rothermel surface fire spread model and associated developments: A comprehensive explanation. *USDA Forest Service - General Technical Report RMRS-GTR*, 371:1–121. Online: https://bit.ly/3fUaBdJ.

Bakhshaii, A. and Johnson, E. (2019). A review of a new generation of wildfire-atmosphere modeling. *Canadian Journal of Forest Research*, 49(6):565–574. Online: https://bit.ly/3CEYH1b.

Banko, G. (1998). *A Review of Assessing the Accuracy of Classifications of Remotely Sensed Data and of Methods Including Remote Sensing Data in Forest Inventory*. International Institute for Applied Systems Analysis. Online: https://bit.ly/3AGan1U.

Barkhordarian, A., Saatchi, S., Behrangi, A., Loikith, P., and Mechoso, C. (2019). A recent systematic increase in vapor pressure deficit over tropical south america. *Scientific reports*, 9(1):1–12. Online: https://go.nature.com/37A2rCK.

Botequim, B., Fernandes, P., Borges, J., González, E., and Guerra, J. (2019). Improving silvicultural practices for mediterranean forests through fire behaviour modelling using lidar-derived canopy fuel characteristics. *International Journal of Wildland Fire*, 28(11):823–839. Online: https://bit.ly/3iIoAFc.

Botequim, B., Fernandes, P., Garcia, J., Silva, A., and Borges, J. (2017). Coupling fire behaviour modelling and stand characteristics to assess and mitigate fire hazard in a maritime pine landscape in portugal. *European Journal of Forest Research*, 136(3):527–542. Online: https://bit.ly/3jPbwgA.

Conver, J., Falk, D., Yool, S., and Parmenter, R. (2018). Modeling fire pathways in montane grassland-forest ecotones. *Fire Ecology*, 14(1):17–32. Online: https://bit.ly/2VIs69z.

DeMagalhães, S., Ribeiro, C., Castro, J., Fernandes, P., Silva, C., Pinheiro, H., and Azevedo, J. (2017). Fire behaviour in different periods and configurations of a landscape in northeastern portugal. *Ciência Florestal*, 27(2):457–469. Online: https://bit.ly/3jJz8TG.

DMQ Fire Department (2018). *Plan de Prevención y Respuesta a Incendios Forestales 2018*. Cuerpo de Bomberos DMQ. Online: https://bit.ly/3CMrgti.

Elia, M., Lafortezza, R., Lovreglio, R., and Sanesi, G. (2015). Developing custom fire behavior fuel models for mediterranean wildland–urban interfaces in southern italy. *Environmental management*, 56(3):754–764. Online: https://bit.ly/3yDpA2Z.

Finney, M. (2006). An overview of flammap fire modeling capabilities. In *Fuels Management-How to Measure Success: Conference Proceedings*, page 213–220.

Fitch, R., Kim, Y., Waltz, A., and Crouse, J. (2018). Changes in potential wildland fire suppression costs due to restoration treatments in northern arizona ponderosa pine forests. *Forest policy and economics*, 87:101–114. Online: https://bit.ly/3yIPK4z.

Government of Canada (2020). Fire management. Online: https://bit.ly/2UcarGP.

Govil, K., Welch, M., Ball, J., and Pennypacker, C. (2020). Preliminary results from a wildfire detection system using deep learning on remote camera images. *Remote Sensing*, 12(1):1–15. Online: https://bit.ly/37B8dny.

Hernández, L., White, S., Del Rey, A., and Sánchez, G. (2007). Modelling forest fire spread using hexagonal cellular automata. *Applied mathematical modelling*, 31(6):1213–1227. Online: https://bit.ly/3m3TXMv.

Jahdi, R., Salis, M., Arabi, M., and Arca, B. (2019). Fire modelling to assess spatial patterns of wildfire exposure in ardabil, nw iran. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, page 577–581. Online: https://bit.ly/3m02DU0.

Jahdi, R., Salis, M., Darvishsefat, A., Alcasena, F., Mostafavi, M., Etemad, V., Lozano, O., and Spano, D. (2016). Evaluating fire modelling systems in recent wildfires of the golestan national park, iran. *Forestry*, 89(2):136–149. Online: https://bit.ly/2Ue6EZL.

Jakubowksi, M., Guo, Q., Collins, B., Stephens, S., and Kelly, M. (2013). Predicting surface fuel models and fuel metrics using lidar and cir imagery in a dense, mountainous forest. *Photogrammetric Engineering y Remote Sensing*, 79(1):37–49. Online: https://bit.ly/37CGHpA.

MAAE (2020). Mapa interactivo. Accessed: 5 October 2020. Online: https://bit.ly/3swh6Ze.

MAGAP (2015). *Memoria tecnica DMQ - Proyecto Cartografía Temática Escala 1:25000.*

Moore, P., Hardesty, J., Kelleher, S., Maginnis, S., and Myers, R. (2003). Forest and wildfires: fixing the futures by avoiding the past. XII World Forestry Congress. Online: https://bit.ly/3mlEnfl.

Mujtaba, T. and Wani, M. (2018). Object detection from satellite imagery using deep learning. In *5th IEEE international conference on computing for sustainable global development*.

NASA (2021). Firms. Online: https://go.nasa.gov/3AR0zlw.

Palaiologou, P., Kalabokidis, K., Ager, A., and Day, M. (2020). Development of comprehensive fuel management strategies for reducing wildfire risk in greece. *Forests*, 11(8):789. Online: https://bit.ly/3yVgkXW.

Rigolot, E., Castelli, L., Cohen, M., Costa, M., and Duché, Y. (2004). Recommendations for fuelbreak design and fuel management at the wildland urban interface: an empirical approach in south eastern france. In *Institute of Mediterranean forest ecosystems and forest products warm international workshop, Athènes*, pages 131–142. Online: https://bit.ly/3CJImrX.

Rios, O., Valero, M., Pastor, E., and Planas, E. (2019). A data-driven fire spread simulator: Validation in vall-llobrega's fire. *Frontiers in Mechanical Engineering*, 5:1–11. Online: https://bit.ly/2VM5dlC.

Scott, J. and Burgan, R. (2005). *Standard fire behavior fuel models: A comprehensive set for use with Rothermel's surface fire spread model*. USDA Forest Service - General Technical Report RMRS-GTR. Online: https://bit.ly/3CJtGc9.

Secretaría de Seguridad DMQ (2015). Atlas de amenazas naturales y exposición de infraestructura del distrito metropolitano de quito. Online: https://bit.ly/37AHasF.

Shinneman, D., Germino, M., Pilliod, D., Aldridge, C., Vaillant, N., and Coates, P. (2019). The ecological uncertainty of wildfire fuel breaks: examples from the sagebrush steppe. *Frontiers in Ecology and the Environment*, 17(5):279–288. Online: https://bit.ly/2UfFIJ6.

Srivastava, A., Wu, J., Elliot, W., Brooks, E., and Flanagan, D. (2018). A simulation study to estimate effects of wildfire and forest management on hydrology and sediment in a forested watershed, northwestern us. *Transactions of the ASABE*, 61(5):1579–1601. Online: https://bit.ly/3jPK5TS.

Stefanidou, A., Gitas, I., Korhonen, L., Stavrakoudis, D., and Georgopoulos, N. (2020). Lidar-based estimates of canopy base height for a dense uneven-aged structured forest. *Remote Sensing*, 12(10):1565. Online: https://bit.ly/3jJIeQk.

Stratton, R. (2009). *Guidebook on LANDFIRE Fuels Data Acquisition, Critique, Modification, Maintenance, and Model Calibration*. Critique.

Xofis, P., Konstantinidis, P., Papadopoulos, I., and Tsiourlis, G. (2020). Integrating remote sensing methods and fire simulation models to estimate fire hazard in a south-east mediterranean protected area. *Fire*, 3(3):31. Online: https://bit.ly/37GnKT0.

Zigner, K., Carvalho, L., Peterson, S., Fujioka, F., Duine, G., Jones, C., Roberts, D., and Moritz, M. (2020). Evaluating the ability of farsite to simulate wildfires influenced by extreme, downslope winds in santa barbara, california. *Fire*, 3(3):29. Online: https://bit.ly/3xHXguY.

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ECOHYDROLOGY

INTERACTIONS BETWEEN LEAF AREA INDEX, CANOPY DENSITY AND EFFECTIVE PRECIPITATION OF A *POLYLEPIS RETICULATA* FOREST LOCATED IN A PARAMO ECOSYSTEM

INTERACCIONES ENTRE ÍNDICE DE ÁREA FOLIAR, DENSIDAD DEL DOSEL Y PRECIPITACIÓN EFECTIVA DE UN BOSQUE DE *POLYLEPIS RETICULATA* UBICADO EN UN ECOSISTEMA DE PÁRAMO

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Abstract

The measurement of vegetation cover is fundamental to quantify the precipitation percentage intercepted by it. The most widely techniques used to measure the cover *in situ* are the leaf area index (LAI) and the canopy density (CD). However, no attention has been paid to the differences recorded in the use of the two techniques or how these variables influence the hydrological balance on the throughfall (TF). For this reason, the objective of the study is to evaluate the relationship between vegetation cover measurements conducted by the LAI and CD methods and to identify how they relate with the TF, important for hydrological applications. The study was developed in a *Polylepis reticulata* forest of 15633 m^2, located at the Zhurucay Ecohydrological Observatory, south of Ecuador, in an altitudinal range of 3765 to 3809 m.a.s.l. The LAI was measured with the CI-110 Plant Canopy Imager equipment and CD with a spherical densiometer, covering a wide range of canopy cover values. The study site was instrumented with 9 tipping-bucket rain gauges to measure TF. The results indicate that LAI and CD averages are 2.43 m^2 m^{-2} y 88% respectively; whose relationship is significant (R^2 = 0.913; $p < 0.05$). Mean annual TF is 773.2 mm, which tends to decrease with the increase of the LAI and CD; although, their relationship is not statistically significant (p-value$>$ 0.05). This study shows the importance of characterizing the vegetation cover to understand the interaction with TF.

Keywords: *Polylepis reticulata*, leaf area index, canopy density, throughfall.

Resumen

La medición de la cobertura vegetal es fundamental para conocer qué porcentaje de la precipitación queda interceptada sobre la misma. Las técnicas más utilizadas para medir la cobertura *in situ* son el índice de área foliar (IAF) y la densidad del dosel (DD). Sin embargo, no se ha puesto atención en las diferencias registradas en el uso de las dos técnicas ni cómo estas variables influyen sobre el balance hidrológico particularmente sobre la precipitación efectiva (PE). Por tal motivo, el objetivo del estudio es evaluar la relación entre las mediciones de la cobertura vegetal realizadas por los métodos de IAF y DD e identificar cómo se relacionan con la PE, importante para aplicaciones hidrológicas. El estudio se desarrolló en un bosque de *Polylepis reticulata* de 15633 m^2, ubicado en el Observatorio Ecohidrológico Zhurucay, sur de Ecuador, en un rango altitudinal de 3765 a 3809 m s.n.m. El IAF se midió con el equipo CI-110 Plant Canopy Imager y la DD con un densiómetro esférico, cubriendo un amplio rango de valores de cobertura de dosel. Para medir la PE se instrumentó el sitio de estudio con 9 pluviógrafos. Los resultados indican que el IAF y DD son en promedio 2,43 m^2 m^{-2} y 88 %, respectivamente; cuya relación resulta ser significativa (R^2 = 0,913; $p<$ 0,05). La PE media anual es de 773,2 mm, que tiende a disminuir con el incremento del IAF y DD; aunque su relación resulta estadísticamente no significativa (valores $p>$ 0,05). Este estudio muestra la importancia de caracterizar la cobertura vegetal para entender la interacción con la PE.

Palabras clave: *Polylepis reticulata*, índice de área foliar, densidad del dosel, precipitación efectiva.

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1 Introduction

Vegetation cover is an essential factor in understanding ecosystems from a hydrological and ecological point of view, as it plays a significant role in forest-water relations (Levia et al., 2011), as well as in the transformation of solar energy into primary production (Hernández et al., 2003). In fact, forests with wide canopy coverage and high aerodynamic roughness cause high rates of potential evaporation (Gerrits et al., 2010), which means that the density of the cover, leaf area index, tilt angle and leaf shape affect hydrological processes such as interception (Crockford and Richardson, 2000; Fleischbein et al., 2005; Gerrits, 2010; Levia et al., 2011), evaporation, effective precipitation, and infiltration. The heterogeneous distribution of the canopy affects water availability in the forest area; in other words, in some places rain can reach the soil in higher quantities than in others, and it may exceed the amount of gross precipitation (Gerrits, 2010), because the canopy and the structure of the branches guide the rain into drip points that cause more intensity of local effective precipitation (Germer et al., 2006; Gerrits, 2010).

One of the most known forests of the high Andes is the *Polylepis* forests, which is seen as scattered ecotones. They are in altitudinal ranges from 3000 to 5000 m.a.s.l, especially in places protected by rocks or along the river banks (Domic et al., 2014), under extreme environmental conditions. Climate and topography have marked the existence of these forests as small isolated patches (Renison et al., 2006; Rangel and Arellano, 2010), which are forests that are sensitive to change due to their high endemism (Gareca et al., 2010), in the group of ecosystems with the highest threat (Herzog et al., 2002). Therefore, it is important to know its contribution to the water balance in the moorland, since the forest vegetation is able to collect more water than brush, including the one that comes from the mist (Nisbet, 2005).

Characterization of the forest canopy is essential because it plays a key role in the partitioning of gross precipitation (effective precipitation, cortical runoff, and interception) (Levia and Herwitz, 2005; Johnson and Lehmann, 2006; Park and Cameron, 2008), in the control of evaporation and storage of water (Levia et al., 2011). In addition, a detailed description of the canopy has facilitated the prediction of water losses by interception (Molicôvá and Hubert, 1994). There are two basic measurement methods: (A) The leaf area index (LAI), which refers to the surface unit ($m^2\ m^{-2}$) of the soil that is covered by the vertical projection of the canopy or leaf area (Jennings et al., 1999), (b) Canopy Density (CD) or Canopy Closure (%), which is the proportion observed from a single point of the sky that is darken by vegetation (Jennings et al., 1999). These differ according to type of forest, density, spatial distribution of trees, type and structure of the canopy, phenological status of species, age and type of management (Lieberman et al., 1989; Pukkala et al., 1991). In the case of *Polylepis* forests, these variables have been determined as part of the research. For example, LAI has been associated with studies of leaf litter decay (Pinos et al., 2017). Meanwhile, CD has identified: the effect of canopy coverage on plant dynamics (Cierjacks et al., 2007), its influence on avifauna (Tinoco et al., 2013), or the structural complexity of the landscape (Renison et al., 2011), since a number of studies have focused on topics such as: distribution in the Andes (Gosling et al., 2009), history and causes of fragmentation (Kessler, 2002; Hoch and Körner, 2005; Valencia et al., 2018), morphological characteristics (Montalvo et al., 2018), floristic composition, and regeneration problems (Domic et al., 2014; Morales et al., 2018) with the purpose of understanding and knowing morphological differences among *Polylepis* species; also, knowing the ecological, climatic conditions in which these forests are developed and activities that have caused their fragmentation over time.

At the canopy scale, two hydrological processes as important as precipitation occur: A) throughfall (TF), which is the amount of water that reaches the soil through the canopy and/or which falls by drip after being in contact with the foliage (Levia and Frost, 2006), and b) interception, which is water retained by leaves and branches of vegetation, reducing the amount of water that reaches the soil (Gerrits, 2010). The properties of the rain also affect these processes (Crockford and Richardson, 2000; Murakami, 2006); for example, a sequence of events with dry period intervals can intercept more water than a storm, as some of the water retained in the canopy is evaporated, creating space for more storage (Levia et al., 2011). Some authors have found that TF varies from 60% to 95% of gross precipitation (Germer et al., 2006; Zimmermann et al., 2007; Berger et al., 2008; Brauman et al., 2010), while interception may represent a variation of 10 to 50 % (Zhang et al., 2006; Roth et al., 2007).This variability affects infiltration, runoff, flow and water storage, which are consecutive processes to complete the hydrological cycle (Tsiko et al., 2012). Few studies have shown the role of *Polylepis* forests in hydrology, such as that carried out by Alfaro (2015) in Peru and that of Harden et al. (2013) in Ecuador, which indicate the influence of *Polylepis racemosa* forests (introduced and managed species) on water infiltration into the soil. Research on effective precipitation and water interception in the canopy has had more emphasis on high Andean forests (Ramos Franco and Armenteras, 2019),low montane forests (Fleischbein et al., 2005; Wullaert et al., 2009), tropical montane forests (Zimmermann et al., 2007; Gomez et al., 2008) and temperate tropical forest (Oyarzún et al., 2011), facilitating the understanding of the hydrological balance. There is little information on the relationship between the characteristics of the canopy and the amount of water that reaches the soil in High Andean forests and even more so in forests that are at the tree boundary; therefore, the role of the vegetative cover in *Polylepis* forests in hydrological processes at the canopy scale is unknown. For this reason, the aim of this research is to evaluate the relationship between the measurements of vegetative cover made using the LAI and CD methods, and to identify how they relate to TF, which is important for hydrological applications.

2 Materials and Methods

2.1 Study area

The study was carried out at the Zhurucay ecohydrological observatory where there is a *Polylepis* forest of 15633 m^2, which has an altitudinal range from 3765 to 3809 m.a.s.l., with slopes ranging from 10 to 50 %. The dominant plant species is *Polylepis reticulata*, finding other tree species such as *Escallonia myrtiloides, Oreopanax sp., Weinmannia sp., Gynoxys sp.,* species of the Melastomataceae family and shrubs such as *Valeriana sp*. *Polylepis reticulata* trees can reach a height of 15 m, have tortuous trunks with several branches, a height diameter of 33.58 cm and a basal area of 925.64 cm^2. Leaves are alternating and measure up to 2.5 cm long, grow as clusters at the ends of the branches, and are made up of 3 or 5 elliptical leaflets.

The climate is influenced by the Pacific moisture and continental air masses coming from the Amazon basin (Córdova et al., 2013). The interannual precipitation is characterized by being highly uniform, and it is slightly higher from January to July; the average annual precipitation is 1300 mm (Ochoa et al., 2018). Precipitation often occurs as drizzle, representing 80 % of rainy days (Padrón et al., 2015). The average daily temperature range is 0.4 °C to 14.2 °C, with an annual average of 6.1 °C. The average annual relative humidity is 93.6 %. The level of solar radiation is 4942 MJm^{-2} year^{-1} with a daily average of 13.73 MJm^{-2} day^{-1}. Wind speed follows a seasonal pattern with a monthly average of 3.21 m s^{-1} from October to March and 4.77 m s^{-1} from June to September (Carrillo et al., 2019). This area has an annual reference evapotranspiration of 723 mm at an altitude of 3780 m.a.s.l. (Córdova et al., 2015) and an annual current evapotranspiration (ETa) of 622 mm (average daily rate of 1.7 mm) (Ochoa et al., 2019).

2.2 Study design

A number of activities were carried out for the location of sites for measuring TF, LAI and CD in the *Polylepis* forest:

1. The forest area was divided into a 20 m × 20 m grid to determine the CD percentage at each point of the intersection (proportion of sky covered by vegetation) with a concave spherical densitometer at the height of the buds (1.20 m above the ground) and at a distance of 30 cm from the operator, method described in section 3.2.
2. The values obtained characterized the spatial CD variability of forest. Several interpolation methods were used to identify the best characterization, and the errors of each were analyzed; the methods used were: Ordinary kriging (spherical model), inverse distance weighting (IDW) and Thiessen polygons.
3. The spatial location of 9 sampling sites distributed in low, medium, and high CD values was identified, considering the edge effect (Figure 1).

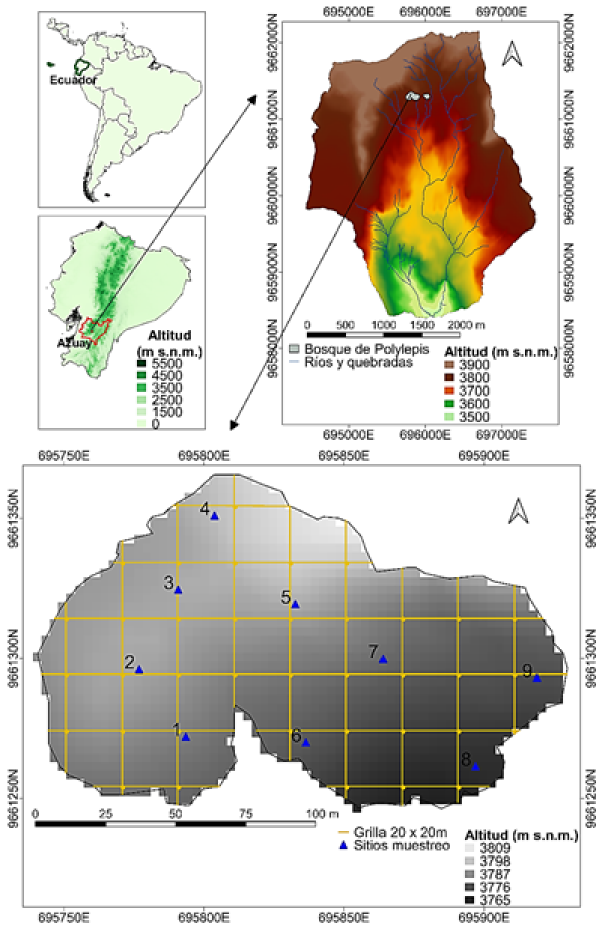

Figure 1. Study area located in the Zhurucay ecohydrological observatory in the south of Ecuador.

2.3 Measurement of the canopy density

Once the sampling sites for the TF measurement have been established, the CD percentage on each rain gauge was measured. A spherical densitometer consisting of a spirit level and a concave mirror divided by a grid of 24 square cells that reflected the incident light at an angle of 180° was used to determine this variable. Each reading consists of the mental subdivision of each cell into 4 squares that are represented by an imaginary point in the center, giving a total of 96 central points, which when found covered by the reflection of the plant cover are counted. An average value of four readings per site (direction of cardinal points) was obtained, the same as for the canopy percentage is multiplied by 1.04 (1/96*100) (Lemmon, 1956, 1957; Cook et al., 1995).

2.4 Leaf area index measurement

LAI measurement (m^2 m^{-2}) was performed at each site where CD was measured. The optical equipment CI-110 Plant Canopy Imager, consisting of an 8-megapixel camera equipped with a 170° angle hemispheric (fisheye) lens was used. The software is based on the calculation of the fraction of the visible sky under the canopy using the Gap-Fraction Inversion procedure (Norman and Campbell, 1989), according to three main equations: Transmission coefficient for diffuse radiation ingress, canopy extinction coefficients (LAI), and the average of the slope angle of the foliage. Canopy images are divided into zenith and azimuthal divisions (canopy sectors). The sky fraction (solar beam transmission coefficient) visible in each division is analyzed by counting the sky portion of the pixels in the image. The machine captures wide-angle images of the canopy while estimating the LAI and measuring photosynthetically active radiation (PAR) levels per sampling site. Images are updated live on the built-in monitor, providing instant data for verification and analysis with the built-in software. LAI is represented by values ranging from 0 to 10, where 0 is equivalent to an area without a canopy or bare soil and 10 represents a dense canopy (Bio-Science, 2016). Optimal sky conditions for measurements should be under a uniform cloud cover in the morning or late afternoon (amount of low radiation) (Bio-Science, 2016).

2.5 Effective Precipitation Measurement

Nine automatic 0.2 mm resolution rain gauges were installed at a ground height of 1.20 m. Rain gauges were calibrated *in situ* and a plastic mesh was placed on each one to collect the leaf litter and thus avoid its plugging. The download of data, maintenance and cleaning of the equipment was carried out weekly from March 9, 2019 until March 8, 2020.

Records were added to have a database every 5 minutes. The amount of TF obtained corresponds to the daily and annual accumulation of the values recorded by the rain gauges at each sampling point within the forest. In case of data loss due to download failure or plugging, a daily data filling was performed using the linear regression method of the rain gauge values that showed data loss with the gauge that presented the best correlation.

2.6 Relationship between CD, LAI, and TF

CD was first compared with LAI by correlation using Pearson method in order to know whether these two variables show the same information regarding canopy coverage. Linear correlations and regressions of CD and LAI were then performed with TF to determine which variable allows the identification of TF variability in the forest canopy.

3 Results

3.1 Canopy density

The spatial variability of the modeled canopy demonstrated better fit and accuracy with the characteristics of the area when using interpolation with the Kriging method compared to IDW and Thiessen polygons (37 points, 20 × 20 m grid). The method was better suited to the data, presenting the lowest errors.

Figure 2 shows that CD in the *Polylepis* forest has a range between 62.5% and 95.2% of spatial variation. In certain areas, values between 87 and 91% predominate, representing approximately an area of 550 m^2.

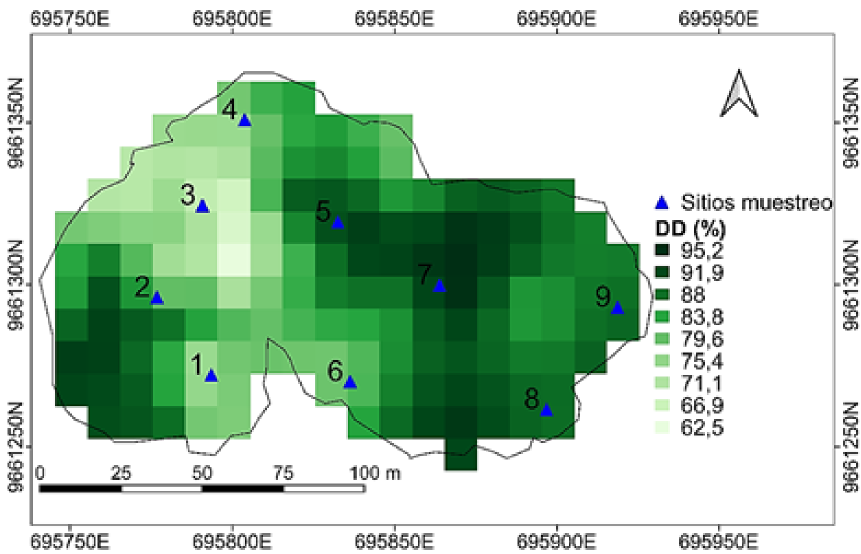

Figure 2. Spatial variability of canopy density by Kriging interpolation method and effective precipitation sampling sites.

As indicated in section 3.4, 9 sampling sites were considered for TF, where CD and LAI were measured (Figure 2). Figure 3 shows that the CD percentage at the 9 sites varies from 79 % (site 1) to 96 % (site 5). The average value of the CD percentage was 88 ± 5.8 %. The variation coefficient was low, without exceeding 10 %, indicating homogeneity in the data.

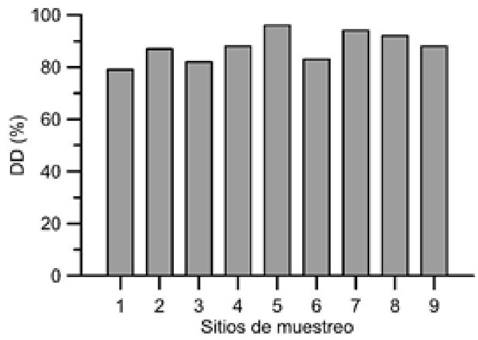

Figure 3. Percentage of canopy density

3.2 Leaf area index

As shown in Figure 4, the estimated LAI at the 9 sampling sites varies between 2.05 m^2 m^{-2} (site 1) and 2.79 m^2 m^{-2} (site 5), with an average of 2.43 ± 0.25 m^2 m^{-2}. Similarly with CD, the variation coefficient was 10 %, confirming a low variability of LAI in the forest.

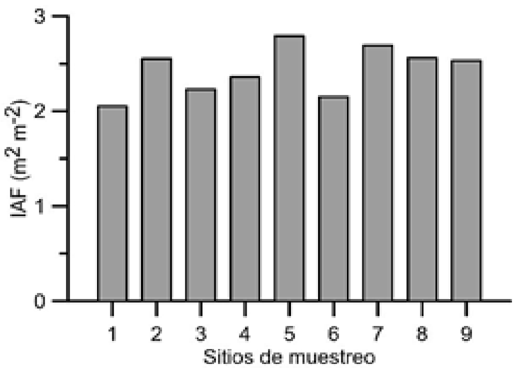

Figure 4. Leaf area index

3.3 Effective Precipitation

It was found that the rain gauge of site 2 had the highest lost data percentage of TF with 3.6 % data to be filled in. It should be emphasized that this procedure did not affect the results because it did not exceed the acceptable limit of lost values (10 %).

The average annual TF estimated by rainfall at 9 sites in the *Polylepis* forest was 773.2 mm $year^{-1}$ ± 212.6 with a daily average of 2.1 ± 0.58 mm day^{-1} (Table 1). The annual quantity of TF varies between 484.9 and 1191.6 mm $year^{-1}$, and the annual average daily quantity varies from 1.3 to 3.3 mm day^{-1}; these values correspond to site 9 and 1, respectively (Table 1 and Figure 5).

Table 1. Annual effective precipitation (TF), annual daily mean, annual daily standard deviation (σ), and annual daily variation coefficient (CV).

Sampling site	Annual TF (MM $year^{-1}$)	Annual TF daily average (MM day^{-1})	σ annual daily	CV annual daily (%)
1	1191.6	3.3	5.2	160
2	825.4	2.3	4.1	180
3	694.5	1.9	3.2	170
4	743.0	2.0	3.5	170
5	592.7	1.6	2.9	180
6	862.5	2.4	4.1	170
7	944.9	2.6	4.7	180
8	619.1	1.7	2.9	170
9	484.9	1.3	2.3	170
x̄	773.2	2.1		
σ	212.6	0.58	3.8	
CV	28	28		180

The variation coefficient for both annual values and annual daily average values for all sites represents 28% variability. When analyzing the annual daily TF at each sampling site, it is observed that the data report a CV of 160% (site 1) to 180% (sites 2, 5 and 8), indicating that TF has high heterogeneity in the forest under study.

Figure 5 shows that the box diagrams show outliers that are concentrated above the upper limit, maybe in response to specific precipitation events, which in this case are daily events exceeding 10 mm.

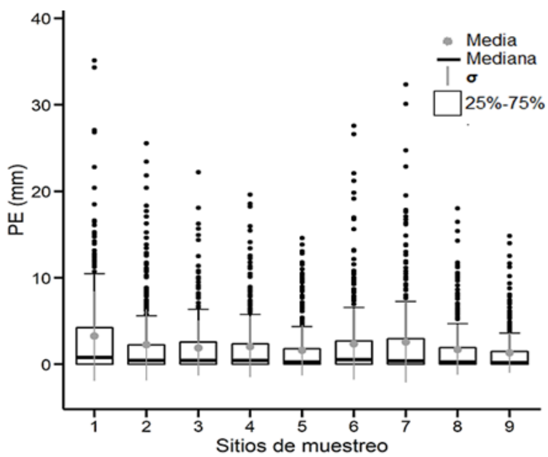

Figure 5. Effective daily precipitation

3.4 Relationship between CD, LAI, and TF

As expected, the correlation between LAI and CD is highly significant with a p value < 0.05 and a R^2 coefficient of 0.913. Figure 6 shows that CD tends to increase when LAI increases.

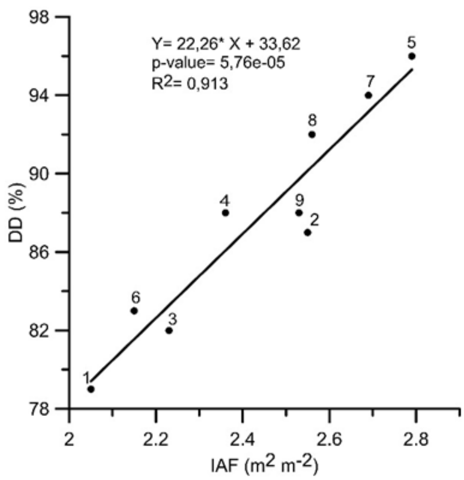

Figure 6. Relationship between leaf area index (LAI) and canopy density (CD) (1-9 sampling sites)

Correlation coefficients indicate an inverse relationship between leaf coverage variables (LAI and CD) and TF, reporting values of −0.535 and −0.524, respectively; as expected, TF tends to decrease when CD or LAI increase (Figure 7).

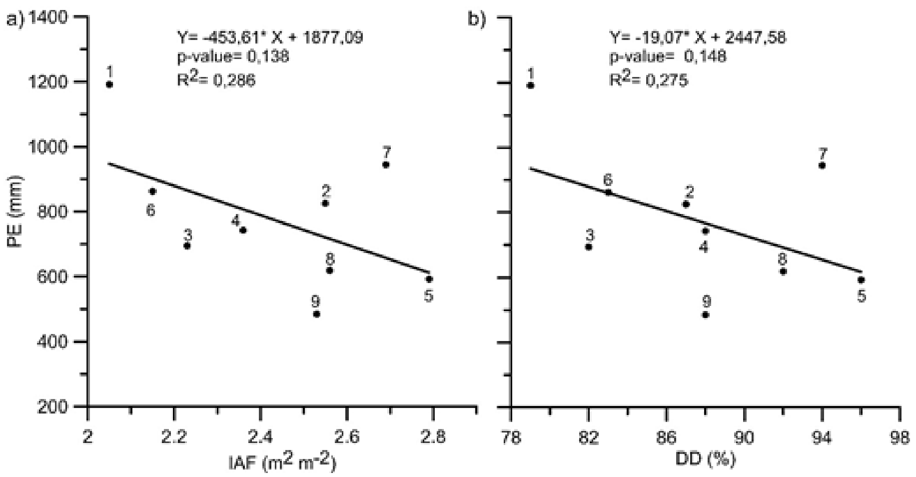

Figure 7. Relationship between (a) leaf area index (LAI), (b) canopy density (CD) and effective precipitation (TF) (1-9 sampling sites)

However, p values > 0.05 indicate that the ratio is not significant. When applying the linear regression method, low R^2 coefficients of 0.286 and 0.275 were found, which indicate little dependence or response of TF to these canopy coverage variables.

4 Discussion

Information about the LAI, CD, TF and the relationship between such variables for the analyzed *Polylepis reticulata* forest represents important information for the High Andean forests, since it facilitates understanding and establishes a foundation on the role of vegetation in hydrological processes that occur in moorland forests.

4.1 Characterization of canopy coverage

Researches conducted in Andean ecosystem forests have shown values of LAI and CD (Table 2), and have characterized canopy coverage and the relationship with different ecological functions.

4.1.1 Leaf area index studies

LAI values of the *Polylepis* forest studied are within the lower values reported by Pinos et al. (2017) for *Polylepis reticulata* forests in the Cajas National Park, which have a LAI between 2.60 to 6.17 m^2 m^{-2} (mean of 3.96 m^2 m^{-2}). This difference may be due to the method used for determining LAI, as the author used specific foliar area and tree density per study plot. In studies carried out on pine plantations established in moorland ecosystems, Alvarado and Muñoz (2017) report a LAI from 0.23 to 2.22 m^2 m^{-2} (mean of 0.92 m^2 m^{-2}), values that are lower than those found in this study, possibly due to the shape of leaves and density of the plantation. Likewise, Jadán et al. (2019) recorded very low LAI values (0.2 m^2 m^{-2}) in plantations of similar species and a LAI of 5.5 m^2 m^{-2} in high montane forests, which is higher than the one found in this research. In a study carried out in high and low montane evergreen forests located in southern Ecuador, Alvarado and Cobos (2019) reported LAI results with less variability than the present study. Fleischbein et al. (2005) indicate that a low montane forest in southern Ecuador has a LAI between 5.2 and 9.3 m^2 m^{-2} (mean of 7.3 m^2 m^{-2}), higher than those identified in the present study. Moser et al. (2007) in tropical montane forests in the south of Ecuador indicate that as the altitude increases the size of the leaves is smaller, therefore, the LAI decreases. Gomez et al. (2008)) in tropical montane forests of Peru found that LAI is 2.5 ± 0.7 to 2.9 ± 0.2 m^2 m^{-2}, values that are higher than those found in the *Polylepis* forest.

4.1.2 Canopy density studies

Studies conducted in *Polylepis* forests have determined CD percentages; as is the case with the study conducted by Cierjacks et al. (2007) in *Polylepis pauta e incana*, forests, in which values of 46.7% were found near the border and 65 - 75% in the inner part of the forest, data that appear to be lower than those of this study near the border (79.83 and 88%; sites 1, 6 and 9) as well as in the inner forest (94 - 96%; site 7 and 5).

Similarly, Renison et al. (2011) in a *Polylepis australis* forest identified CD variability that is lower than in the present study with percentages of 8, 23, 54, and up to 72%. This may be because the results of the studies present a subjectivity bias because they were determined visually, a method that depends entirely on the experience of the technician. In pine plantations located in moorland ecosystems, Alvarado and Muñoz (2017) reported that these forests have a CD range from 5.5 to 74.7% (mean 44.5%). Similarly, Quiroz et al. (2019) presented CD percentages (19.3% - 64.8%) lower than those found at the study site. In high and low montane evergreen forests located in the south of Ecuador, CD averages were 53 ± 4% and 72 ± 3.2% lower than those found in this study (Alvarado and Cobos, 2019). The research carried out by Gomez et al. (2008), in a tropical montane forest in Peru has similarities in CD values (87.9% ± 6.2 to 90.7% ± 1.6) with data reported from *Polylepis* forest.

According to the observed, the low similarity of the LAI and the CD percentage between forests is because such variables depend on the specific conditions of the area, which generally influence the development and characteristics of each tree species. Influential parameters are: leaf size, tree density per surface unit, architecture and structure of branches and topography; therefore, they can vary significantly from one site to another, even so it is the same forest species.

The close relationship between LAI and CD is observed by regression analysis, revealing a strong proportionality between the two variables, which is consistent with the study carried out by Buckley et al. (1999), in which they report a R^2 of 0.93 and 0.99 in oak and pine forests, stating that this happens because the forests studied have a uniform structure. However, these authors also comment that the relationship between variables can change when there are differences between forest species, treetop architecture and development stage.

Table 2. LAI and CD of forests located in Andean ecosystems

Ecosystem and Type of forest	**Study site and height (m.a.s.l)**	**LAI measurement (m^2 m^{-2})**	**CD Measurement (%)**	**Reference**
Moorland: *Polylepis reticulata* Forest	Ecuador, Zhurucay River Basin, (3765 – 3809)	2.05 – 2.79	79 – 96	Present study
Moorland: *Polylepis reticulata* Forest	Ecuador, Parin Boxes, (3735 – 3930)	2.60 – 6.17		Pinos et al. (2017)
Moorland: *Polylepis pauta* and incana	Ecuador, Papallacta, (3500 – 4100)		46.7 - 75	Cierjacks et al. (2007)
Moorland: *Polylepis australis* forest	Argentina, Córdoba, (1400 – 2500)		8-72	Renison et al. (2011)
Moorland: Pine plantation	Ecuador, Azuay, (3500 – 3700)	0.23 – 2.22	5.5 – 74.7	Alvarado and Muñoz (2017)
Moorland: Pine plantation	Ecuador, Azuay, (3600 – 3800)		19.3 – 64.8	Quiroz et al. (2019)
Moorland: Pine plantation High montane f orest	Ecuador, Azuay, (3800 y 2500)	5.5 and 0.2		Jadán et al. (2019)
High and low montane evergreen forests	Ecuador, Azuay, (2000 – 3800)	1.6 – 2.5	53 – 72	Alvarado and Cobos (2019)
Low montane forest	Ecuador, Loja - Zamora, (1900 – 2000)	5.2 – 9.3		Fleischbein et al. (2005)
Tropical montane forest	Ecuador, Loja, (1050 – 3060)	5.1 – 2.9		Moser et al. (2007)
Cloudy tropical montane forest	Peru, Yanachaga-Chemillén National Park, (2815 – 2468)	2.5 – 2.9	87.9 – 90.7	Gomez et al. (2008)

4.2 Variability of effective precipitation and relationship with canopy coverage

This study showed that TF in the *Polylepis* forest was heterogeneous. The literature does not report another TF study conducted in *Polylepis* forests. Studies in premontane tropical forests (Teale et al., 2014), low montane forest (Fleischbein et al., 2005) and mixed oak forest (Staelens et al., 2006) also found that TF is very variable. These studies explain that this variable may be influenced by the shape of the canopy, morphological characteristics of the leaves and in some cases by a higher epiphyte load on the canopy that can generate more dripping points, which increases TF variability. Similarly, the study conducted by Zimmermann et al. (2007) explains that spatial variability depends mainly on the complexity of the canopy and is influenced by the number of species per area, irregular height, epiphytic presence, age, structure and arrangement of trees. Another possible explanation is that TF also depends on the precipitation depth, reason for which the spatial variability of TF increases, suggesting that spatial patterns of TF volume can be independent of the ecosystem. Germer et al. (2006) and Roth et al. (2007) show that there are characteristics such as species diversity, vegetation size and structure that result in rain distribution, dripping and storage points located in the lower canopy, producing spatially heterogeneous patterns. Zimmermann et al. (2009) and Macinnis et al. (2014) show similar results in their studies, since vegetation influences the movement of water through the canopy, and certain forms or its distribution within the forest area can create dripping points. In addition, other studies such Zimmermann et al. (2008) indicate that TF is affected by background canopy conditions such as moisture. In this study, the annual daily variation coefficient turns out to be higher than the annual. Carlyle and Price (2007) explain that when TF is observed at a time resolution of lower aggregation, such as daily aggregation or event aggregation, this value is influenced by the intensity conditions of gross precipitation, and it even depends on wind conditions. The variation coefficient in TF may increase or decrease when the intensity of rain is its main change factor (Weiqing et al., 2007).

Although the correlations found between the variables LAI, CD and TF are not statistically significant in this study, the results show an inverse proportionality between the canopy cover variables and TF, which is consistent with previous research in which TF tends to decrease as LAI increases (Llorens and Gallart, 2000; Loescher et al., 2002; Nadkarni and Sumera, 2004). Similarly, Holwerda et al. (2006) indicate that TF in a Puerto Rico forest was higher in areas with low canopy amounts, because a smaller canopy surface correlates with a smaller amount of intercepted water. In the study conducted by Fleischbein et al. (2005) a negative correlation between LAI and TF (Pearson r = -0.49) was reported, being slightly lower than the coefficient found in this study. However, when compared to interception, Fleischbein et al. (2005) show that LAI accounts for only 12% of the variation, stating that the area of plant cover measured on TF rain gauges is higher than the area of the gauge. Thus, the difference in the capture area of the TF meters and the area covered by the LAI and CD equipment could explain the variability of the interception, or in the case of this study, TF variation in similar LAI values and the low determination coefficients between the canopy cover variables with TF. When comparing the results with the study conducted by Teale et al. (2014) in a forest in Costa Rica, it is confirmed that the relationship between LAI and TF is statistically non-significant, probably because locations with similar LAI may have different leaf type, wood coverage, orientation of foliage and branches, among other features that create retention points and drip points. For this reason, it is clear that vegetation influences the way water moves through the canopy; while TF is generally lower than gross precipitation, certain arrangements and vegetation forms can create dripping points, thereby exceeding precipitation. Overall, the results of studies that attempted to relate canopy coverage or vegetation characteristics with TF have been limited (Keim et al., 2005). Similarly, Zimmermann et al. (2009) when talking about the relationship between the canopy opening and TF at the measuring points, say that it is weaker as the magnitude of the precipitation event increases. In a study conducted by Molina et al. (2019) in pine and oak forests, it is indicated that TF is not significantly related when CD values are lower than 60%. However, when increasing this variable over a range of 60 to 100% a significant pattern of TF reduction with increased CD is observed, showing a negative correlation of 0.51 and 0.61, respectively. Authors such as Park and Cameron (2008) found that there is an interaction between impacts produced by canopy characteristics in TF with the influence of precipitation; however, statistical analysis could not identify any pattern. (Levia et al., 2011) indicate that spatial patterns of TF vary significantly between ecosystems, so it is not possible to identify a relationship between the canopy and TF.

As mentioned before, the possible explanation for the non-significant relationship between canopy cover variables and TF is that this hydrological process does not only depend on CD or LAI, but on other factors such as vegetation (structure, branch architecture, density, age, angle of inclination of the leaves) and climate (intensity of rain and wind).

On the other hand, studies carried out in deciduous forests indicate the effect of foliage dynamics on TF, because they present remarkable periods of leaf loss, which is the opposite in perennial forests such as *Polylepis*. However, it is clear that its foliage presents a dynamic that consists on the clearing and renewal of leaves, as indicated by Pinos (2014), when reporting that *Polylepis* forests have 0.61 year^{-1} overshoot rates and the foliar renewal period occurs 1.75 years. For this reason, this dynamic should be taken into account for future research with more measurement points, at different times or seasons of the year.

5 Conclusions

This study is a pioneer in comparing measurements of LAI and CD and their relationship with TF in *Polylepis* forests, which are characterized as part of moorland ecosystems. LAI and CD are variables that differ according to the conditions the forests are exposed to during their growth, for example, soil nutrients, water, wind, precipitation, temperature; as well as characteristics typical of the species that make up the forest such as: leaf shape and size, architecture and branch structure, height, age, among others.

A strong relationship was found between the measured canopy variables, which in turn provide similar coverage information, concluding that any technique could be used to estimate canopy coverage. However, due to its greater comfort, ease of operation and low cost, the technique of measuring the CD percentage using the spherical densitometer method is the most optimal for this activity.

When studying effective precipitation, it was observed that it is not only influenced by the variables mentioned above, but by the set of characteristics and distribution of forest species that increase plant complexity in the forest and the heterogeneity of TF. In addition, the finer the temporal resolution used in the TF estimation (daily, schedule, minutes), possibly the more influenced by environmental conditions such as the intensity and duration of precipitation, wind, solar radiation, background conditions, dry or canopy moisture.

The non-significant relationship between LAI and CD with TF can be due to the difference in measuring areas of the 2 variables (canopy cover and precipitation), since the area covered by rain gauges is much smaller than the area projected by the equipment used to measure canopy coverage. Therefore, measurements of plant cover – with any technique – are limited to properly characterize the variability of TF in the ecosystem studied.

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References

Alfaro, G. (2015). Caracterización de la infiltración en bosques de *Polylepis spp.*, de 11 y 29 años, parque nacional huascarán, quebrada quilcayhuanca, huaraz, ancash. Tesis de grado, Universidad Agraria La Molina. Online: https://bit.ly/3ooQaZh, Perú.

Alvarado, A. and Muñoz, L. (2017). Evaluación de la regeneración natural y su relación con la altitud y cobertura de dosel en plantaciones no manejadas de *Pinus patula* en zonas alto andinas, en la provincia del azuay. Tesis de grado, Universidad de Cuenca. Online: https://bit.ly/3ol1YvI, Cuenca, Ecuador.

Alvarado, I. and Cobos, C. (2019). Relaciones entre la estructura y cobertura arbórea con el carbono almacenado en bosques montanos andinos en el macizo del cajas, azuay-ecuador. Tesis de grado, Universidad de Cuenca. Online: https://bit.ly/3yc33dL, Cuenca, Ecuador.

Berger, T., Untersteiner, H., Schume, H., and Jost, G. (2008). Throughfall fluxes in a secondary spruce (*Picea abies*), a beech (*Fagus sylvatica*) and a mixed spruce-beech stand. *Forest Ecology and Management*, 255(3-4):605–618. Online: https://bit.ly/3ftBtQD.

Bio-Science (2016). *Manual CI-110 / 120 Plant Canopy Imager*.

Brauman, K., Freyberg, D., and Daily, G. (2010). Forest structure influences on rainfall partitioning and cloud interception: A comparison of native forest sites in kona, hawai'i. *Agricultural and Forest Meteorology*, 150(2):265–275. Online: https://bit.ly/3ot1jrY.

Buckley, D., Isebrands, J., and Sharik, T. (1999). Practical field methods of estimating canopy cover, par, and lai in michigan oak and pine stands. *Northern Journal of Applied Forestry*, 16(1):25–32. Online: https://bit.ly/3brumXW.

Carlyle, D. and Price, A. (2007). Modelling canopy interception loss from a madrean pine-oak stand, northeastern mexico. *Hydrological Processes: An International Journal*, 21(19):2572–2580. Online: https://bit.ly/2Rdx7Fr.

Carrillo, G., Silva, B., Rollenbeck, R., Célleri, R., and Bendix, J. (2019). The breathing of the andean highlands: Net ecosystem exchange and evapotranspiration over the páramo of southern ecuador. *Agricultural and Forest Meteorology*, 265:30–47. Online: https://bit.ly/2SS1odg.

Cierjacks, A., Iglesias, J., Wesche, K., and Hensen, I. (2007). Impact of sowing, canopy cover and litter on seedling dynamics of two *Polylepis* species at upper tree lines in central ecuador. *Journal of Tropical Ecology*, pages 309–318. Online: https://bit.ly/3hwP78i.

Cook, J., Stutzman, T., Bowers, C., Brenner, K., and Irwin, L. (1995). Spherical densiometers produce biased estimates of forest canopy cover. *Wildlife Society Bulletin*, 23(4):711–717. Online: https://bit.ly/3uTrieF.

Córdova, M., Carrillo, G., and Célleri, R. (2013). Errores en la estimación de la evapotranspiración de referencia de una zona de páramo andino debidos al uso de datos mensuales, diarios y horarios. *Aqua-LAC*, 5(2):14–22. Online: https://bit.ly/3fem8mM.

Córdova, M., Carrillo, G., Crespo, P., Wilcox, B., and Célleri, R. (2015). Evaluation of the penman-monteith (fao 56 pm) method for calculating reference evapotranspiration using limited data. *Mountain Research and Development*, 35(3):230–239. Online: https://bit.ly/3bplNwH.

Crockford, R. and Richardson, D. (2000). Partitioning of rainfall into throughfall, stemflow and interception: effect of forest type, ground cover and climate. *Hydrological processes*, 14(16-17):2903–2920. Online: https://bit.ly/3buU0ei.

Domic, A., Camilo, G., and Capriles, J. (2014). Small-scale farming and grazing reduce regeneration of *Polylepis tomentella* (rosaceae) in the semiarid andes of bolivia. *Biotropica*, 46(1):106–113. Online: https://bit.ly/33INigu.

Fleischbein, K., Wilcke, W., Goller, R., Boy, J., Valarezo, C., Zech, W., and Knoblich, K. (2005). Rainfall interception in a lower montane forest in ecuador: effects of canopy properties. *Hydrological Processes: An International Journal*, 19(7):1355–1371. Online: https://bit.ly/3eMJGjI.

Gareca, E., Hermy, M., Fjeldså, J., and Honnay, O. (2010). *Polylepis* woodland remnants as biodiversity islands in the bolivian high andes. *Biodiversity and conservation*, 19(12):3327–3346. Online: https://bit.ly/3osFHvW.

Germer, S., Elsenbeer, H., and Moraes, J. (2006). Throughfall and temporal trends of rainfall redistribution in an open tropical rainforest, southwestern amazonia (rondônia, brazil). *Hydrology* *and Earth System Sciences*, 10(3):383–393. Online: https://bit.ly/3oie8FJ.

Gerrits, A., Pfister, L., and Savenije, H. (2010). Spatial and temporal variability of canopy and forest floor interception in a beech forest. *Hydrological Processes*, 24(21):3011–3025. Online: https://bit.ly/2RYbo4g.

Gerrits, M. (2010). *The role of interception in the hydrological cycle*. Doctoral thesis, Technische Universiteit Delft. Online: https://bit.ly/3omnEr7, Delft, Netherlands.

Gomez, D., Oberbauer, S., McClain, M., and Philippi, T. (2008). Rainfall and cloud-water interception in tropical montane forests in the eastern andes of central peru. *Forest Ecology and Management*, 255(3-4):1315–1325. Online: https://bit.ly/3tWXhJx.

Gosling, W., Hanselman, J., Knox, C., Valencia, B., and Bush, M. (2009). Long-term drivers of change in *Polylepis* woodland distribution in the central andes. *Journal of Vegetation Science*, 20(6):1041–1052. Online: https://bit.ly/3eXxCfQ.

Harden, C., Hartsig, J., Farley, K., Lee, J., and Bremer, L. (2013). Effects of land-use change on water in andean páramo grassland soils. *Annals of the Association of American Geographers*, 103(2):375–384. Online: https://bit.ly/2RuPGVp.

Hernández, M., Granados, D., and Sánchez, A. (2003). Productividad de los ecosistemas en las regiones áridas. *Revista Chapingo. Serie Ciencias Forestales y del Ambiente*, 9(2):113–123. Online: https://bit.ly/33O6XLO.

Herzog, S., Cahill, J., Fjeldså, J., Kessler, M., Yensen, E., Tarifa, T., Capriles, J., Fernández, E., Hensen, I., Ibisch, P., Loayza, I., Renison, D., Dellacassa, E., Flores, E., Cingolani, A., Lorenzo, D., Matthysen, E., Schinner, D., Soria, R., Troncoso, A., Ståhl, B., and Vilaseca, A. (2002). Ecology and conservation of high-andean *Polylepis* forests. *Ecotropica*, 8:93–95. Online: https://bit.ly/3hB4WL0.

Hoch, G. and Körner, C. (2005). Growth, demography and carbon relations of *Polylepis* trees at the world's highest treeline. *Functional Ecology*, 19(6):941–951. Online: https://bit.ly/3fjdzHD.

Holwerda, F., Scatena, F., and Bruijnzeel, L. (2006). Throughfall in a puerto rican lower montane rain forest: A comparison of sampling strategies. *Journal of Hydrology*, 327(3-4):592–602. Online: https://bit.ly/3ymj1lO.

Jadán, O., Cedillo, H., Pillacela, P., Guallpa, D., Gordillo, A., Zea, P., Díaz, L., Bermúdez, F., Arciniegas, A., Quizhpe, W., and Vaca, C. (2019). Regeneración de árboles en ecosistemas naturales y plantaciones de *Pinus patula* (pinaceae) dentro de un gradiente altitudinal andino (azuay, ecuador). *Revista de Biología Tropical*, 67(1):182–195. Online: https://bit.ly/3f12psa.

Jennings, S., Brown, N., and Sheil, D. (1999). Assessing forest canopies and understorey illumination: canopy closure, canopy cover and other measures. *Forestry: An International Journal of Forest Research*, 72(1):59–74. Online: https://bit.ly/2RwoANR.

Johnson, M. and Lehmann, J. (2006). Double-funneling of trees: Stemflow and root-induced preferential flow. *Ecoscience*, 13(3):324–333. Online: https://bit.ly/3tUJzqG.

Keim, R., Skaugset, A., and Weiler, M. (2005). Temporal persistence of spatial patterns in throughfall. *Journal of Hydrology*, 314(1-4):263–274. Online: https://bit.ly/3wd4CGD.

Kessler, M. (2002). The "*Polylepis* problem": where do we stand. *Ecotropica*, 8(2):97–110. Online: https://bit.ly/3ymoHw0.

Lemmon, P. (1956). A spherical densiometer for estimating forest overstory density. *Forest science*, 2(4):314–320. Online: https://bit.ly/3eNKKDW.

Lemmon, P. (1957). Using forest densiometers. *Journal of Forestry*, 55(9):1–2. Online: https://bit.ly/33LBfyP.

Levia, D. and Frost, E. (2006). Variability of throughfall volume and solute inputs in wooded ecosystems. *Progress in Physical Geography*, 30(5):605–632. Online: https://bit.ly/2RV0MmL.

Levia, D. and Herwitz, S. (2005). Interspecific variation of bark water storage capacity of three deciduous tree species in relation to stemflow yield and solute flux to forest soils. *Catena*, 64(1):117–137. Online: https://bit.ly/3eOMgFR.

Levia, D., Keim, R., Carlyles, D., and Frost, E. (2011). *Forest Hydrology and Biogeochemistry*, chapter Throughfall and Stemflow in Wooded Ecosystems, pages 425–443. Online: https://bit.ly/3ynopVt. Springer.

Lieberman, M., Lieberman, D., and Peralta, R. (1989). Forests are not just swiss cheese: canopy stereogeometry of non-gaps in tropical forests. *Ecology*, 70(3):550–552. Online: https://bit.ly/3w4TN9i.

Llorens, P. and Gallart, F. (2000). A simplified method for forest water storage capacity measurement. *Journal of hydrology*, 240(1-2):131–144. Online: https://bit.ly/3uREiBH.

Loescher, H., Powers, J., and Oberbauer, S. (2002). Spatial variation of throughfall volume in an old-growth tropical wet forest, costa rica. *Journal of Tropical Ecology*, pages 397–407. Online: https://bit.ly/3bwU8d7.

Macinnis, C., Flores, E., Müller, H., and Schwendenmann, L. (2014). Throughfall and stemflow vary seasonally in different land-use types in a lower montane tropical region of panama. *Hydrological Processes*, 28(4):2174–2184. Online: https://bit.ly/2Rne4bB.

Molicová, H. and Hubert, P. (1994). Canopy influence on rainfall fields' microscale structure in tropical forests. *Journal of Applied Meteorology*, 33(12):1464–1467. Online: https://bit.ly/3ydzWXB.

Molina, A., Llorens, P., Garcia, P., de Las Heras, M., Cayuela, C., Gallart, F., and Latron, J. (2019). Contributions of throughfall, forest and soil characteristics to near-surface soil water-content variability at the plot scale in a mountainous mediterranean area. *Science of the Total Environment*, 647:1421–1432. Online: https://bit.ly/3fqMMZX.

Montalvo, J., Minga, D., Verdugo, A., López, J., Guazhambo, D., Pacheco, D., Siddons, D., Crespo, A., and Zárate, E. (2018). Características morfológico-funcionales, diversidad arbórea, tasa de crecimiento y de secuestro de carbono en especies y ecosistemas de *Polylepis* del sur de ecuador. *Ecología Austral*, 28(1-bis):249–261. Online: https://bit.ly/33KSQXI.

Morales, L., Sevillano, C., Fick, S., and Young, T. (2018). Differential seedling regeneration patterns across forest–grassland ecotones in two tropical treeline species (*Polylepis* spp.). *Austral Ecology*, 43(5):514–526. Online: https://bit.ly/3ykOMLS.

Moser, G., Hertel, D., and Leuschner, C. (2007). Altitudinal change in lai and stand leaf biomass in tropical montane forests: a transect study in ecuador and a pan-tropical meta-analysis. *Ecosystems*, 10(6):924–935. Online: https://bit.ly/33NC6z3.

Murakami, S. (2006). A proposal for a new forest canopy interception mechanism: Splash droplet evaporation. *Journal of Hydrology*, 319(1-4):72–82. Online: https://bit.ly/3yfx6Bn.

Nadkarni, N. and Sumera, M. (2004). Old-growth forest canopy structure and its relationship to throughfall interception. *Forest Science*, 50(3):290–298. Online: https://bit.ly/3tTlMr0.

Nisbet, T. (2005). Water use by trees. *Forestry Commision*, 65:1–8. Online: https://bit.ly/33Lk14T.

Norman, J. and Campbell, G. (1989). *Plant physiological ecology*, chapter Canopy structur, pages 301–325. Springer. Online: https://bit.ly/2SLIwfO.

Ochoa, A., Crespo, P., Carrillo, G., Sucozhañay, A., and Célleri, R. (2019). Actual evapotranspiration in the high andean grasslands: A comparison of measurement and estimation methods. *Frontiers in Earth Science*, 7:1–16. Online: https://bit.ly/3ols2GS.

Ochoa, A., Crespo, P., and Célleri, R. (2018). Quantification of rainfall interception in the high andean tussock grasslands. *Ecohydrology*, 11(3):e1946. Online: https://bit.ly/33KbQpo.

Oyarzún, C., Godoy, R., Staelens, J., Donoso, P., and Verhoest, N. (2011). Seasonal and annual throughfall and stemflow in andean temperate rainforests. *Hydrological Processes*, 25(4):623–633. Online: https://bit.ly/3hCi7vc.

Padrón, R., Wilcox, B., Crespo, P., and Célleri, R. (2015). Rainfall in the andean páramo: new insights from high-resolution monitoring in southern ecuador. *Journal of Hydrometeorology*, 16(3):985–996. Online: https://bit.ly/3yfFYHa.

Park, A. and Cameron, J. (2008). The influence of canopy traits on throughfall and stemflow in five tropical trees growing in a panamanian plantation. *Forest Ecology and Management*, 255(5-6):1915–1925. Online: https://s.si.edu/2RYcVqS.

Pinos, J. (2014). Biomasa foliar, desfronde y descomposición de la hojarasca en los rodales de *Polylepis* reticulata del parque nacional cajas. Tesis de grado, Universidad de Cuenca. Online: https://bit.ly/3uRJg1d, Cuenca, Ecuador.

Pinos, J., Studholme, A., Carabajo, A., and Gracia, C. (2017). Leaf litterfall and decomposition of *Polylepis reticulata* in the treeline of the ecuadorian andes. *Mountain Research and Development*, 37(1):87–96. Online: https://bit.ly/3hARMxX.

Pukkala, T., Becker, P., Kuuluvainen, T., and Oker, P. (1991). Predicting spatial distribution of direct radiation below forest canopies. *Agricultural and Forest Meteorology*, 55(3-4):295–307. Online: https://bit.ly/33LmEnh.

Quiroz, C., Marín, F., Arias, R., Crespo, P., Weber, M., and Palomeque, X. (2019). Comparison of natural regeneration in natural grassland and pine plantations across an elevational gradient in the páramo ecosystem of southern ecuador. *Forests*, 10(9):1–30. Online: https://bit.ly/2SVwUHl.

Ramos Franco, A. and Armenteras, D. (2019). Interceptación y escorrentía del bosque altoandino en la reserva forestal protectora "el malmo". *Acta Biológica Colombiana*, 24(1):97–108. Online: https://bit.ly/3hruCKc.

Rangel, O. and Arellano, H. (2010). *Colombia Diversidad Biótica X. Cambio Global (Natural) y Climático (Antrópico) en el páramo colombiano. Bogotá*, chapter Bosques De Polylepis: Un Tipo de vegetación condenado a la extinción, pages 443–478. Instituto de Ciencias Naturales-Facultad de Ciencias-Universidad Nacional de Colombia. Online: https://bit.ly/3yoWpki.

Renison, D., Hensen, I., and Suarez, R. (2011). Landscape structural complexity of high-mountain *Polylepis australis* forests: a new aspect of restoration goals. *Restoration Ecology*, 19(3):390–398. Online: https://bit.ly/2RlsUze.

Renison, D., Hensen, I., Suarez, R., and Cingolani, A. (2006). Cover and growth habit of *Polylepis* woodlands and shrublands in the mountains of central argentina: human or environmental influence? *Journal of Biogeography*, 33(5):876–887. Online: https://bit.ly/3ojlLM6.

Roth, B., Slatton, K., and Cohen, M. (2007). On the potential for high-resolution lidar to improve rainfall interception estimates in forest ecosystems. *Frontiers in Ecology and the Environment*, 5(8):421–428. Online: https://bit.ly/2QsQda8.

Staelens, J., De Schrijver, A., Verheyen, K., and Verhoest, N. (2006). Spatial variability and temporal stability of throughfall deposition under beech (*Fagus sylvatica* l.) in relationship to canopy structure. *Environmental Pollution*, 142(2):254–263. Online: https://bit.ly/33LDl1R.

Teale, N., Mahan, H., Bleakney, S., Berger, A., Shibley, N., Frauenfeld, O., Quiring, S., Rapp, A., Roark, E., and Washington, R. (2014). Impacts of vegetation and precipitation on throughfall heterogeneity in a tropical pre-montane transitional cloud forest. *Biotropica*, 46(6):667–676. Online: https://bit.ly/3hzDlKj.

Tinoco, B., Astudillo, P., Latta, S., Strubbe, D., and Graham, C. (2013). Influence of patch factors and connectivity on the avifauna of fragmented *Polylepis* forest in the ecuadorian andes. *Biotropica*, 45(5):602–611. Online: https://bit.ly/2RmA4mY.

Tsiko, C., Makurira, H., Gerrits, A., and Savenije, H. (2012). Measuring forest floor and canopy interception in a savannah ecosystem. *Physics and Chemistry of the Earth, Parts A/B/C*, 47:122–127. Online: https://bit.ly/2RmAgTe.

Valencia, B., Bush, M., Coe, A., Orren, E., and Gosling, W. (2018). *Polylepis* woodland dynamics during the last 20,000 years. *Journal of Biogeography*, 45(5):1019–1030. Online: https://bit.ly/33UhWn1.

Weiqing, Z., Zhiqiang, Z., Jun, W., and Jinqiang, X. (2007). Spatial variability of throughfall in a chinese pine (*Pinus tabulaeformis*) plantation in northern china. *Frontiers of Forestry in China*, 2(2):169–173. Online: https://bit.ly/3uUfo4b.

Wullaert, H., Pohlert, T., Boy, J., Valarezo, C., and Wilcke, W. (2009). Spatial throughfall heterogeneity in a montane rain forest in ecuador: extent, temporal stability and drivers. *Journal of Hydrology*, 377(1-2):71–79. Online: https://bit.ly/3eRSBk1.

Zhang, G., Zeng, G., Jiang, Y., Huang, G., Li, J., Yao, J., Tan, W., Xiang, R., and Zhang, X. (2006). Modelling and measurement of two-layer-canopy interception losses in a subtropical evergreen forest of central-south china. *Hydrology and Earth System Sciences*, 10(1):65–77. Online: https://bit.ly/3eOg71c.

Zimmermann, A., Germer, S., Neill, C., and Krusche, A.and Elsenbeer, H. (2008). Spatio-temporal patterns of throughfall and solute deposition in an open tropical rain forest. *Journal of Hydrology*, 360(1-4):87–102. Online: https://bit.ly/3hwkrnt.

Zimmermann, A., Wilcke, W., and Elsenbeer, H. (2007). Spatial and temporal patterns of throughfall quantity and quality in a tropical montane forest in ecuador. *Journal of Hydrology*, 343(1-2):80–96. Online: https://bit.ly/3tS49rM.

Zimmermann, A., Zimmermann, B., and Elsenbeer, H. (2009). Rainfall redistribution in a tropical forest: Spatial and temporal patterns. *Water Resources Research*, 45(11):1–18. Online: https://bit.ly/3huuc5H.

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Sustainable diets

Influence of educational interventions on nutrition and sustainability in Ecuadorian university students residing in Honduras

Influencia de intervenciones educativas sobre nutrición y sostenibilidad en universitarios Ecuatorianos residentes en Honduras

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Abstract

Eating habits can be compromised in the transition to college life specially in a new country. In addition, the eating patterns of college students could be improved through various strategies during the college adjustment process. A key point is nutrition and sustainability, whose content can be taught through educational sessions at universities. The objective of this study was to evaluate the effect of educational interventions and adherence to the Mediterranean diet (MD) in Ecuadorian first-year university students in Honduras, where the student population of Ecuador ranks second, after Honduras. Eating patterns were evaluated using a questionnaire on adherence to MD and one on eating behaviors. The educational interventions focused on the benefits of sustainability, culture, environment, and health that MD provides. The study had a diagnostic phase with the participation of the universe of students (n = 65), and an intervention phase where 32 students participated: 18 in the group that received nutritional education and 14 in the control group. The group that received educational intervention improved their eating behaviors, going from unhealthy to moderately healthy, however, adherence to MD did not show increases at the end of the interventions ($p > 0.05$). The control group did not present changes in any attribute, remaining in unhealthy behaviors and low adherence to MD. Fifty percent of the students in the intervention group returned to Ecuador during the COVID-19 crisis, while in the control group it was 71.4%. In conclusion, it is important to provide advice on nutrition and sustainability from the beginning of university studies, since young people migrate to a country with totally different customs from those of Ecuador and even the Andean Community.

Keywords: Eating habits, Ecuadorian students, nutritional education, sustainable diets.

Resumen

Los hábitos alimenticios pueden verse comprometidos en la transición a la vida universitaria especialmente en un nuevo país. Además, los patrones alimenticios de los jóvenes universitarios podrían mejorarse mediante diversas estrategias durante el proceso de adaptación a la universidad. Por lo cual, un punto clave lo constituyen la nutrición y la sostenibilidad, cuyo contenido puede ser impartido mediante sesiones educativas en las universidades. El objetivo de este estudio fue evaluar el efecto de intervenciones educativas en la adherencia a la dieta mediterránea (DM) y hábitos alimenticios en estudiantes ecuatorianos de primer año universitario en Honduras, donde la población estudiantil de Ecuador se posiciona en segundo lugar, luego de Honduras. Los patrones alimenticios se evaluaron mediante un cuestionario de adherencia a la DM y uno de conductas alimenticias. Las intervenciones educativas se centraron en los beneficios sobre la sostenibilidad, cultura, ambiente y salud que brinda la DM. El estudio tuvo una fase diagnóstica con la participación del universo de estudiantes ($n = 65$), y una fase de intervenciones donde participaron 32 estudiantes: 18 en el grupo que recibió educación nutricional y 14 en el grupo control. El grupo que recibió intervención educativa mejoró sus conductas alimenticias pasando de poco saludables a moderadamente saludables, sin embargo, la adherencia a la DM no presentó incrementos al final de las intervenciones ($p > 0{,}05$). El grupo control no presentó cambios en ninguna evaluación, manteniéndose en conductas poco saludables y una baja adherencia a la DM. Cincuenta por ciento de los estudiantes del grupo con intervención regresaron a Ecuador durante la crisis de COVID-19, mientras que en el grupo control fue el 71,4%. En conclusión, es importante brindar asesoramiento sobre nutrición y sostenibilidad desde el inicio de los estudios universitarios, ya que los jóvenes migran hacia un país con costumbres totalmente distintas a las de Ecuador e incluso de la Comunidad Andina.

Palabras clave: Dietas sostenibles, educación nutricional, estudiantes ecuatorianos, hábitos alimenticios.

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1 Introduction

Changes in agricultural practices have increased global food supply capacity in a more productive way, providing greater food diversity and less seasonal dependence (Kearney, 2010). Therefore, it is important to guarantee food stability through access, use and economic conditions in food, which is closely linked to the principles of food security (Anderson, 2019). In addition, according to the World Health Organization (WHO), non-communicable diseases (NCDs) are the leading cause of death in the world (WHO, 2014). On the other hand, an encouraging fact indicates that the probability of premature death from NCD has decreased 15% globally in the last decade, with high-income countries showing the greatest progress due to reduced mortality (WHO, 2015).

There are alternative consumption patterns such as organic food that seek to improve people's health and eating habits, for this reason they are considered healthier, tastier and more authentic than traditional food, however they are also listed as more expensive (Bryła, 2016). In this sense, price is one of the main barriers to healthy diets. For example, in Galapagos-Ecuador, residents have increased consumption of processed and ultra-processed food due to its easy access, thus reducing consumption of fresh produce (Freire et al., 2018).

Thus, sustainable diets aim to meet energy requirements through safe, high nutritional quality foods, being attainable, accessible and culturally appropriate (Dernini et al., 2016). In addition, having a reduced environmental impact, they contribute to food and nutrition security (FNS) and guide the population toward healthy living (FAO, 2012; Donini et al., 2016). Sustainable diets include the Mediterranean diet (MD), being presented as a cultural and ecological model for prevention and risk reduction of NCD as autoimmune, cardiovascular, metabolic syndrome, cancer and neurodegenerative diseases (Dussaillant et al., 2016; Cadarso et al., 2017; Gómez, 2018), which can have severe consequences in adulthood, but an appropriate lifestyle especially since college years or even before can help prevent them.

Most college campuses have cafeterias that offer a variety of food choices, generating positive but also not so adequate eating choices (Abraham et al., 2018). Transition to college causes significant changes in dietary options, generating dietary challenges. Even school customs can be a determining factor to eating habits in college. Sánchez et al. (2018), at an Ecuadorian school found that 90% of their students consume junk food and snacks during their recess, pointing to the risk of early appearance of metabolic diseases with a high social and economic cost to the family and the state.

Students may have an important knowledge of nutritional requirements. However, the transition to college life gives them more freedom to choose the type and amount of food they eat. This pattern is generated by the situation that college students face in a new environment for meal preparation and planning during the transition to college life (Abraham et al., 2018).

Educational interventions allow a consumer to relate to the concept of responsible consumption, which involves some awareness and active choices. In Quito, citizens can influence their food environment through campaigns and organizations that promote the creation of open and agroecological markets (Paredes et al., 2019). However, a single promotional measure is not enough to discourage the consumption of unhealthy foods.

Currently, no studies have been carried out on eating behaviors for Ecuadorian university students in Honduras. For this reason, the objective of this study was to evaluate the effect of educational interventions and the consumption of a healthy and sustainable diet (Mediterranean diet) in freshmen Ecuadorian students in Honduras.

2 Materials and Methods

2.1 Study design

An analytical, longitudinal, descriptive study was conducted between February and June 2020 at the Zamorano Pan-American Agricultural School, located in Honduras, which has a student population from 29 countries, especially from Latin America, who live in the campus from January to December, for four years. The data presented in this study are derived from surveys of food behaviors and consumption of MD before and after nutritional educational interventions during COVID-19 pandemic.

2.2 Participants

Sixty-five Ecuadorian students were invited to a nutritional master class during the first period of the 2020 academic year, before the beginning of the COVID-19 pandemic in Latin America. The meeting took advantage of the voluntary recruitment of these students, prior to socializing the study indicating the objective, subject matter and benefits for the participant and the researcher. Participation was voluntary, by signing an informed consent. For this analysis, only first-year Ecuadorian students were considered, and the first data collection took place in the second month of classes. In addition, second, third- and fourth-year students were excluded, since they had already had their critical transition to the university system and the cultural environment of the new country.

2.3 Diagnosis phase

In order to contextualize the situation of the 65 Ecuadorian students, data were taken on nutritional behaviors and adherence to MD. Forty-two participants were male and 23 female.

2.4 Intervention phase

At the beginning of the first year, the university equally randomizes students by nationality and gender in eight subgroups. With this background, four of these subgroups were randomly assigned to form the control group and the remaining four to form the intervention group. A final sample of 32 participants was obtained. A group (n = 18) was provided with nutritional education interventions, out of which 7 students were male and 11 females. Eight sessions of approximately one hour each were held, four of them in-person and four online due to COVID-19. The topic focused on the benefits of MD in the areas of nutrition, health, sustainability, biodiversity and environmental impact. The electronic platforms used to share content between the researcher and participants were social networks (Facebook, WhatsApp and Microsoft Teams). The use of social media included educational information, messages, reminders, surveys, and event information related to MD. Emphasis was placed on the proper choice of food by consumers and its future benefits. For its part, the control group (n= 14) received no nutritional education; this group was formed by 6 male participants and 8 females.

2.5 Instruments

A 31 multi-choice questionnaire designed and validated by Márquez et al. (2014) was used, omitting two questions that represent the schedules and people with whom students eat during the week and the weekend, since they eat in the campus with an established meal schedule and the social circle of the students is always the same, having a final number of 29 questions. The topic of the questions focused on eating habits, behaviors, and tastes in personal, family, cultural, and institutional settings. The scores obtained from eating habits are grouped into four categories: Healthy (23-30 points), moderately healthy (16-22 points), unhealthy (8-15 points) and very unhealthy (<8 points). Self-perception of improvement in food behaviors during COVID-19 was also taken into consideration.

For the adherence of the MD, the 14-point questionnaire used in the PREDIMED study (Prevention with Mediterranean Diet) was applied, which is a nutritional intervention study carried out and validated in Spain and was used to evaluate the long-term efficacy of MD in the primary prevention of cardiovascular diseases (Martínez et al., 2015). The questionnaire is composed of 14 direct questions about the consumption of the main food of MD: Olive oil, fruits, vegetables, legumes, fish, nuts, moderate consumption of wine and white meat, and low consumption of red and processed meat. The scores obtained are grouped into four categories: High (12-14 points), medium (8-11 points), low (5-7 points) and very low (<5 points).

2.6 Statistics

For the diagnosis phase, the results were summarized using descriptive statistics with means, percentages and standard deviation. For the intervention phase, a comparison test of independent samples (control group and group to which educational interventions were applied) was performed, with the aim of identifying the effect of educational interventions on behaviors and adherence to MD. Paired samples were also analyzed using student´s t test (before and after, in each group) to identify differences between behavioral effects and adherence to MD. In addition, McNemar test was performed to evaluate the significance of adherence distributions and dietary behaviors over the two periods. All analyzes had a 95 % confidence level, and the JAMOVI and Statistical Analysis Software SAS® versión 9.4 programs were used.

3 Results

3.1 Diagnosis phase

The overall mean for dietary behaviors was 14.28, showing unhealthy eating behaviors. Most students (68 %) had unhealthy and very unhealthy behaviors. In addition, none of the participants had healthy behaviors. In the case of MD adherence, an overall mean of 8.05 was obtained, indicating a mean adherence. The majority of participants (94 %) had a medium and low MD adherence (Table 1).

Table 1. Distribution of food behaviors and adherence to MD through their respective levels.

Food behaviors	n	%	Adherence to MD	n	%
Healthy	0	0	High adherence	2	3
Moderately healthy	21	32	Medium adherence	40	62
Unhealthy	43	66	Low adherence	21	32
Very unhealthy	1	2	Very low adherence	2	3

3.2 Intervention phase

The group that received educational interventions for dietary behaviors from the first data collection showed 72 % of participants with unhealthy behaviors. However, in the second data collection, 50 % of participants showed moderately healthy and healthy behaviors. In terms of MD adherence, in the first data collection, 61 % had a medium adherence level, remaining in the same classification with 44 % of participants for the second data collection (Table 2). In this group, 50 % of students were on campus during the pandemic and 50 % in Ecuador.

For the control group, 64 % of participants in the first data collection had unhealthy behaviors, remaining in the same classification in the second data collection with 43 % of participants. In relation to the adherence to MD, 64 % of the observations in the first data collection belonged to medium adherence and 36 % to low adherence. In the second collection, medium adherence was observed in 50 % of the participants (Table 2). In this group, 28.6 % of students were on campus during the pandemic and 71.4 % in Ecuador.

According to McNemar's test, changes in dietary behavior distributions over the two periods were significant in the group with unhealthy behaviors that received educational interventions ($p = 0.046$). Regarding MD adherence, this was only significant in the control group, presenting a medium adherence ($p = 0.025$).

Table 3 shows that the group that received educational interventions increased from 13.89 (unhealthy) to 16 (moderately healthy). As the control group, the first data collection reported an overall average of 14.79 with unhealthy eating behaviors. However, the average dietary behavior was 14.71 in the second data collection.

According to the t-test of paired samples, there was only significance for the group with educatio-

Table 2. Distribution of the group with interventions and control in the two data collection using McNemar test.

	Group intervention					Control group				
	Before		After		*p*	Before		After		*p*
Food behavior	n	%	n	%		n	%	n	%	
Healthy	0	0	1	6	-	0	0	1	7	-
Moderately healthy	5	28	8	44	0.083	5	36	6	43	0.317
Unhealthy	13	72	9	50	0.046	9	64	6	43	0.083
Very unhealthy	0	0	0	0	-	0	0	1	7	-
Adherence to MD										
High adherence	1	6	0	0	-	0	0	1	7	-
Medium adherence	11	61	8	44	0.083	9	64	4	29	0.025
Low adherence	6	33	8	44	0.157	5	36	7	50	0.157
Very low adherence	0	0	2	11	-	0	0	2	14	-

Spaces that do not have a numerical value for probability are due to zero observations in one of the two periods

nal interventions in dietary behaviors, where there was a difference between the dietary behaviors after interventions ($p < 0.001$). Regarding the analysis of independent samples, MD behaviors and adherence were not significantly different in any period ($p > 0.05$).

Table 4 shows that the overall adherence mean in the group with interventions was initially 8.5, and it was then 7.06 for the second data collection. As the control group, the initial mean was 7.93 showing low adherence and in the second collection the mean was 7, evidencing low adherence.

According to the t-test of paired samples, there was only significance for the group with educational interventions, where there was a difference between initial and posterior adherence ($p = 0.010$). As for the analysis of independent samples, MD behaviors and adherence were not significantly different in any period ($p > 0.05$).

Table 3. Food behavior of the two groups during the two periods with paired and independent samples.

	Intervention		Control		*p* Independent samples
	Mean	SD	Mean	SD	
Initial food behavior	13.89	3.14	14.79	3.45	0.449
Posterior food behavior	16.00	3.34	14.71	5.34	0.410
	Student's t	*p*	Student's t	*p*	
Paired Samples	−4.421	< 0.001	0.053	0.959	

Table 4. Adherence to the Mediterranean Diet (MD) of the two groups in the two periods with paired and independent samples.

	Intervention		Control		*p* Independent samples
	Mean	SD	Mean	SD	
Initial adherence to MD	8.50	1.76	7.93	2.09	0.407
Posterior adherence to MD	7.06	1.80	7.00	2.60	0.943
	Student's t	*p*	Student's t	*p*	
Paired Samples	2.890	0.010	1.447	0.172	

4 Discussion

The unhealthy eating behavior of the total group of Ecuadorian students (n = 65) is a negative indicator since it could cause overweight, obesity or even chronic diseases. In this sense, Racette et al. (2005), mention that the greatest increases in overweight and obesity occur in people between 18 and 29, which is an age range of college students. In addition, most college students leaving their parents' homes adapt to social, environmental changes, and experience new financial responsibilities (Das and Evans, 2014), which might worsen unhealthy behaviors.

University students may represent a high-risk group to develop abnormal eating behavior and compulsive exercise (Guidi et al., 2009). In addition, there are limitations to have a healthy diet, such as time constraints, unhealthy refreshments, caloric snacks, stress, expensive healthy food and easy access to junk food (Sogari et al., 2018). In general, university students are affected by constrains related to time availability, environmental barriers such as the lack of cheap, tasty, and healthy dining options in the university's dining room (Hilger and Diehl, 2019). Therefore, a timely nutritional education intervention can be a key point in improving the lifestyles of young university students.

Educational interventions have improved eating habits from unhealthy to moderately healthy ($p < 0.001$) in the group that completed the training course. This is consistent with Hekler et al. (2010), where students who took a Food and Society course increased their healthy eating habits, improving their vegetable consumption and decreasing the intake of fatty dairy products. In addition, Boyle and LaRose (2009) found that intra-personal, inter-personal, and environmental factors affect the physical activity and eating habits of college students. Boucher et al. (2015), found that educational interventions allowed students to increase the consumption of fruits and vegetables, emphasizing the importance of developing interventions in university students to promote healthy behaviors. On the other hand, those who perceive that food poisoning is a personal threat tend to eat less dangerous food (Byrd et al., 2008).

The change observed in 22 % of students (from 72 % to 50 %) with unhealthy eating behavior ($p = 0.046$) shows the willingness of the participants to change the eating patterns, contrary to the control group where, despite the decrease from 64 % to 43 %, there was no significant difference ($p = 0.083$). This is consistent with Reed et al. (2011), in which 10 to 19 % of university students participating in the study modified their food choices after receiving intervention.

An effectiveness survey of a health-promoting smartphone application for university students showed that many students were unhealthy and did not have healthy behavior despite mentioning that the application was useful, beneficial, and increased self-awareness (Miller et al., 2015). This is consistent with the current study where despite completing the nutrition education course with good participation, not all students improved their eating habits. One possibility is that because of the pandemic, stress related to confinement has caused alterations with respect to binge eating and dietary restrictions (Flaudias et al., 2020).

50 and 71.4 % of the students in the intervention and control group, respectively, returned to Ecuador due to the pandemic, which could be one of the

causes of positive results in improving eating habits, since they had the family support to apply the acquired knowledge. This would be consistent with an ethnographic study that examined the university trajectories of first-generation rural students by stating that families should be involved and family support models should be replicated due to the importance of family, institutional, state and federal policies and practices (Beasley, 2016).

Attempts to change the diets of the population often adopt highly individualistic approaches which may overlook structural factors that influence access to and availability of healthy food options (VanHeuvelen and VanHeuvelen, 2019). Most people agree that the population's eating habits are unhealthy, however, they feel that they eat healthier than other people around them (Sproesser et al., 2015). Therefore, efforts are needed at university campuses to promote healthy lifestyles among their student population during the college years (Gropper et al., 2012).

When evaluating adherence to MD of the entire group of Ecuadorian students in the diagnostic phase, an average of 8.05 points were obtained, positioning the group in medium adherence. However, once the interventions were completed with the 18 participants in this group, there was a significant decrease ($p = 0.01$) of this adherence, reducing it to low adherence, indicating levels higher than 50% in the two groups with low and very low adherence. This is similar to what was presented by Míguez et al. (2013), who found that 90% of university students need to modify their eating habits to adapt to this dietary pattern. In addition, a study carried out in a Spanish university population also agrees with the current research, where 96.1% of participants need to improve the quality of their diet and only 5.3% of the students achieved a high adherence to the (García et al., 2014).

A study of nutritional knowledge in Italy shows that it was significantly associated with higher adherence to MD regardless of socioeconomic factors (Bonaccio et al., 2013). This contrasts with this research, where socioeconomic factors, especially COVID-19, may have limited the availability of certain food in students in Ecuador. Navarro et al. (2014), found that students living in their parents' home had a high adherence percentage, which was significantly higher than those living in apartments or student residences. In addition, the pandemic threatens millions of people living or are at risk of developing food insecurity (Paslakis et al., 2020), a situation that could occur in both groups due to limited access to certain food in all countries.

A study that aimed to determine adherence to the Mediterranean diet of a university population and to analyze several factors that can condition its nutritional quality found that 9.5% of university students had a low adherence, 62.1% showed an intermediate adherence and 28.4% a high adherence (Durá and Castroviejo, 2011), which is consistent with our first data collection. Therefore, it is necessary to ensure that food security, healthy eating attitudes and behaviors are a global priority in order to ensure the health of the population, especially during the pandemic (Paslakis et al., 2020).

5 Conclusions

This study indicates a higher trend in improving dietary behaviors when educational interventions are performed at a university level. Therefore, these programs can reduce the bad eating habits generated in the transition from home to university life in a new country. However, adherence to a healthy and sustainable dietary pattern reduced, which may have been due to problems of accessibility to certain food as a result of the pandemic.

Policies and programs to support students need to be developed to strengthen their knowledge of nutrition and sustainability. These notions should generate an impact factor on students that will enable them to improve their eating habits and adopt dietary patterns that benefit human and environmental health. In addition, it is important to give this support from the beginning of university studies, because young people migrate to countries with customs which are totally different from their home country. The improvement in food habits in times of pandemic among Ecuadorian students reflects the need to develop institutional programs that facilitate their transition to university.

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References

Abraham, S., Noriega, B., and Shin, J. (2018). College students eating habits and knowledge of nutritional requirements. *Journal of Nutrition and Human Health*, 2(1):13–17. Online: https://bit.ly/2RgCFOO.

Anderson, J. (2019). Concepts of stability in food security. In *Encyclopedia of Food Security and Sustainability*, pages 8–15. Online: https://bit.ly/3xkh4FX. Elsevier.

Beasley, E. (2016). Country roads take me ... ?: A cultural analysis of college pathways among rural, first-generation students. In *Paradoxes of the Democratization of Higher Education (Research in Social Problems and Public Policy)*, volume 22, pages 127–163. Online: https://bit.ly/3aTGyQY. Emerald Group Publishing Limited.

Bonaccio, M., Di Castelnuovo, A., Costanzo, S., De Lucia, F., Olivieri, M., Benedetta, M., De Gaetano, G., Lacoviello, L., and Bonanni, A. (2013). Nutrition knowledge is associated with higher adherence to mediterranean diet and lower prevalence of obesity. results from the moli-sani study. *Appetite*, 68:139–146. Online: https://bit.ly/3uPmJ4H.

Boucher, D., Gagné, C., and Côté, F. (2015). Effect of an intervention mapping approach to promote the consumption of fruits and vegetables among young adults in junior college: A quasi-experimental study. *Psychology & Health*, 30(11):1306–1325. Online: https://bit.ly/32m7jZj.

Boyle, J. and LaRose, N. (2009). Personal beliefs, the environment and college students' exercise and eating behaviors. *American Journal of Health Studies*, 23(4):195–200. Online: https://bit.ly/3giRhYm.

Bryła, P. (2016). Organic food consumption in poland: Motives and barriers. *Appetite*, 105:737–746. Online: https://bit.ly/2SaKzK3.

Byrd, C., Maurer, J., Wheatley, V., Schaffner, D., Bruhn, C., and Blalock, L. (2008). Risky eating behaviors of young adults - implications for food safety education. *Journal of the American Dietetic Association*, 108(3):549–552. Online: https://bit.ly/32emzHU.

Cadarso, A., Dopico, X., Iglesias, E., Cadarso, C., and Gude, F. (2017). Calidad de vida relacionada con la salud y su relación con la adherencia a la dieta mediterránea y la actividad física en universitarios de galicia (health related to quality of life and their relationship with adherenceto the mediterranean diet and physical activity at the university in galicia). *Nutrición Clínica y Dietética Hospitalaria*, 37(2):42–49. Online: https://bit.ly/3x0SY2y.

Das, M. and Evans, E. (2014). Understanding weight management perceptions in first-year college students using the health belief model. *Journal of American College Health*, 62(7):488–497.Online: https://bit.ly/3aiX6RR<.

Dernini, S., Berry, E., Serra, L., La Vecchia, L., Capone, R., Medina, F., Aranceta, J., Belahsen, R., Burlingame, B., Calabrese, G., Corella, D., Donini, L., Lairon, D., Meybeck, A., Pekcan, A., Piscopo, S., Yngve, A., and Trichopoulou, A. (2016). Med diet 4.0: the mediterranean diet with four sustainable benefits. *Public Health Nutrition*, 20(7):1322–1330. Online: https://bit.ly/3gghSp6.

Donini, L., Dernini, S., Lairon, D., Serra, L., Amiot, M., Del Balzo, V., Giusti, A., Burlingame, B., Belahsen, R., Maiani, G., Polito, A., Turrini, A., Intorre, F., Trichopoulou, A., and E., B. (2016). A consensus proposal for nutritional indicators to assess the sustainability of a healthy diet: The mediterranean diet as a case study. *Frontiers in nutrition*, 3(37):1–14. Online: https://bit.ly/3uZqogy.

Durá, T. and Castroviejo, A. (2011). Adherence to a mediterranean diet in a college population. *Nutrición Hospitalaria*, 26(3):602–608. Online: https://bit.ly/3aimiIi.

Dussaillant, C., Echeverría, G., Urquiaga, I., Velasco, N., and Rigotti, A. (2016). Evidencia actual sobre los beneficios de la dieta mediterránea en salud (current evidence on the health benefits of the mediterranean diet). *Revista médica de Chile*, 144(8):1044–1052. Online: https://bit.ly/3mRgcnm.

FAO (2012). *Sustainable Diets and Biodiversity*. Rome. Online: https://bit.ly/3nEQv9Q, 1st edition.

Flaudias, V., Iceta, V., Zerhouni, O., Rodgers, R., Billieux, J., Llorca, P., Boudesseul, J., de Chazeron, I., Romo, L., Maurage, P., Samalin, L., Bègue, L., Naassila, M., Brousse, G., and Guillaume, S. (2020). Covid-19 pandemic lockdown and problematic eating behaviors in a student population. *Journal of Behavioral Addictions*, 9(3):826–835. Online: https://bit.ly/3mRloHS.

Freire, W., Waters, W., Román, D., Jiménez, E., Burgos, E., and Belmont, P. (2018). Overweight, obesity, and food consumption in galapagos, ecuador: a window on the world. *Globalization and Health*, 14(93):1–9. Online: https://bit.ly/3gg5plc.

García, M., Burriel, F., García, V., and Serrano, R. (2014). Adherence to mediterranean diet in a spanish university population. *Appetite*, 78:156–164. Online: https://bit.ly/3dn6s0S.

Gómez, R. (2018). Revisión sobre el aceite de oliva: historia, impacto mediático y sus aplicaciones médicas en la dieta mediterránea (review of olive oil: history, media impact and its medical applications in the mediterranean diet). *Revista Colombiana de Endocrinología, Diabetes & Metabolismo*, 5(4):26–31. Online: https://bit.ly/3tqnPU5.

Gropper, S., Simmons, K., Connell, l., and Ulrich, P. (2012). Weight and body composition changes during the first three years of college. *Journal of Obesity*, 2012:1–6. Online: https://bit.ly/3e8N86X.

Guidi, J., Pender, M., Hollon, S., Zisook, S., Schwartz, F., Pedrelli, P., Farabaugh, A., Fava, M., and Petersen, T. (2009). The prevalence of compulsive eating and exercise among college students: An exploratory study. *Psychiatry Research*, 165(1-2):154–162. Online: https://bit.ly/2Qu3n6g.

Hekler, E., Gardner, C., and Robinson, T. (2010). Effects of a college course about food and society on students eating behaviors. *American Journal of Preventive Medicine*, 38(5):543–547. Online: https://bit.ly/3upMxo0.

Hilger, J. and Diehl, K. (2019). 'oh god, i have to eat something, but where can i get something quickly?' a qualitative interview study on barriers to healthy eating among university students in germany. *Nutrients*, 11(10):2440. Online: https://bit.ly/3ajn6N8.

Kearney, J. (2010). Food consumption trends and drivers. *Philosophical transactions of the royal society B: biological sciences*, 365(1554):2793–2807. Online: https://bit.ly/3gXjKTV.

Márquez, Y., Salazar, E., Macedo, G., Altamirano, M., Bernal, M., Salas, J., and Vizmanos, B. (2014). Diseño y validación de un cuestionario para evaluar el comportamiento alimentario en estudiantes mexicanos del área de la salud (design and validation of a questionnaire to evaluate eating behavior in mexican students in the health area). *Nutrición Hospitalaria*, 30(1):153–164. Online: https://bit.ly/3x5aEtU.

Martínez, M., Salas, J., Estruch, R., Corella, D., Fitó, M., and Ros, E. (2015). Benefits of the mediterranean diet: insights from the predimed study. *Progress in Cardiovascular Diseases*, 58(1):50–60. Online: https://bit.ly/3ueZBfY.

Míguez, M., Castro, L., Collins, A., and De la Montaña, J. (2013). Variations of the diet of galician university students (ourense campus) in relation to the pattern of the cardioprotective mediterranean diet). *Nutrición Hospitalaria*, 28(6):2099–2106. Online: https://bit.ly/3dpiPtx.

Miller, T., Chandler, L., and Mouttapa, M. (2015). A needs assessment, development, and formative evaluation of a health promotion smartphone application for college students. *American Journal of Health Education*, 46(4):207–215. Online: https://bit.ly/2QOzQ7R.

Navarro, I., López, R., Rodríguez, A., Ros, G., Martínez, M., and Doménech, G. (2014). Adherence to the mediterranean diet by nursing students of murcia (spain). *Nutrición Hospitalaria*, 30(1):165–172. Online: https://bit.ly/3ebOpv1.

Paredes, M., Cole, D., Muñoz, F., April, G., Valero, Y., Beltrán, P., Boada, L., and Peter Berti, R. (2019). Assessing responsible food consumption in three ecuadorian city regions. In *Sustainable Food System Assessment*. Routledge. Online: https://bit.ly/3vATWRF.

Paslakis, G., Dimitropoulos, G., and Katzman, G. (2020). A call to action to address covid-19 induced global food insecurity to prevent hunger, malnutrition, and eating pathology. *Nutrition Reviews*, 79(1):114–116. Online: https://bit.ly/3vA7LQr.

Racette, S., Deusinger, S., Strube, M., Highstein, G., and Deusinger, R. (2005). Weight changes, exercise, and dietary patterns during freshman and sophomore years of college. *Journal of American College Health*, 53(6):245–251. Online: https://bit.ly/3aW2JG5.

Reed, J., Powers, A., Greenwood, M., Smith, W., and Underwood, R. (2011). Using "point of decision messages to intervene on college students eating behaviors. *American Journal of Health Promotion*, 25(5):298–300. Online: https://bit.ly/3tsM6sB.

Sánchez, M., Morales, Y., Bastidas, C., and Jara, M. (2018). Evaluación del estado nutricional de adolescentes en una unidad educativa de ecuador (evaluation of the nutritional status of adolescents in an educational unit of ecuador). *Ciencia Unemi*, 10(25):1–12. Online: https://bit.ly/3v2v7h9.

Sogari, G., Velez, C., Gómez, M., and Mora, C. (2018). College students and eating habits: A study using an ecological model for healthy behavior. *Nutrients*, 10(12):1823. Online: https://bit.ly/2Q4eL9i.

Sproesser, G., Kohlbrenner, V., Schupp, H., and Renner, B. (2015). I eat healthier than you: Differences in healthy and unhealthy food choices for oneself and for others. *Nutrients*, 7(6):4638–4660. Online: https://bit.ly/2QbSUN1.

VanHeuvelen, T. and VanHeuvelen, J. (2019). The (economic) development of healthy eating habits: Gender, nutrition, and health outcomes in 31 countries. *Sociology of Development*, 5(1):91–113. Online: https://bit.ly/2RHZBqC.

WHO (2014). *Global Status Report of noncommunicable diseases 2014*. Online: https://bit.ly/3akfc60.

WHO (2015). *Health in 2015: from MDGs, Millennium Development Goals to SDGs, Sustainable Development Goals*. Online: https://bit.ly/2P20PvU.

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Agricultural Sciences

Abya Yala Universidad Politécnica Salesiana

The action groups and the application of high productivity technology for temporary corn in locations of the Puebla Plan, Mexico

Los grupos de acción y la aplicación de tecnología de alta productividad para maíz de secano en localidades del Plan Puebla, México

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Abstract

The aim of this study is to show the importance of action groups and the application of technology, not only in maize production but also in the economic income of farmers. Action groups are the means to make consolidated purchases of inputs, manage financial resources and promote better marketing of the product. The methodology consisted of systematizing information from the follow-up of an action group made up of ten producers who applied improved technology to produce maize; this information was complemented with a socioeconomic survey of 30 farmers from three municipalities. The results indicate that the integration of action groups allows to increase the yields by almost 50% more with respect to the control group and a b/c ratio of 2.44 is obtained. In conclusion, a sufficient volume of maize production is produced to satisfy the families' self-consumption needs and surpluses for sale. These production levels favor the reproduction of rural families. This article provides information for decision-making in the implementation of maize production programs in other locations.

Keywords: Action group, technology, corn production, Puebla.

Resumen

El objetivo del artículo es evidenciar la importancia que tienen los grupos de acción y la aplicación de tecnología no solo en la producción de maíz sino también en los ingresos económicos de los agricultores. Los grupos de acción constituyen el medio para hacer compras consolidadas de insumos, gestionar recursos financieros y favorecer una mejor comercialización del producto. La metodología consistió en sistematizar información del seguimiento de un grupo de acción constituido por diez productores que aplicaron tecnología mejorada para producir maíz; esta información se complementó con una encuesta socioeconómica de 30 agricultores de tres municipios. Los resultados indican que la integración de grupos de acción permite incrementar los rendimientos en casi un 50 % más respecto al grupo testigo, obteniendo una relación b/c de 2,44 en promedio. En conclusión, se produce un volumen de producción de maíz suficiente para satisfacer las necesidades de autoconsumo de las familias y excedentes para la venta; estos niveles de producción favorecen la reproducción de las familias rurales. Este artículo aporta información para la toma de decisiones en la implementación de programas de producción de maíz en otras localidades.

Palabras clave: Grupo de acción, tecnología, producción de maíz, Puebla.

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1 Introduction

Even though corn is native from Mexico, the country has production problems. According to ASERCA (2019), currently 16.2 million of maize is imported, because the federal government for many years guided its policy to the import of maize and abandoned local production, considering that it was cheaper to import the grain than to produce it, having consequences on food security and sovereignty. However, most small producers of family farming continued to produce maize without government support, even though maize is a staple grain for family consumption and animal feed. On the other hand, in the face of this limited government support for local maize production, some institutions such as the Graduate School continued to do technology generation and dissemination activities for smallholder farmers, specifically in maize production.

There is now a more favorable policy for producing domestic maize, and the experience obtained by the Graduate School and other institutions in the process of generating, disseminating and applying technology must be leveraged to boost local maize production and reduce the import of this grain.

Technology is a combined process of thought and action whose purpose is to create useful solutions. Likewise, Aguilar (2011) mentions that technology is conceived as the set of knowledge, skills and means needed to reach a foredetermined end. For its part, the Graduate School implemented this technological development process in farmers' land and considered traditional knowledge to generate high productivity technology that is appropriate to the conditions of producers and to solve a low food production. The generation of technology also involved dissemination and escalation, since these processes were carried out by an integrated scientific-technical team that was in constant communication.

One of the strategies of the Graduate School to carry out the dissemination and escalation of technology was to associate with farmers to integrate action groups; social learning was promoted in this environment thanks to the interaction between different actors, i.e., participants in the action group learned through observation, technological demonstrations, and the components and processes that integrated the dissemination and escalation strategy.

With regard to action groups, Friedmann (2001) points out that the central axis in social learning is the action group that is composed by twelve people (or less) who are oriented towards a specific task; in this approach the action group learns from its own practice. The same author mentions that the correct method of bringing such change is social experimentation, careful observation of results and willingness to admit and learn from mistakes.

Plan-Puebla program was an agricultural development strategy that operated in the Puebla Valley. This strategy was implemented in three sectors: producers, industry institutions and a technical team of the Graduate School. The technical team was responsible for generating, disseminating and applying technology. Through this agricultural development program, social change was achieved through increased maize production with the generation and application of technology and the formation of solidarity groups. In another Mexican context, in Tehuantepec Regalado et al. (2005) used a strategy to carry out social experimentation in projects conducted with producer associations, mainly with the indigenous population; the variables that make up the strategy are: 1) information, 2) participation of the actors involved, 3) generation of initiatives, 4) action and 5) development.

On the other hand, Cazorla et al. (2013) and Cazorla et al. (2018), developed the model called "working with people", which is understood as a professional practice that seeks to connect knowledge and action through joint projects that integrate learning and values into people (action groups) involved in joint work. This model has had a wide application with favorable results in Europe and other countries.

The experiences mentioned demonstrate the importance of action groups and the process of social experimentation in the agricultural field. A proof of the scope of the Plan-Puebla development program with these groups and social learning was observed in the town of Tlaltenango, where farmers produced yields between 600 to 800 kg/ha at the beginning of the program and at the end of the program reached production levels of 7000 kg/ha; with these maize yields they solved grain needs for the family and the surplus was earmarked for livestock feed and sale, and families improved their income and well-being. With these achievements, producers do not need to complement their income with off-farm activities, contrary to what happens in other areas (Chapman and Tripp (2004); cited in Maziya et al. (2017)).

In this context, the following questions arise: what was the social experimentation process in Plan-Puebla development program? What was the role played by beneficiaries and action groups in bringing about favorable changes in maize production?

The topic studied in this article is important as there is a significant deficit in maize production in Mexico, thus actions to reduce maize production need to be taken. Action groups, with support for the dissemination and application of technology, are also relevant as they are an alternative to improving farmers' production, income and well-being; however, this knowledge had been little explored given the existence of an unfavorable policy for domestic production. In the current scenario of a more self-sufficient policy, this knowledge can contribute to maize production. The objective of this study was to analyze a case study in three municipalities of Puebla to show the importance of action groups and the application of technology, not only in increasing maize yields but also in improving the income and well-being of farmers.

2 Methodology

This research was based on a case study that, according to Yin (1994) cited by Arzaluz (2005), is a research strategy that allows to organize social data without losing sight of all the relationships of the phenomenon being studied; it also uses some qualitative and quantitative elements (Hernández et al., 2014). The research stages were: participatory workshops with key informants with extensive experience in maize production; integration of action groups with outstanding producers; establishment of demonstration plots on farmers' land and escalation of experience to other producers; these activities were monitored and yields were estimated at the end of the agricultural cycles.

To characterize the socioeconomic context, 30 producers from Tlaltenango, Santa Ana Xalmimilulco and Calpan were interviewed. The instrument used was a questionnaire that included questions based on the producers and their families.

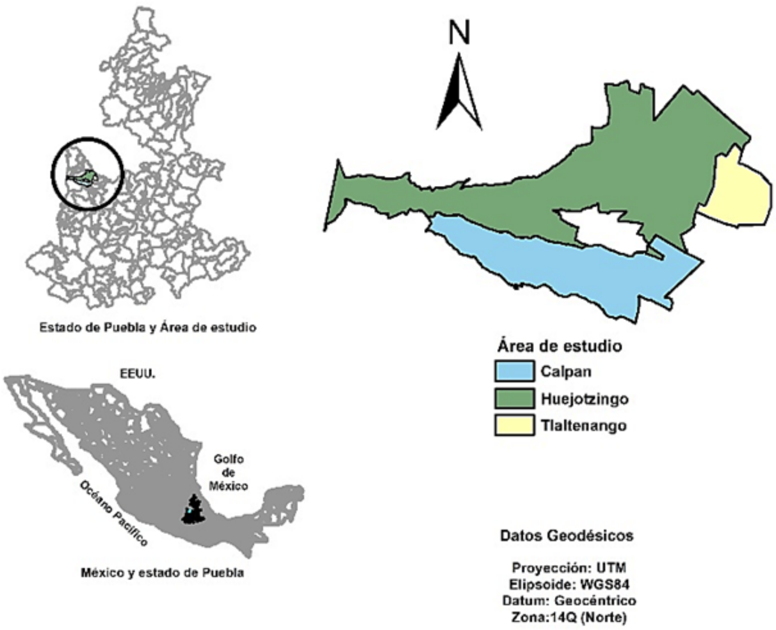
Information from the different stages of the research was systematized and the survey data were included in Excel to estimate basic parameters of the dataset.

2.1 Study area

The study area included three municipalities in the state of Puebla, and these are part of the Huejotzingo Priority Care Microregion (MAP) (Figure 1). The study took place in the municipality of Tlaltenango, in Huejotzingo, and the municipality of Calpan was considered the witness to compare the results. According to the Graduate School **?**, the MAP is conceptualized as a geographical space with productive, environmental or social nature problems, and where the COLPOS Campuses, through their academics, define areas to carry out activities of linkage and technological transfer in an organized and systematized way, providing feedback of education and research activities.

Agricultural activities represent the main sources of income for the population. According to INEGI (2007), there were 12 949 units in the area, of which 3 239 units were productive and 9 710 were not. On an area of 33616.7 ha, units showed temporary agriculture, and based on the knowledge and resources available producers were able to employ strategies that allow them to guarantee the internal needs of the units and more participation in the local market. Strategies consist of two production systems: 1) a system based on maize production combined with milk and meat production, and 2) traditional maize system interspersed in fruit trees; the first is more common in the municipality of Tlaltenango and in Santa Ana Xalmimilulco and the second in Calpan.

Figure 1. Municipalities that are part of the study area.



Georeferenced spatial data from INEGI, 2012.

2.2 Action groups

The action group in San Pedro Tlaltenango consisted on maize producers who combine grain production with livestock. The group in San Ana Xalmimilulco was formed as a Rural Production Company (SPR by its acronyms in Spanish), a legal company created to carry out production, marketing, among other activities. While in San Andrés Calpan 7 individual producers were identified, and whose plot's performance estimates were made to know their levels of maize production.

These groups practice two production systems related to maize production. The first consists of a system based on the production of maize under dry conditions that is combined with milk and meat production; and the second of a traditional maize system interspersed in fruit trees. The first is more common in the municipality of Tlaltenango and in Santa Ana Xalmimilulco, and the second is more used in the municipality of Calpan. Key producers were identified in both locations to streamline processes for the formation of action groups; one of the leaders of in Tlaltenango played this role, and the representative of the Rural Production Society was the representative of the group in Santa Ana Xalmimiluco; each of these producers were responsible in their localities. In Tlaltenango, the responsible was the head of the Decision Committee of the Intensive Program for Maize Production, and in Santa Ana Xalmimilulco the person in charge was the group manager.

3 Results and Discussion

The process of social experimentation provided evidence in variables on: information on the technology used (fertilization dose), integration and behavior of action group producers and institutional factors.

Technology used

The technology that caused changes in maize production was generated under the approach designed by Laird (1977) to develop experimental field work of the producers, using the components of the scientific method, which was introduced in the Puebla Plan (CIMMYT (1974)).
This approach presented an advantage at the dissemination stage because it maintained agricultural practices carried out by producers. The components

of the technology were 130 kilograms of nitrogen, 40 kilograms of phosphorus for a population density of 50 000 plants ha^{-1}. Subsequently, nitrogen, phosphorus and potassium levels were increased, using improved seeds and a population density of 60 000 plants ha^{-1} to obtain higher grain volume and fodder. During the period 1967 to 1992, there were changes in maize production (Díaz et al., 1999), and it was observed the presence of Tlaltenango producers with production levels higher than 6 ton/ha (Regalado et al., 1996). Technological information in the diagnosis is set out in the following paragraphs.

Fertilization: Based on Table 1, the relationship between fertilizer application levels, use of hybrid seeds and yields per hectare is noted. In some cases, the data show a difference of more than 50% between the volume of grain produced with improved materials and the native materials.

Table 1. Fertilization dosages and production levels with the use of improved and creole seed.

Producer	Dose kg ha^{-1}			Yield t ha^{-1} with seed:	
	N	P	K	Hybrid	Creole
Producer I	174	46	—	8.2	4.0
Producer II	150	57	—	8.0	5.0
Producer III	128	46	30	4.5	4.0
Producer IV	165	69	—	7.5	3.5
Producer V	142	69	—	6.2	4.0

Source: Workshop on "Recognition of Local Production Technology"

Public workers believe that the income of maize producers is very low, and sometimes they even lose money; however, cost-benefit calculations proved otherwise, as shown in Table 2. This calculation was made considering the cost of $4.0 per kilogram of corn. The cost benefit ratio was positive even with a yield of 4.5 t/ha. This income is obtained only from the grain without considering the fodder; however, if both products are considered to be intended for the feeding of livestock to obtain meat and milk, then profits are higher.

This analysis shows that maize production is cost-effective. In the social field, the introduction of technological components contributed to the development of conditions to strengthen such initiatives at the Community level, taking into consideration experiences to improve production processes and bring about changes in the institutional components. From the environmental perspective, Turrent (2019) notes that the results of studies carried out in wheat with NPK agronomic doses every year, with and without soil acidity correction, with and without crop rotation, with and without incorporation of manure show that the use of agronomic doses of fertilizers acts as a long-term soil degrader. However, more specific studies related to the impact of technological components on water are needed.

Tlaltenango Action Group

The experience of these producers led to the following questions: how to visualize the use of technology for maize production that allows producers to improve their income and stay without migrating? The answer was to select the top 10 producers in this municipality to form an action group that would allow to transfer this knowledge to other producers both locally and beyond, as well as managers of local, state and federal institutions, seeking to incorporate public policy expertise for maize production. The strategy of selecting the best maize producers coincided with Manrrubio and H. (2010), which considered the principle of building on what the experts know. Based on these elements, the group established 10 ha of demonstrative lots to expose the application of high productivity technology and obtain high maize yields; Table 3 shows the sources and volume of fertilizer used.

The Graduate School (CP)-Campus Puebla financed the planting of the 10 hectares in this first year. Each producer worked on one hectare with this resource for demonstration purposes and the rest of the area was financed by themselves; in terms of percentage, the amount contributed by the CP accounted for 30% of production costs per hectare, and the remaining 70% was provided by each of the group members. In terms of financing and as a result of the first year, a scheme was created for maize production which was operated in the following years and consisted on the contribution of 50% of the municipality and 50% of the action group. In the second year, the surface was expanded to approximately 147 ha and the group bought a precision seed drill. In the third year, the program was extended to more producers, mostly young people who after their migration experience re-started agricultural activities. It was very interesting to note that the group of first participants stablished a minimum yield of 6.0 t ha^{-1} as a requirement for new income producers to receive funding from the municipality. In terms of yields and based on Table 4, it was noted that in maize production levels during the first year (2011), the initiators of the project recorded an average production volume of 7.24 t ha^{-1}, a production level that is sustained during the period 2013-2014; additionally, there were cases in which some members of the group obtained yields higher than 10 t ha^{-1}. These yield levels exceeded production levels from 2.2 to 3.7 t ha^{-1} raised by the Mas Agro strategy, which is a national program aimed at standardizing the level of maize production on temporary terms among small producers (Turrent et al., 2017).

Table 2. Production costs ($), yield (t/ha) and b/c ratio in maize cultivation in Tlaltenango

Concept	Participating producers				
	Benito Cordero	Ignacio Pérez	Crescencio Lima	Heliodoro Lima	Aron Lima
Preparing the land and planting					
Harrow	(3) 900	(2) 600	(2) 600	(2) 600	(2) 600
Fallow	(1) 600	(1) 600	(1) 600	(1) 600	(1) 600
Disc harrow	(1) 250	(1) 250	(1) 250	(1) 250	—
Furrow	—	(1) 250	(1)250	(1) 250	—
	Seed drill	Use of animal	Use of animal	Use of animal	Seed drill
Machine and worker	600	500	500	500	600
Seed cost	1200	1 200	1 200	1 200	1200
Fertilization costs					
18-46-00	1 520	950	1 140	1 140	760
Urea	1 380	1 265	1 380	1 150	920
Potassium	—	—	—	—	400
1 application	250	250	300	300	300
Tilled	300	300	300	300	300
2 applications	300	300	300	300	300
Cost of weed control					
Agrochemicals	270	280	270	130	330
Application	200	200	200	200	200
Pest control costs (does not apply)					
Mowing costs					
$14/ Furrows	1 300	1 300	1 300	1 300	1 300
Harvest costs					
Wages	2 000	2 000	1 500	1 200	1 000
Shelling costs					
Wages	420	420	200	350	300
Sheller	350	350	250	250	250
Hauling	500	500	500	500	500
Yield, total cost and b/c ratio					
Tons/ha	8.2	8.0	7.5	6.0	4.50
Total cost/ha	12 340	11 515	11 040	10 520	9 860
Ratio b/c	2.65	2.77	2.71	2.28	1.80

The numbers in parentheses in the soil preparation and planting area indicate how often producers performed these activities.

Table 3. Yields (t ha^{-1}) obtained by the first and second participants in Tlaltenango

Producers	First participants			
	2011	**2012**	**2013**	**2014**
Producer I	7.8	10.4	7.2*	9.76
Producer II	7.9	10.6	9.1**	10.94
Producer III	5.8	5.1	8.2***	9.44
Producer IV	6.8	8.8	8.8**	8.00
Producer V	9.2	10.9	8.5**	9.7
Producer VI	7.3	9.2	10.8**	9.1
Producer VII	6.2	12.3	10.7**	10.5
Producer VIII	5.0	9.1	8.8*	9.4
Producer IX	9.4	9.6	10.6**	8.3
Producer X	6.9	7.9	6.0*	—
Average	7.2	9.4	8.9	9.5
Producers	Second participants			
	2011	**2012**	**2013**	**2014**
Producer XI	—	—	10.7***	7.5
Producer XII	—	—	7.9*	6.8
Producer XIII	—	—	8.8***	6.4
Producer XIV	—	—	9.4*	11.4*
Producer XV	—	—	10.8*	1.1
Producer XVI	—	—	9.7***	9.7
Producer XVII	—	—	7.6*	8.5
Average	—	—	9.3	8.8

Data from 2012-2015 campaigns; Note (*) HS-2 Seed of the Graduate School, (**) Mist Seed, (***) ASPROS Seed.

The use of improved seed extended among the members of the action group; however, at the local level this use is low. According to Espinosa et al. (2003) this type of behavior is similar to the use of improved seeds at the national level.

Escalation in other locations

Based on the results obtained and by the effort to produce HS-2 seed, belonging to the Postgraduate School through a collaboration agreement and by the interest of an action group represented by Rural Production Society (SPR) to use this seed, the municipality of Huejotzingodesigned and operated a similar funding scheme used by the Tlaltenango action group.

Santa Ana Xalmimilulco

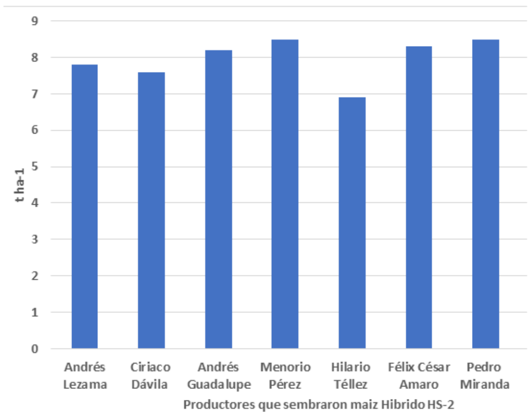
The factors that determined the training and participation of the action group in the HS-2 maize project were: 1) the participation of the head of the Santa Ana Xalmimilulco group in the Municipal Council for Sustainable Rural Development of San Miguel Huejotzingo, 2) feedback of experience on the use of hybrid seeds with San Pedro Tlaltenango producers, and 3) participation of some members of the group in a pilot project to introduce HS-2 hybrid maize among producers. These actions allowed the producers to participate in the planting of 100 ha of HS-2 hybrid maize (Regalado et al., 2010).

The results of this first experience in Santa Ana Xalmimilulco corroborated the possibility of increasing the levels of yields of the grain and fodder through the most accurate application of technological components, including the use of this seed. Based on the yield data of the first members who used this seed as shown in Figure 2, it was determined that the use of this material would be an alternative to obtain a higher volume of grain to supply the production and fodder unit for green and dry silage that is used throughout the year in significant quantity and quality to support livestock activity with the aim of maintaining or increasing milk production which, according to the producers, is estimated at a volume of 90 thousand liters per day.

San Andrés Calpan (witness producers)

During the first three years of the maize production project using high-productivity technology, yield estimates were carried out on the lands of the members of the action groups; however, in order to understand the differences in carrying out maize production in the form of an action group, in 2014, in addition to making estimates of yields in lots of producers belonging to two action groups, a group of Calpan producers who cultivated maize during the spring-summer 2014 was included, without having participated in programs implemented in Tllatenango and Santa Ana Xalmimilulco.

Figure 2. Yields in t ha^{-1} obtained in the maize project HS-2.



Comparison of technological variables and personal characteristics of producers with and without action groups

This analysis is based on the information obtained through the application of a questionnaire that included variables related to the levels of maize yields, technological components used, and other personal factors of the members of the action groups, as well as witness producers.

Maize yields

Based on the data on Table 5, a relationship between action groups and maize yields can be observed, especially with regard to average and maximum yields. Such behavior can be considered to mention that the use of technology is applied more precisely when producers are part of an action group, since it is possible to achieve financial resources for obtaining inputs through this partnership.

The relationship between the use technology on maize yield is mentioned in different studies (Regalado et al., 1996; Díaz et al., 1999; Damián et al., 2007), coinciding with the results obtained in Tlaltenango. Likewise, Gürel (2019) agrees that advances in agriculture have often been the result of innovations in individual components (such as improvement, chemical inputs, irrigation technologies); however, changes occurred in Tllatenango and in Santa Xalmimilulco when considering the application of technological knowledge through action groups as a variable. Noriega et al. (2019) relate the training and dissemination of technological innovations under the field school model with maize productivity; additionally, Velázquez et al. (2019) found that the use of technologies determines the productivity and competitiveness of maize production. These changes in maize production generate a surplus of grain and fodder, which is mentioned by Lutz and Herrera (2007) as a positive impact on families and communities. While the producers of Tlaltenango and Santa Ana Xalmimilulco included the technological components to produce high levels of maize yields, the achievement of the resources to acquire the inputs for their application becomes effective as long as the producers conduct this practice as action groups, as in Tlaltenango and in Santa Ana Xalmimilulco. A questionnaire was used as an instrument for gathering field information from action group members as well as witness producers. Table 6 shows the technological components that producers used during the 2014 agricultural cycle to produce changes in maize production. Based on this information, it was observed that in the locations where the activities were carried out as action groups, the producers more accurately applied the technological components generated by the agronomic research of the Puebla Plan, used improved seed and carried out more moisture conservation practices, which allowed them to sow in April and achieve a more homogeneous germination of the seed.

Characteristics of the producers who were part of the Action Groups

Based on information collected in questionnaires, it was noted that 80% of the heads of families in the localities are men, and few women make decisions in agricultural production, rather, their participation is to support other activities at home such as the care of family members and the preparation of food for workers during harvest.

With regard to age, a larger adult population was observed in Calpan and with fewer years of study, while in the two action groups, a larger young population was noticed; in this sense, there was a case of a member who migrated to the United States of America and once he returned to Tlaltenango he started agricultural activities. Currently the families of the members of the three localities remain in the community, carrying out activities inside and outside the family unit.

Table 4. Yields obtained with and without action group

Action group	Members by group	Yield t ha^{-1}		
		Average	Minimum	Maximum
Tlaltenango	16	8.9	4.3	11.4
Santa Ana Xalmimilulco	7	7.8	6.5	12.3
Calpan (Witness)	7	4.4	2.4	6.4

Elaboration with field data, 2015.

Table 5. Technological components used by action groups for temporary maize production

Technological practices	Tlaltenango (Action Group)		Sta. Ana Xalmimilulco (Action Group)		Calpan (Witness)	
	Modality	%	Modality	%	Modality	%
Moisture conservation practices	1 a 3	93	1 a 3	66	1 a 3	42
Date to sow	April	56	April	66	April	57
Machine used	Tractor	75	Tractor and worker	66	Tractor and worker	42
Seed type	Improved	100	Improved	100	Creole	100
Color of the grain	white	62	white	77	white	100
Use of fertilizers	Yes	100	Yes	100	Yes	100
Type of fertilizers	Urea 46%	62	Urea and black urea	33	Urea	57
Implementation time (stage)	In 1st and 2nd sow	50	In 1st and 2nd sow	66	In 1st and 2nd sow	85
Application of manure	Yes	81	Yes	100	Yes	57
Type of manure	Several	81	Several	100	Several	57
Amount of manure	100-200 t ha^{-1}	37	40-50 t/ha	55	No data	42
Frequency of application	Once a year	43	Every three years	44	Once a year	57
Harvest time	November	93	November	55	November	57

Elaboration with field data, 2014.

Table 6. Age and years of study of the members of the Action Groups

Action groups	Age			Years of study		
	Average	Min.	Max.	Average	Min.	Max.
Tlaltenango	53	23	82	8	6	17
Santa Ana Xalmimilulco	56	43	77	8	3	15
Calpan (Witness)	70	60	86	3	0	12

Elaboration with field data, 2014.

Action groups and management strategy

Action groups managed a set of components that constituted the strategy to apply the technology and produce high maize yields; these components were: inputs, seeds, financing, technical assistance and marketing process.

Inputs

Tlaltenango's action group argued on topics related to the acquisition of inputs and seed in a consolidated way with the company that offered better product quality and full weights. These decisions were based on the experiences of some group partners, as well as on the advantage of having economic resources that would allow a better negotiation to acquire inputs at a better price and in a timely manner. In the first year of operation of the project, the Tlaltenango group and the Puebla Campus bought their inputs one month before planting.

In the second year, the municipality participated in the project and tried to make the purchase with another company and with the same products, seeking to further lower the price of the inputs; that proposal did not succeed because the group requested an analysis of the product from the supplier to verify that the percentage of active ingredient was the same as that shown on the packaging, but the supplier refused to submit it; hence, the municipality, through the agricultural regulations, bought the inputs with the company suggested by the group.

Financing

Tlaltenango generated a financing scheme called near funding management in rural development program in Europe (Cazorla et al., 2005). This scheme consisted of a mixture of resources of beneficiaries and local authority in the form of a subsidy, avoiding indebtedness which is a factor that limits access to financing (Almeraya et al., 2011). The incorporation of local authorities into this type of project allowed a closer relationship with the groups, especially to plan actions such as: definition of beneficiaries, planted area, needs of inputs, amount to be contributed by the people involved, proposal of possible suppliers, definition of type of fertilizers, solution of problems during the purchase process, field tours, and harvest estimate.

Technical assistance

The study conducted by Afful et al. (2015) showed that maize producers, upon receiving information on the public extension, increased their levels of maize production under dry conditions. These results coincide with the idea developed in Tllatenango, which was underscored with the believe that producers knew about the management of maize cultivation and that the work of the technician should be as a facilitator. Technical assistance consisted of providing technical information and the benefits they had as a group to carry out management processes with other actors.

4 Conclusions

The integration of an action group with the best maize producers in Tlaltenango to convey their experiences by establishing demonstrative lots with the participation of the Graduate School and local authorities was a strategy to bring about changes in maize production.

The social learning process contributed to the creation of action groups that defined: 1) technological components to be implemented in demonstrative modules, 2) strategy for input management, 3) the establishment of relationships with institutional and local actors, and 4) technical assistance to facilitate processes in the technical and financing fields; actions that created the conditions for the group to demonstrate its ability to produce changes in maize production, and the viability of maize production.

It is possible to incorporate the experience generated by the action groups into a broader state maize production program, in areas with more potential for the production of maize, through more business management to integrate this type of agriculture into the value network; however, this requires the political will of decision-making actors at this level.

References

Afful, D., Oluwatayo, I., Kyei, K., Ayisi, K., and Zwane, E. (2015). Contribution of public extension to food security of smallholder farmers in limpopo province, south africa in an era of climate variability. *Journal of Human Ecology*, 50(3):205–212. Online: https://bit.ly/3fUHLsJ.

Aguilar, F. (2011). Reflexiones filosóficas sobre la tecnología y sus nuevos escenarios. *Sophía*, (11):123–172. Online: https://bit.ly/3vD64lw.

Almeraya, S., Figueroa, B., Díaz, J., Figueroa, K., and Pérez, L. (2011). Uso del crédito: implicaciones para el desarrollo rural. *Revista mexicana de ciencias agrícolas*, 2(1):111–124. Online: https://bit.ly/34xzuWC.

Arzaluz, S. (2005). La utilización del estudio de caso en el análisis local. *Región y sociedad*, 17(32):107–144. Online: https://bit.ly/2R3GnM0.

ASERCA (2019). Reporte del mercado de maíz. Apoyos y Servicios a la Comercialización Agropecuaria. Consultado 26 de noviembre 2020. Online: https://bit.ly/2WIxKsS.

Cazorla, A., De los Ríos, I., and Afonso, A. (2018). Conclusiones. In *Jornadas de diálogo para la inclusión de los Principios para la Inversión Responsable en la Agricultura (IAR) y las Directrices Voluntarias de Gobernanza de la Tierra (DVGT) en el ecosistema universitario de Latinoamérica*. Online: https://bit.ly/3fRyaD4.

Cazorla, A., de los Ríos, I., and Díaz, J. (2005). La iniciativa comunitaria leader como modelo de desarrollo rural: aplicación a la región capital de españa. *Agrociencia*, 39(6):697–708. Online: https://bit.ly/3cnyZTp.

Cazorla, A., De Los Ríos, I., and Salvo, M. (2013). Working with people (wwp) in rural development projects: A proposal from social learning. *Cuadernos de desarrollo rural*, 10(SPE70):131–157. Online: https://bit.ly/3yLT9jk.

CIMMYT (1974). *El Plan Puebla, siete años de experiencias, 1967-1973*. Centro Internacional de mejoramiento de maíz y trigo. México.

Damián, M., Ramírez, B., Parra, F., Paredes, J., Gil, A., López, J., and Cruz, A. (2007). Tecnología agrícola y territorio: el caso de los productores de maíz de tlaxcala, méxico. *Investigaciones geográficas*, (63):35–55. Online: https://bit.ly/2RWznRE.

Díaz, C., Jiménez, S., Laird, R., and Turrent, F. (1999). *Análisis de una estrategia de desarrollo de la agricultura tradicional*. Colegio de Postgraduados México, México.

Espinosa, A., Sierra, M., and Gómez, N. (2003). Producción y tecnología de semillas mejoradas de maíz por el inifap en el escenario sin la pronase. *Agronomía mesoamericana*, 14(1):117–121. Online: https://bit.ly/3wESVIM.

Friedmann, J. (2001). *La planificacián en el ámbito público*. Ministerio de administraciones públicas.

Gürel, B. (2019). The role of collective mobilization in the divergent performance of the rural economies of china and india (1950-2005). *The Journal of Peasant Studies*, 46(5):1021–1046. Online: https://bit.ly/3fYKBwL.

Hernández, S., Fernández, C., and Baptista, L. (2014). *Metodología de la investigación*. McGraw-Hill, México.

INEGI (2007). *Censo agrícola, ganadero y forestal*. Instituto Nacional de Estadística Geografía e Informática. Online: https://bit.ly/3fyo8HV.

Laird, R. (1977). *Investigación agronómica para el desarrollo de la agricultura tradicional*. Colegio de Postgraduados.

Lutz, B. and Herrera, F. (2007). Organizaciones de productores de maízen el estado de méxico: papel de las instituciones e importanciade las coyunturas políticas. *Ciencia Ergo Sum*, 14(1):15–26. Online: https://bit.ly/3wKlO6p.

Manrrubio, R. and H., S. (2010). *Del extensionismo agrícola a las redes de innovación rural*, chapter Del extensionismo a las redes de innovación, pages 31–67. Universidad Autónoma Chapingo.

Maziya, M., Mudhara, M., and Chitja, J. (2017). What factors determine household food security among smallholder farmers? insights from msinga, kwazulu-natal, south africa. *Agrekon*, 56(1):40–52. Online: https://bit.ly/34wH9nN.

Noriega, D., Vázquez, R., Morales, M., Martínez, J., Salinas, E., and Contreras, J. (2019). Adopción de innovaciones en maíz bajo el modelo escuelas de campo en tlalcozotitlán, guerrero. *Revista mexicana de ciencias agrícolas*, 10(8):1903–1909. Online: https://bit.ly/3fRcYNm.

Regalado, J., Jiménez, L., Laird, R., Estrella, N., Paredes, J., and Ramírez, B. (1996). Factores asociados a la utilización de la tecnología de alta productividad entre productores de maíz de temporal. *Agrociencia*, 30(1):139–146. Online: https://bit.ly/3fCuKVZ.

Regalado, J., Niño, E., and López, G. (2005). Generación y transferencia de una semilla de maíz, una experiencia en el plan regional tehuantepec, oaxaca, méxico. In *Actas del congreso internacional de dirección e ingeniería de proyectos 2002-2010*. Online: https://bit.ly/2SKZfQB.

Regalado, L., Cervantes, J., Pérez, R., Méndez, J., and Ramírez, J. (2010). *Revalorización de los sistemas de producción locales: el caso del maí en Santa Ana Xalmimilulco, Puebla*. Colegio de Postgraduados. Online: https://bit.ly/3c8sL9z.

Turrent, A. (2019). Agronomía vs agroecología. Consulta: 25 octubre 2019. Online: https://bit.ly/3pbP3fV.

Turrent, A., Cortés, J., Espinosa, A., Hernández, E., Camas, R., Torres, J., and Zambada, A. (2017). Masagro o miaf ¿cuál es la opción para modernizar sustentablemente la agricultura tradicional de méxico? *Revista mexicana de ciencias agrícolas*, 8(5):1169–1185. Online: https://bit.ly/3wKy9aT.

Velázquez, J., Juárez, J., Ramírez, B., Jiménez, J., Taboada, O., and Del Valle, M. (2019). Adopción de tecnología agrícola y su influencia en la productividad y competitividad del maíz en el centro-oriente del estado de puebla, méxico. *Revista de Geografía Agrícola*, (63):101–119. Online: https://bit.ly/3i5c5Ua.

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Forestry

Sexual and asexual propagation of *Brosimum alicastrum* Swartz in Campeche, Mexico

Propagación sexual y asexual de *Brosimum alicastrum* Swartz en Campeche, México

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Abstract

Brosimum alicastrum is a tree species in Mexico with wide potential for animal and human food, which is distributed naturally with no silvicultural management, so there is little information on the propagation methods of the species. The objective of this work was to analyze the scientific research published on *B. alicastrum*, through literature review to know the techniques that exist on its propagation. In addition, the quality of the seedling obtained by sexual propagation and asexual methods (cuttings, layers and grafts) was evaluated in the nursery, by means of experimental designs. 550 scientific articles on *B. alicastrum* were found, the disciplines where they were published were: Ecology (44.18%), Botany (13.27%), Forest Sciences (11.27%, of which 2.54% worked propagation in the nursery), Zoology (11.09%), Agriculture (9.64%), Anthropology (5.45%) and others (5.10%). Regarding the seed propagation method, the best seedling quality was associated with low porosity substrates (bush soil) and containers with large diameters (36 cm). In the case of asexual propagation, with the layering method when peat was used as the substrate 90% survival was obtained, and by lateral grafting technique 75% yield was found. Due to the little research that exists on the propagation of the species, it is recommended that the selection of the propagation technique is based on the purpose of the seedling; if it is required to shorten the seed production cycles of *B. alicastrum* the asexual techniques grafting and layering can be more efficient.

Keywords: Ramon, forestry, forest nursery, graft, rooting of cuttings, air layering.

Resumen

Brosimum alicastrum es una especie arbórea en México con amplio potencial para la alimentación animal y humana, que se distribuye de manera natural con nulo manejo silvícola, por lo que existe poca información sobre los métodos de propagación de la especie. El objetivo de este trabajo fue analizar la producción científica reportada sobre *B. alicastrum* mediante minería de textos para conocer las técnicas que existen sobre su propagación; y evaluar en vivero la calidad de plántulas obtenidas por métodos de propagación sexual y asexual (estacas, acodos e injertos) mediante diseños experimentales. Se encontraron 550 artículos científicos sobre *B. alicastrum*, las disciplinas donde se publicaron fueron: Ecología (44,18 %), Botánica (13,27 %), Ciencias Forestales (11,27 %, de los cuales el 2,54 % trabajó propagación en vivero), Zoología (11,09 %), Agricultura (9,64 %), Antropología (5,45 %) y otras (5,10 %). Respecto al método de propagación por semilla, la mejor calidad de plántula se asoció con sustratos de baja porosidad (tierra de monte) y con contenedores con diámetros grandes (36 cm). Para el caso de la propagación asexual por acodos, cuando se empleó turba como sustrato se obtuvo 90 % de sobrevivencia, y por injerto de enchape lateral se encontró 75 % de prendimiento. En virtud de la poca investigación que existe sobre la propagación de la especie se recomienda que la selección de la técnica de propagación esté en función de la finalidad de la plántula. Las técnicas asexuales de injerto y acodo pueden ser más eficientes en caso de requerir acortar los ciclos de producción de la semilla de *B. alicastrum*.

Palabras clave: Ramón, silvicultura, vivero forestal, injerto, enraizamiento de estacas, acodo aéreo

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1 Introduction

Brosimum alicastrum Swartz, commonly known as Ramon or breadnut, is a tree native from Mesoamerica and the Caribbean, and it is widely distributed in Mexico (Peters and Pardo, 1982). It is known by having high nutrient content foliage, mainly for cattle and goats and also for its availability during the dry season (Hernández et al., 2014; Rojas et al., 2017). Ramon represents an ecologically important element in the floristic composition of the low and medium forests of southern Mexico (Gutiérrez and Dirzo, 2009).

Ramon produces four times more food and 10 times more protein per hectare than maize, without causing damage to the environment. In addition, its seed, foliage, latex and wood have high economic potential for food (animal and human) and for medicinal and cultural uses (Ramírez et al., 2017; Domínguez et al., 2019). Even though its importance, the species is distributed mostly naturally, with no forest management (Vergara et al., 2014).

The establishment of plantations requires trees with outstanding phenotypic and genotypic characteristics, thus the propagation method for obtaining germplasm is key to good silvicultural management (Hernández et al., 2015). Its dissemination can be sexual or asexual (Molina et al., 2015).

During the sexual reproduction of trees, parents may inherit desirable and undesirable characteristics (Molina et al., 2015). Meanwhile during vegetative propagation, germplasm with genetic information and traits of economic importance can be obtained in shorter periods, with the limitation that the genetic diversity of the species is reduced by the uniformity of the offspring (Bailey et al., 2009). In both cases, nursery management is observed in the quality of the seedlings produced, through their morphological characteristics and their ability to adapt to the area (Rueda et al., 2014).

Traditional techniques of asexual propagation in forest species are cuttings, layers and grafts (Pardo et al., 2002). Thanks to biotechnology, *in vitro* propagation has become an alternative for those species with high commercial value and difficulty to disseminate by traditional techniques (Bailey et al., 2009). However, the main limitation of vegetative propagation is the low multiplication percentage, hence it is important to expand the number of species to be propagated and improve the technique, since plants reproduced vegetatively have better silvicultural management (Sampayo et al., 2016).

There is almost no research on propagation techniques in *B. alicastrum*, and the one reported does not have any scientific rigor (Gillespie et al., 2004; Molina et al., 2015). Due to the importance of the species in the Yucatan peninsula as an alternative plant resource for animal and human feeding for food security and climate change (Ramírez et al., 2017), research that develops around the forest management of the species will be very useful and important (Hernández et al., 2015).

In this context, the aim of this paper is to analyze the scientific production reported on *Brosimum alicastrum* Swartz, using text mining to know the techniques that exist on its propagation; and to evaluate in nursery conditions the quality of seedlings obtained by sexual and asexual propagation methods through experimental designs (cuttings, layers and grafts).

2 Materials and Methods

2.1 Study area

The research was carried out in the experimental nursery located in the facilities of the Campus Campeche Graduate School (Champotón, Campeche). Vegetative material of *B. alicastrum* was collected in different areas of the research center (Figure 1). The region is characterized by having a cover of medium subperennifolia forest and high perennifolia forest, with clay soils and precipitation of 600 to 4000 mm with estimated periods from three to seven months, average annual temperature of 18 °C to 27 °C and altitudes of 20 to 1000 masl. The main economic activities of this region are the cattle raising and crop of maize (*Zea mays* L.), beans (*Phaseolus vulgaris* L.), chihua (*Cucurbita argyrosperma* H.) and sugar cane (*Saccharum officinarum* L.) (White and Hood, 2004). It is noted that the main feed for cattle during drought is Ramon tree (Góngora et al., 2016).

2.2 Text mining and bibliometric analysis

In order to know the techniques used in the propagation of *B. alicastrum*, the scientific articles on the species available in the main publishing houses (Elsevier, Springer and Scopus) and websites (Latindex, SciELO, Redalyc, Thomson-Reuters, Periodica, DOAJ, Google Scholar and Conricyt) were analyzed. The keyword used in the search was *Brosimum alicastrum*, identifying it in the titles and keywords of the publications.

The variables that were analyzed for each article were: year to know the time of the research; discipline of study to determine the area of knowledge where more research has been conducted; and authors to know the actors involved in the research. The information was systematized in a spreadsheet. Using the plugin RcmdrPlugin.temis of the R statistical software (Bouchet and Bastin, 2013), the time of the research and the frequency of the publications by study discipline were obtained.

The network of authors was created with the Sci2tool software (Börner, 2011). Authors with more publications on the network were associated with the area of knowledge. The syntax used in the Sci2tool software was Extract bipartite Network, for its visualization the software Gephi was used (Jacomy et al., 2014).

2.3 Sexual propagation

In March 2019, Ramon seed was collected in the location called 20 de noviembre (Calakmul, Campeche). The methodology described by Vallejos et al. (2010), and the trees with the best phenotypic (dasometric) characteristics with a minimum distance between selected trees of 100 m were selected. The germplasm was stored in sterilized plastic bags that were moved to the facilities of the College of Postgraduates, Campeche campus (Champotón, Campeche), Mexico.

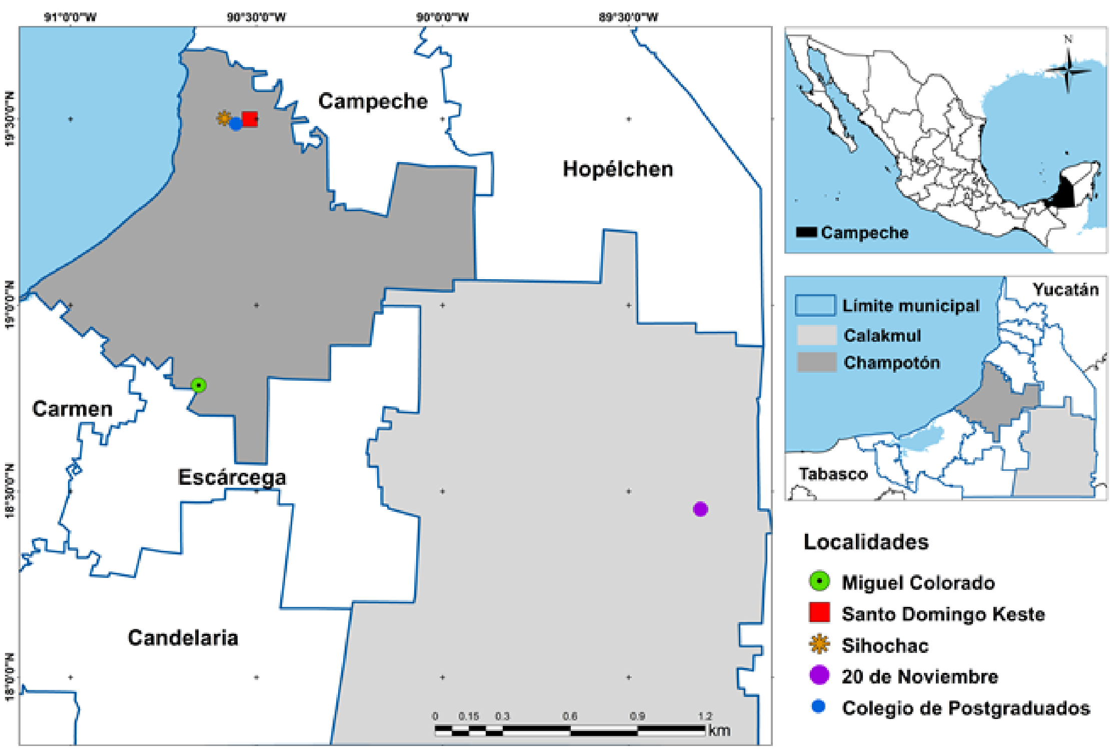

Figure 1. Spatial location of the localities where the vegetative material was collected and where experiments were conducted to evaluate the propagation of *Brosimun alicastrum* Swartz in Campeche, Mexico.

Seeds were subjected to a purity analysis and viability test with tetrazolium chloride® at 0.5%, according to the methodology described by Orantes et al. (2013). It was evaluated in a rustic forest nursery from April to June 2020, where a completely randomized experimental design with factorial arrangement was established. The factors analyzed were: 1) type of container: Tubes (36 and 21 cm in diameter) and plastic bag (36 and 21 cm in diameter), and 2) substrate: (peat moss 50% + agrolite 25% + perlite 25%) and (bush soil 60% + lumbricompost 40%).

The mixture (peat moss 50% + agrolite 25% + perlite 25%) was characterized by a slightly acidic pH with high porosity and moisture retention capacity; while the mixture (bush soil 60% + lumbricompost 40%) showed a neutral pH with low porosity and high-water retention capacity (Pérez de la Cruz et al., 2012). For the eight treatments, a manual watering was applied every three days to the experimental units according to the moisture retention of the substrates used (Del Amo et al., 2002).

30 days after the experimental design was established, the germination percentage per treatment was evaluated. A variance analysis and Tukey mean tests ($\alpha = 0.05$) were used to determine the statistical differences per treatment three months after the experiment was established for the variables: height (cm), number of leaves, stem diameter (cm), dry stem biomass (kg), root width (cm), root length (cm) and dry root biomass (kg). Dry biomass of the root and stem was obtained on an analytical scale after extracting the vegetative material from a stove with forced air circulation at 70 °C for 24 hours.

2.4 Asexual propagation

Three asexual propagation techniques were tested: cuttings, laters and grafts. In the case of cuttings, plant material was collected in March 2019 at Miguel Colorado community (Champotón, Campeche). Through a field tour, healthy, vigorous, pest-free trees were selected with fruits at the time of harvest and straight trees without bifurcation. The plant material was wrapped in wet newspaper to prevent it from becoming dehydrated during its transfer to the nursery of the Graduate School, Campeche campus.

Cuttings were placed in polythene bags with traditional nursery substrate (peat moss 50%, agrolite 25% and perlite 25%). Shoots and roots in cuttings were evaluated at three months (April-June) using a fully randomized experimental design with factorial arrangement. The factors considered were: type of rooting powder (Auxin, Fortimax, Raidzone Plus and Magic Plus), and stake position (basal, intermediate, and apical). For the 12 treatments, manual irrigation was applied every three days to the experimental units. The variables analyzed were number and length (cm) of aerial shoots, and dry and fresh biomass of roots and stems (kg), vertical height (cm) and horizontal height (cm) of the root.

In May 2019, *in vivo* propagation by layers to young Ramon trees (under 5 years) was conducted in the town of Sihochac (Champotón, Campeche). Through a field trip, healthy, vigorous, pest-free and straight trees without bifurcation were selected. A completely randomized experimental design was considered with three treatments (T) and 30 replications per treatment: T1 (Auxin + peat moss), T2 (Auxin + vermiculite) and T3 (Auxin + Perlite). The variables analyzed were: survival rate at three months, and number, length (cm) and dry biomass (kg) of the roots.

In July 2019, in the town of Santo Domingo Keste (Champotón, Campeche), *in vivo* propagation by graft to Ramon trees under one year old was carried out with vegetative material of trees of the same species not less than five years old and with the capacity to produce fruits. For the selection of the standard trees and from which the scion wood to be grafted were obtained, healthy, vigorous, pest-free and straight trees without bifurcation were selected.

The graft techniques used were: cleft, bud, lateral and simple English. A completely randomized experimental design was established, where each graft technique was taken as a treatment with 20 replications per treatment. The variables analyzed were growth percentage at three months, height (cm), diameter (cm), number of leaves and number of shoots of grafted vegetative material. To establish statistical differences by treatments and variables analyzed, a variance analysis and Tukey mean tests ($\alpha = 0.05$) were performed for cuttings, layers and grafts propagation method.

3 Results and Discussion

3.1 Text Mining and Bibliometric Analysis

From 1970 to 2019, 550 scientific articles were published, in which *B. alicastrum* appeared in the title or keywords. According to De Granda et al. (2005) the title indicates the precise subject matter of the work and the keywords allow to place the topic studied in the article. The disciplines that published themes related to *B. alicastrum* were: Ecology (44.18 %), Botany (13.27 %), Forestry (11.27 %, of which 2.54 % worked in nursery propagation), Zoology (11.09 %), Agriculture (9.64 %), Anthropology (5.45 %) and others (5.10 %).

Figure 2 shows the network of authors of the 550 papers analyzed. The authors with the highest number of contributions per area were highlighted. Ecology turned out to be the discipline where most researches have been conducted. This aspect has been reported by Vergara et al. (2014), who agreed that there is little research on the silvicultural management of Ramon. For this reason, it is an area of research opportunity, since according to Ramírez et al. (2017) the species has broad potential for the livestock food, particularly in the following sectors: pig, bovine, sheep, poultry and aquaculture for food security and climate change.

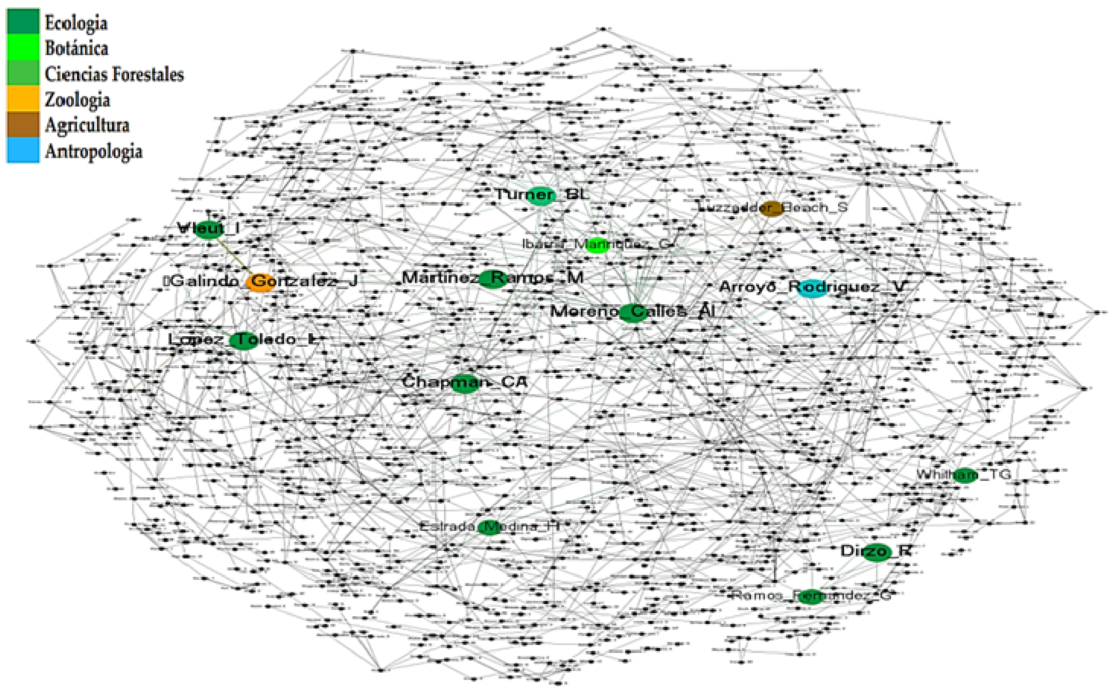

Figure 2. A network of authors from the disciplines where more research has been conducted on *Brosimum alicastrum* Swartz.

Hernández et al. (2014) mentioned the importance that Ramon's plantations in southeastern Mexico would have for the livestock feed agroindustry in guaranteeing the raw material of its operations. According to Vergara et al. (2014) no silvicultural management of the species happens because the industry around *B. alicastrum* is emerging and current research focuses on evaluating its potential properties and uses.

3.2 Sexual propagation

For the purity test, 858 *B. alicastrum* seeds with a total biomass of 2128 g were analyzed. 91 % of seeds (785; 1944 g) were not broken, stained and showed no trace of insect attack (holes and/or larvae). However, the high purity percentage contrasted with the viability (germination potential) of the seed. The results of direct contact of the seeds with tetrazolium® solution at room temperature and with limited light for 24 hours showed on average a high viability in 20% of the seeds, medium viability (27.5%) and low viability (52.5%) for the four replications with 10 seeds per replication.

The low germination potential of *B. alicastrum* seeds has been mentioned by Gillespie et al. (2004) with values lower than 50%, which coincided with the results obtained in this research, but contrasted with the one reported by Del Amo et al. (2002) with germination percentages higher than 75%. These differences were explained because Ramon's seeds are recalcitrant (García et al., 2012; Loría and Larqué, 0015), fact that makes them more sensitive to dehydration and rapid viability loss, limiting their storage for propagation purposes (Magnitskiy and Plaza, 2007). The germination evaluation 30 days after the crop por sow resulted in 59.6%, which coincided with the low viability of the seed obtained in the tetrazolium® test (Table 1). However, it differed from what was reported by Laborde and Corrales-Ferrayola (2012), who found 75% of germination when the seeds fell directly from the tree to the soil. According to Del Amo et al. (2002) the germination percentage of *B. alicastrum* seeds in nurseries was directly related to the collection-planting temporality, due to the recalcitrant property of the seed. Table 1 presents the results of the variance analysis and Tukey mean test ($\alpha = 0.05$) by treatment and evaluated variables. Statistical differences were observed between the treatments used ($P < 0.0001$). Tukey multiple tests indicated that treatment 6 (bag with 36 cm of diameter with substrate 2: bush soil 60% + lumbricompost 40%) presented the highest values for the phenotypic characteristics evaluated.

The type of container (tube or plastic bag) showed no statistical difference. This result coincided with that reported by Luna et al. (2012), who found that the use of plastic bags as a container in nursery occurs by economic reasons. The factor that was statistically significant was the size of the container diameter. The highest values for the phenotypic characteristics evaluated were presented in those containers of higher diameter (36m).

This result contrasted with that reported by Pérez de la Cruz et al. (2012), who found that in the first month *B. alicastrum* seeds in nursery showed faster growth in containers with 21 cm diameters. However, according to Luna et al. (2012) larger diameter containers provided better nursery characteristics to large leaf species because of the space between plants, which allowed them to make better use of light, heat, water and nutrients.

3.3 Asexual propagation

Propagation by cuttings was not significant, and the experimental units evaluated in the different treatments failed to survive. No experimental unit achieved root formation, and only 7 out of 240 experienced aerial shoots (Table 2). Sampayo et al. (2016) found that aerial shoots were common in forest species disseminated by cuttings. However, the success of this technique was measured by the rooting percentage achieved (Peralta et al., 2017).

According to González et al. (2019), the obtaining of non-significant results in the asexual propagation by cuttings of forest species may be due to inadequate management in nurseries, the lignified tissue of the plant material and even the collection date. However, the results were consistent with those reported by Vergara et al. (2014) and Molina et al. (2015) who stated that stake propagation for *B. alicastrum* was a non-viable technique due to the lignified tissue of the species.

Layers and grafting methods were significant, and Tukey mean test showed statistical differences among treatments with 95% of confidence level ($\alpha = 0.05$). Regarding layers, the treatment with peat moss substrate showed the highest results (Table 3). In the case of graft, the lateral technique was the one that was more significant with 75% (15 out of 20 replications), higher than the cleft (20.00%; 4 out of 20 repetitions), bud (0.00%; 0 out of 20 replications) and simple English (10.00%; 2 out of 20 replications) (Table 4).

Molina et al. (2015) when conducting a research in some regions of El Salvador found that for *B. alicastrum* graft is the most viable form of asexual propagation. However, unlike their study, no previous treatments with growth hormones were considered for grafted vegetative materials in this research. In both studies, lateral grafting technique was the one with the highest growth percentage achieved: 75% in this research and 42% for Molina et al. (2015).

Table 1. Phenotypic variables in *Brosimum alicastrum* Swartz seedling propagated by seed.

Treatment*	Replications		Height (cm)	Leaves	Stems		Root		
	Total	% Germination			Diameter (cm)	Biomass (kg)	Width (cm)	Lenght (cm)	Biomass (kg)
T1 (T36+S1)	30	73.33 (22)	26.75 AB	5.77 AB	3.58 AB	0.76 B	10.60 A	12.67 AB	0.65 AB
T2 (T36+S2)	30	80.00 (24)	25.90 BC	6.08 AB	3.37 B	0.54 BCD	12.10 A	12.40 ABC	0.51 BCD
T3 (T21+S1)	30	50.00 (15)	25.70 BC	5.35 BC	3.20 BC	0.54 BCD	4.87 B	10.35 BC	0.39 CDE
T4 (T21+S2)	30	63.33 (19)	19.10 D	3.13 D	2.47 C	0.28 D	2.78 B	9.97 CD	0.24 E
T5 (B36+S1)	30	60.00 (18)	28.35 AB	5.91 AB	3.47 AB	0.66 BC	9.91 A	10.30 BC	0.530 BC
T6 (B36+S2)	30	73.33 (22)	32.50 A	6.96 A	4.18 A	1.18 A	9.56 A	14.17 A	0.83 A
T7 (B21+S1)	30	40.00 (12)	23.71 BC	5.00 BC	3.06 BC	0.43 CD	4.50 B	7.50 DE	0.31 CDE
T8 (B21+S2)	30	36.67 (11)	20.13 CD	4.06 CD	2.49 C	0.31 D	4.69 B	7.22 E	0.28 DE
Total	240	59.58 (143)							

* T36: Tube 36 cm; T21: Tube 21 cm; B36: Bag 36 cm; B21: Bag 21 cm; S1: peat moss 50 % + agrolite 25 % + perlite 25 %; S2: bush soil 60 % + lumbricompost 40 %. Means with the same letter per column are not statistically different (Tukey, $\alpha = 0.05$).

In relation to the substrate type, substrate 2 (bush soil 60 % + lumbricompost 40 %) was slightly higher than substrate 1 (peat moss 50 % + agrolite 25 % + perlite 25 %). This result was in accordance with the one reported by Laborde and Corrales (2012), Pérez de la Cruz et al. (2012) and Hernández et al. (2015) who mentioned that *B. alicastrum* had a better performance on local substrates with physicochemical characteristics similar to the areas where it was distributed naturally, rather than on commercial substrates commonly used in nurseries.

Table 2. Phenotypic variables of the vegetative material of *Brosimun alicastrum* propagated asexually by the stake technique.

Treatment	Replications		Aerial shoots		Root (length: Cm)		
	Total	Significant	Number	Length (cm)	Biomass	Vertical	Horizontal
T1 (AU_BA)	30	2	3	0.5	0	0	0
T2 (AU_IN)	30	2	2	0.25	0	0	0
T3 (AU_AP)	30	2	3	3.93	0	0	0
T5 (FO_IN)	30	1	1	2.35	0	0	0
Others **	240	0	0	0	0	0	0

Rooting powder: Auxin (AU), Fortimax (FO), Raidzone Plus (RP), Magic Plus (MP). cutting position: Basal (BA), Intermediate (IN), apical (AP). **T4 (FO_BA), T6 (FO_AP), T7 (RP_BA), T8 (RP_IN), T9 (RP_AP), T10 (MP_BA), T11 (MP_IN), T12 (MP_AP).

Table 3. Phenotypic variables of the vegetative material of *Brosimun alicastrum* Swartz propagated asexually by the bud technique.

Treatment	Replications		Root		
	Total	% Survival	Number	Length (cm)	Biomass (kg)
T1 (Peat moss)	30	90 (27) A	13.56 A	11.99 A	0.61 A
T2 (Vermiculite)	30	80 (24) B	12.44 AB	8.55 B	0.52 AB
T3 (Perlite)	30	80 (24) B	10.78 B	9.05 B	0.31 B

The rooting powder used for all treatments was auxin. Means with the same letter per column are not statistically different (Tukey, $\alpha = 0.05$). The survival% was calculated by treatment, the number of surviving replications of the total per treatment is in parentheses

Table 4. Phenotypic variables of the vegetative material of *Brosimun alicastrum* Swartz propagated asexually by the graft technique.

Type of graft	Replications		Grafted Vegetative Material			
	Total	Growth %	Height (cm)	Diameter (cm)	Leaves (number)	Shoots (number)
Cleft	20	20.00 (4) B	8.75 AB	0.11 B	8.72 B	1.25 B
Layer	20	0.00 (0) C	0.00 C	0.00 C	0.00 D	0.00 C
Lateral	20	75.00 (15) A	10.35 A	0.139 A	15.59 A	2.63 A
Simple English	20	10.00 (2) B	5.54 B	0.06 C	5.28 C	0.74 B

Means with the same letter per column are not statistically different (Tukey, α =0.05). The growth% was calculated by the type of graft. The number of replications that presented growth of the total by type of graft is indicated in parentheses.

The difference in the growth percentages could be explained by the juvenile condition of the vegetative materials used (5 years old with non-lignified tender cuttings) and pattern (1 year old). According to Alba et al. (2017) the growth percentage of the grafted vegetative material was associated with the juvenile condition of the materials, so the younger the individual, the faster and easier its propagation, making graft the most effective asexual propagation method (Bailey et al., 2009).

In relation to the propagation technique by layers, no research was found where the use of this technique was reported in the asexual propagation of *B. alicastrum*. According to Vergara et al. (2014) the lack of silvicultural management of the species has limited the development of research on its forms of propagation.

4 Conclusions

The scientific production found on *B. alicastrum* focused on analyzing and describing aspects of ecology and botany of the species; research on its propagation was scarce. Therefore, the conduction of research on this topic is a priority area to contribute to the silvicultural management of the species.

In the seed propagation method, the percentage of nursery germination was associated with neutral pH substrates and low porosity, and the quality of seedlings to containers with large diameters (36 cm). Asexual propagation by cuttings was not successful; the best results were obtained with layers with a 90% of survival, and graft with the lateral technique with a 75% increase in growth.

Because of the little research on the dissemination of the species, it is recommended that the selection of propagation technique is based on the purpose of the seedling, and asexual graft and bud techniques may be more efficient if the aim is to shorten the seed production cycles of *B. alicastrum*.

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References

Alba, J., Mendizábal, L., Ramírez, E., Ramírez, J., Cruz, H., and Rodriguez, M. (2017). Injertos de fenotipos selectos de *Pinus greggii* engelm. de una prueba genética en villa aldama, veracruz, méxico. *Foresta Veracruzana*, 19(2):57–61. Online: https://bit.ly/3lokErO.

Bailey, J., Bímová, K., and Mandák, B. (2009). Asexual spread versus sexual reproduction and evolution in *Japanese Knotweed* s.l. sets the stage for the "battle of the clones". *Biological Invasions*, 11(5):1189–1203. Online: https://bit.ly/33Cgd6v.

Börner, K. (2011). Science of science studies: Sci2 tool. *Communications of the ACM*, 54(3):60–69. Online: https://bit.ly/2S2A7ED.

Bouchet, M. and Bastin, G. (2013). Rcmdrplugin.temis, a graphical integrated text mining solution in r. *The R Journal*, 5(1):188–196. Online: https://bit.ly/3iDUUFW.

De Granda, J., Río, F., Vázquez, F., Sacristán, J., Jiménez, T., and Sánchez, L. (2005). Las palabras clave como herramientas imprescindibles en las búsquedas bibliográficas. análisis de las áreas del sistema respiratorio a través de archivos de bronconeumología. *Archivos de Bronconeumología*, 41(2):78–83. Online: https://bit.ly/3f399o9.

Del Amo, S., Vergara, M., Ramos, J., , and Sainz, C. (2002). *Germinación y manejo de especies forestales tropicales*. CONAFOR-CONACYT. Online: https://bit.ly/3y2cxbE.

Domínguez, P., García, I., Güemes, N., and Totosaus, A. (2019). Textura, color y aceptación sensorial de tortillas y pan producidos con harina de ramón (*Brosimum alicastrum*) para incrementar la fibra dietética total. *Ciencia & Tecnología Agropecuaria*, 20(3):699–719. Online: https://bit.ly/3uCgiCc.

García, C., Roque, A., and Méndez, M. (2012). Aprovechamiento del ábol nativo *Brosimum alicastrum* swartz (moraceae) en la selva zoque chiapas, méxico. *LACANDONIA*, 6(1):71–76.

Gillespie, A., Bocanegra, D., and Jimenez, J. (2004). The propagation of ramon (*Brosimum alicastrum* sw.; moraceae) in mayan homegardens of the yucatan peninsula of mexico. *New Forests*, 27(1):25–38. Online: https://bit.ly/3bhlvaW.

Góngora, R., Flores, S., Ruenes, M., Aguilar, W., and García, J. (2016). Uso tradicional de la flora y fauna en los huertos familiares mayas en el municipio de campeche, campeche, méxico. *Ecosistemas y recursos agropecuarios*, 3(9):379–389. Online: https://bit.ly/3wfYuxf.

González, A., Rodríguez, D., Corona, A., and Vera, J. (2019). Propagation by cuttings and plant quality in *Acer negundo* l. *Revista mexicana de ciencias forestales*, 10(51):224–243. Online: https://bit.ly/3y9iSC6.

Gutiérrez, G. and Dirzo, R. (2009). Remoción de semillas, herbivoría y reclutamiento de plántulas de brosimum alicastrum (moraceae) en sitios con manejo forestal contrastante de la selva maya, quintana roo, méxico. *Boletín de la Sociedad Botánica de México*, 85:51–58. Online: https://bit.ly/3ylbJ1y.

Hernández, O., Vergara, S., and Larqué, A. (2014). Studies on the productivity of brosimum alicastrum a tropical tree used for animal feed in the yucatan peninsula. *Bothalia J. Bothanical Life Sci. Res*, 44(6):70–81. Online: https://bit.ly/3hewXbm.

Hernández, O., Vergara, S., and Larqué, A. (2015). Primeras etapas de crecimiento de *Brosimum alicastrum* sw. en yucatán. *Revista mexicana de ciencias forestales*, 6(27):38–49. Online: https://bit.ly/3bBZHXP.

Jacomy, M., Venturini, T., Heymann, S., and Bastian, M. (2014). Forceatlas2, a continuous graph layout algorithm for handy network visualization designed for the gephi software. *PloS one*, 9(6):e98679. Online: https://bit.ly/36DghVD.

Laborde, J. and Corrales, I. (2012). Direct seeding of *Brosimum alicastrum* sw. (moraceae) and *Enterolobium cyclocarpum* (jacq.) griseb. (mimosaceae) in different habitats in the dry tropics of central veracruz. *Acta botánica mexicana*, 100:107–134. Online: https://bit.ly/3tYx0ur.

Loría, L. and Larqué, A. (20015). The effect of salicylic acid on the growth of seedling roots of *Brosimum alicastrum*, a perennial tree from the mexican tropics which produces recalcitrant seeds. *Sylwan*, 158(6):338–346. Online: https://bit.ly/3hfGPBA.

Luna, T., Landis, T., and Dumroese, R. (2012). *Producción de plantas en viveros forestales*, chapter Contenedores: aspectos técnicos, biológicos y económicos, pages 78–85. Online: https://bit.ly/3uz9SUA. Consejo Federal de Inversiones, Centro de Investigación y Extensión Forestal Andino Patagónico, y Universidad Nacional de la Patagonia San Juan Bosco.

Magnitskiy, S. and Plaza, G. (2007). Fisiología de semillas recalcitrantes de árboles tropicales. *Agronomía colombiana*, 25(1):96–103. Online: https://bit.ly/3hdKxf9.

Molina, M., Castillo, L., Parada, F., Lara, F., , and Linares, A. (2015). Caracterización morfológica in situ de ojushte (*Brosimum alicastrum* swartz) y su incidencia en la selección de germoplasma de alto potencial nutricional en el salvador. *Producción Agropecuaria y Desarrollo Sostenible*, 3:61–76. Online: https://bit.ly/3f7TpAg.

Orantes, C., Pérez, M., Rioja, T., and Garrido, E. (2013). Viabilidad y germinación de semillas de tres especies arbóreas nativas de la selva tropical, chiapas, méxico. *Polibotánica*, (36):117–127. Online: https://bit.ly/3tSxWkd.

Pardo, D., Verdugo, F., and Hernández, J. (2002). Reproducción vegetativa de dos especies arbóreas en un manglar de la costa norte del pacífico mexicano. *Madera y Bosques*, 8(2):57–71. Online: https://bit.ly/3bhu0mm.

Peralta, M., Nava, J., Santos, G., García, A., , and Salado, N. (2017). Reguladores del crecimiento y sustratos en la propagación vegetativa de nanche (*Malpighia mexicana* a. juss. y *Byrsonima crassifolia* (l) hbk). *Revista Brasileira de Fruticultura*, 39(3):1–9. Online: https://bit.ly/33QkJhc.

Pérez de la Cruz, S., Orantes, C., Garrido, E., , and Cruz, J. (2012). Diferencias en crecimiento y desarrollo de plántulas de mojú (*Brosimum alicastrum* swartz) en condiciones de vivero. *LACANDONIA*, 6(2):51–57.

Peters, C. and Pardo, E. (1982). *Brosimum alicastrum* (moraceae): uses and potential in mexico. *Economic Botany*, 36(2):166–175. Online: https://bit.ly/3o1F4cA.

Ramírez, S., Ibáñez, D., Gutiérrez, M., Ortega, M., García, L., and Larqué, A. (2017). El ramón (*Brosimum alicastrum* swartz) una alternativa para la seguridad alimentaria en méxico. *Agroproductividad*, 10(1):80–83. Online: https://bit.ly/33v94Ec.

Rojas, J., Sarmiento, L., Sandoval, C., and Santos, R. (2017). Utilización del follaje de ramón (*Brosimum* *alicastrum* swarth) en la alimentación animal. *Tropical and Subtropical Agroecosystems*, 20(3):363–371. Online: https://bit.ly/3vT7nMZ.

Rueda, A., Benavides, J., Saenz, J., Muñoz, H., Prieto, J., and Orozco, G. (2014). Calidad de planta producida en los viveros forestales de nayarit. *Revista mexicana de ciencias forestales*, 5(22):58–73. Online: https://bit.ly/33SpJSe.

Sampayo, S., Jiménez, M., López, J., Sánchez, V., Jasso, J., Equihua, A., and Castillo, C. (2016). Enraizado de miniestacas de *Cedrela odorata* l. *Agrociencia*, 50(7):919–929. Online: https://bit.ly/3bAIkqo.

Vallejos, J., Badilla, Y., Picado, F., and Murillo, O. (2010). Metodología para la selección e incorporación de árboles plus en programas de mejoramiento genético forestal. *Agronomía Costarricense*, 34(1):105–119. Online: https://bit.ly/3hyGw55.

Vergara, S., Briceño, C., Pérez, J., Hernández, O., Rosado, L., and Larqué, A. (2014). *Publicaciones de* Brosimum alicastrum. Centro de Investigaciones Cientificas de Yucatán, Mérida, Yucatán, México.

White, D. and Hood, C. (2004). Vegetation patterns and environmental gradients in tropical dry forests of the northern yucatan peninsula. *Journal of Vegetation Science*, 15(2):151–160. Online: https://bit.ly/3vTkzBI.

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Pollutant Analytics

Review on maximum limits of cadmium in cocoa (*Theobrama cacao L.*)

Revisión sobre limites máximos de cadmio en cacao (*Theobroma cacao L.*)

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Abstract

Cadmium (Cd) tends to bioaccumulate in *Thebroma cacao* beans, affecting human health and its marketing possibilities. For this reason, the European Union (EU) approved Regulation No 488/2014 for processed cocoa products, which applies from January 2019, and motivated authors to conduct research on its bioaccumulation in beans, the potential risks to health, quality, and its export possibilities. The results show high levels in different regions of the main Latin American (LA) producing countries: Brazil, Ecuador, Colombia, Peru, the Dominican Republic, Bolivia, Honduras, and others. However, EU regulation does not stipulate maximum limits for raw cocoa. In the absence of it, research has been classified by reference to the limits for processed cocoa, generating oversized metal levels, controversies in the producer's and setback in replacing illegal coca cultivation in this region. Thus, this review article will detail research on Cd levels in cocoa beans in major Latin American producing countries, the application of EU regulation No 488/2014 to raw cocoa, proposals to set maximum limits on raw beans and their implications for replacing illicit crops.

Keywords: Raw cocoa, Latin American cocoa, beans cadmium, illicit crops, maximum limits, regulations.

Resumen

El cadmio (Cd) tiende a bioacumularse en granos de *Theobroma cacao*, afectando la salud humana y sus posibilidades de comercialización. Esto llevó a la Unión Europea (UE) a aprobar el Reglamento N° 488/2014 para productos procesados del cacao, y motivó a la comunidad científica a realizar investigaciones sobre su bioacumulación en granos, los potenciales riesgos a la salud, calidad, y sus posibilidades de exportación. Los resultados evidencian altos niveles en diferentes regiones de los principales países productores Latinoamericanos (LA): Brasil, Ecuador, Colombia, Perú, República Dominicana, Bolivia, Honduras, y otros. Sin embargo, el reglamento 488/2014 no estipula límites máximos en cacao sin procesar; en ausencia de este, las investigaciones han clasificado estos límites, tomando como referencia los límites para cacao procesado, generando sobredimensionamiento de los niveles del metal, controversias en el mercado y retroceso en la sustitución del cultivo ilegal de la coca en esta región. Por lo tanto, en este artículo de revisión se detallarán las investigaciones realizadas sobre los niveles de Cd en granos de cacao en principales países productores de América Latina, la aplicación del reglamento N° 488/2014 a cacao sin procesar, las propuestas para establecer límites máximos en granos sin procesar y sus implicaciones en la sustitución de cultivos ilícitos.

Palabras clave: Cacao sin procesar, cacao de América Latina, cadmio en granos, cultivos ilícitos, límites máximos, reglamento.

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1 Introduction

Cadmium (Cd) is a heavy metal with intermediate properties between zinc (Zn) and mercury (Hg) (Pérez and Azcona, 2012; Antoine et al., 2017), that has been widely used in the industry for 50 years (Pérez and Azcona, 2012; Gunnar, 2013). It is currently causing health disorders in vital organs: lungs, kidneys, bone and probably the development of carcinogenesis (Reyes et al., 2016), as a result of its high mobility and bioaccumulative power (Reyes et al., 2016; Engbersen et al., 2019; Raju et al., 2020; Gunnar, 2013). Recent studies consider cadmium, along with lead, mercury and chromium, as dangerous elements for human nutrition (Casteblanco, 2018; Engbersen et al., 2019); fact that has attracted the attention of the scientific community oriented to its description and behavior in biological systems, and propose prevention, control and remediation alternatives.

The implementation of Regulation No 488/2014 established tolerable limits from 0.1 to 0.8 μg g^{-1} to cocoa-derived products (Jiménez, 2015; Kruszewski et al., 2018), mentioned in scientific reports that showed high levels of cadmium in soils (Cd) and beans (CdA) (Prieto et al., 2009; Mite et al., 2010; Sánchez et al., 2011; Bravo et al., 2014). In this regard, research has shown that soils generally have low Cd levels and their bioavailability depends on soil characteristics (Bravo et al., 2014; He et al., 2015; Gramlich et al., 2017; Díaz et al., 2018; Gramlich et al., 2018). CdA concentrations higher than the soil itself produced by various factors between the soil-cocoa system are also reported (Chávez et al., 2015; Arévalo et al., 2017b; Gramlich et al., 2017; Hernández et al., 2017; Tantalean and Huauya, 2017; Casteblanco, 2018; Díaz et al., 2018; Florida et al., 2018; Gramlich et al., 2018; Kruszewski et al., 2018; Argüello et al., 2019; Barraza et al., 2019; Florida et al., 2019; Romero et al., 2019; Zug et al., 2019), as well as values that exceed the tolerable limits established by the EU.

In this context, scientific reports have taken as a reference Regulation No 488/2014 (European Union-EU, 2014), in force since January 2019 (Jiménez, 2015; Kruszewski et al., 2018; Meter et al., 2019)for determining Cd levels and establish tolerable limits between 0.1 a 0.8 μg g^{-1} for cocoa products, and do not provide maximum limits for unprocessed beans. In addition, there is an incorrect classification when tolerable limits on derived or processed products are applied to concentrations in raw cocoa beans (Pastor, 2017). Thus, a maximum limit of Cd should be set in dried beans or raw cocoa mass, using certain criteria on the basis of what is already established in the current EU regulation (Meter et al., 2019). In this context, the aim of this review is to detail the research carried out on the Cd cacao levels of the main producers in Latin America to analyze the application of the current EU regulation, explain the proposed limits on raw beans and the implications of the regulatory gap on the producer and on the substitution of illicit crops in the region.

2 Methodology

A search of the literature was conducted on SciELO, Web of Science and Scopus databases, focusing on cadmium in the main cocoa producing countries in Latin America, such as Peru, Colombia, Ecuador, Brazil, Bolivia, Honduras, Venezuela and the Dominican Republic. The search was carried out restricting the results with the keywords: Cadmium, cadmium in cocoa, cadmium in plants, toxicity of cadmium and cadmium in health.

The topic is mainly discussed in the following journals: Science of The Total Environment, Water Air Soil Pollution, Ecotoxicology and Environmental Safety, Agronomic Act and others, as primary sources and as secondary sources institutions such as the Food and Agriculture Organization of the United Nations (FAO), European Union (EU), Codex Alimentarius (CODEX), United States Environmental Protection Agency (USEPA) and Government Sectors of Peru: Ministry of Agriculture and Irrigation - MINAGRI and the Institute of Statistics and Informatics - INEI. Later, the search was extended to other journals through search engines such as Google Scholar, as well as congresses organized by the International Cocoa Organization (ICO). Researches conducted in the last 10 years were selected, excepting some papers that are cited very frequently in the rest of the publications discussed in this review.

3 Cd in Latin American cocoa

Before 2014 and between 2014 and 2019, adaptation period to the entry into force of the EU regulation and after the entry into force, researches have been carried out (Table 1) in the main Latin American producers at national, regional and experimental scales.

Table 1 shows the scientific reports published in indexed and arbitrated journals, and the countries with the most scientific reports are Ecuador and Peru; in addition, the highest average values reported are Peru, Costa Rica, and Venezuela. The classification of Cd levels was carried out according to the tolerable limits of EU Regulation No 488/2014, which sets a maximum tolerable limit of 0.8 μg g^{-1} for chocolates with cocoa solids higher than or equal to 50%. According to this criterion, 70.59% of reports correspond to high levels of cadmium and only 29.4% would be within the limits required by the EU.

The results shown (Table 1), regardless the determination method, were classified in some cases taking as a reference the EU Regulation, despite the fact that they are Cd levels in raw beans. In this sense, different concepts are shown with regard to the application of the EU Regulation:

1. **Authors that differentiate the application of EU regulations,** including Barraza et al. (2017) and Furcal and Torres (2020) explain that the European Food Safety Authority has not set a limit for Cd in the raw matter of chocolate, and that studies show that Cd concentrations in beans may reach levels higher than the ones established by the EU.

2. **Authors who differentiate but consider its application to be indistinct,** such as Lanza et al. (2016) state that the EU maximum limit could be equally applied to cocoa grains and that their Cd contents (1.62 μg g^{-1}) exceed the maximum value set out in the EU Regulation.

3. **Authors who do not differentiate the application of EU regulations,** including Gramlich et al. (2018), mention that Cd concentrations in beans (1.1 μg g^{-1}) exceeded the limit proposed by the EU. With this same criterion, Arévalo et al. (2017a) classifies Cd levels (1.13 μg g^{-1}) in cocoa beans grown in the Amazon regions, Piura and Tumbes (Northern Zone of Peru) as high, compared to the EU standard. Florida et al. (2018) classify its Cd levels (0.98 μg g^{-1}) as higher than that allowed by the EU. Also, Zug et al. (2019) refer the Cd in Peruvian cocoa as the highest in relation to the permitted limits, specially the CCN-51 in comparison to fine and flavor cocoa. Finally, Chávez et al. (2015) not only apply incorrectly the Regulation, but are also wrong when referring that Cd in grains above a critical level of 0.6 μg g^{-1} would cause concern in the consumption of chocolate, when the Regulation accepts up to 0.8 μg g^{-1}.

4 EU 488/2014 Regulation

The current EU regulation by the European Food Safety Authority (EFSA) was elaborated by the Technical Committee on Contaminants in the Food Chain (CONTAM). EFSA considered it necessary to change again the maximum levels for certain pollutants such as the Cd, set out in Regulation 1881/2006, incorporating new information and developments in the Codex Alimentarius (European Union-EU, 2014; Zug et al., 2019; Furcal and Torres, 2020).

The current EU regulation is based on three fundamental aspects:

1. **Food exposure;** CONTAM conducted tolerable weekly intake studies and determined the average food exposure of Cd in European countries of 2.5 μg/kg body weight (European Union-EU, 2014; Abt and Lauren, 2020).

2. **Per capita consumption;** high consumption of cocoa derivatives can raise cadmium levels in the body (Table 2); and in the case of the European community, the per capita consumption is three times the consumption of Latin American countries.

3. **ALARA Principle,** by its abbreviation "As Low As Reasonably Achievable" which means as low as possible (European Union-EU, 2014).

For EFSA, it is reasonable that the reduction in exposure of vulnerable consumers could be achieved by establishing a maximum content for cocoa derivatives. Regulation 488/2014 amending Regulation 1881/2006 (Table 3), which adds cocoa derivatives to the list of controlled products, was thus adopted on 12 May 2014 (European Union-EU, 2014; Gramlich et al., 2018; Kruszewski et al., 2018; Argüello et al., 2019; Barraza et al., 2019; Romero et al., 2019; Zug et al., 2019; Abt and Lauren, 2020).

This Regulation assigns a high value to chocolates with a total percentage of dry matter ≥ 50 % (Antolinez et al., 2020), and it establishes tolerable limits for Cd in four types of chocolate (final consumption); however, it uses arguments from Environmental Quality Standards (EQAs) and is inconsistent in setting similar values to very different food in origin and representativeness in the total food exposure of cadmium from consumers. They have values with excess and without sufficient scientific research, which can become obstacles to the productive process and technical barriers to trade, by confusing the tolerable limits to derived or processed products for the marketing of cocoa beans (Pastor, 2017).

Table 1. Cd in cocoa beans (*Theobroma cacao* L.) in Latin American Countries

References	Country	Cd Average (µg g-1)	Min. – Max	Determination Method	Reported Level according to Regulation No 488/2014
Furcal and Torres (2020)	Costa Rica	0.44 ± 0.64*	0.0 – 1.8	ICP OES	Nb
		2.25 ± 2.06***	0.0 – 8.7		Na
Argüello et al. (2019)	Ecuador	0.9 ± –	–	ICP MS	Na
Barraza et al. (2019)		1.26 ± 0.18	–	ICP-MS	Na
Barraza et al. (2017)		1.12 ± –	–	ICP-MS	Na
Chávez et al. (2015)		0.94 ± –	–	EAA	Na
Mite et al. (2010)		0.84 ± 0.32	0.32 – 1.80	EAA	Na
Romero et al. (2019)		0.75 ± –	–	ICP OES	Nb
Lanza et al. (2016)	Venezuela	1.62 ± –	0.95 – 2.09	ICP OES	Na
Oliveira et al. (2019)	Brazil	0.13 ± –	0.04 – 0.82	ICP OES	Nb
Gramlich et al. (2018)	Honduras	1.10 ± 0.2	–		Na
Arévalo et al. (2017a)	Peru	1.13 * ± –	–	ICP OES	Na
		0.45 ** ± –	–		Nb
		0.20 *** ± –	–		Nb
Florida et al. (2018)		0.98 ± 1.42	0.18 – 6.7	EAA	Na
Tantalean and Huauya (2017)		1.08 ± –	–	EAA	Na
Zug et al. (2019)		2.46 ± 0.75	0.2 – 12.56	GFAAS	Na
Results exceeding limits according to this criterion (%)					70.59

*North area, **Central area, ***South area of the corresponding country, Na is High level, Nb is Low level, EAA Atomic absorption spectrophotometer, ICP OES Optical emission spectrometry with inductive coupling, ICP-MS Plasma mass spectroscopy with inductive coupling, GFAAS Graphite furnace atomic absorption spectrometer, – not specified by the author.

5 Proposals for maximum limits in raw cocoa

The categorization of total cadmium levels in raw beans using Regulation 488/2014 is a mistake (Pastor, 2017; Meter et al., 2019).The above-mentioned EU standard (Table 3) is not applicable to raw whole grains, although, as explained above, most authors point out that their values exceed that set by the EU at a maximum of 0.8 $\mu g\ g^{-1}$; it is therefore tacitly understood that this limit is being used to classify their found levels. It should be noted that the vast majority of cocoa is exported from Peru and other countries of the region in the form of dry fermented grain (MINAGRI, 2019). Paradoxically, tolerable limits for chocolate are being used to judge and adjust the price of raw grain (Pastor, 2017). Therefore, some proposals that do not alter the criteria that originated the current Regulation and incorporate new criteria as a simple proportionality relationship are analyzed below (Meter et al., 2019).

a) Meter Proposal

One of the proposals for Cd levels in beans has been established by Meter et al. (2019), who applies a proportionality ratio to the limits set in the EU Regulation and calculates a maximum Cd limit value in raw dried beans, as the raw mass contains a similar quantity of Cd to that of the grains of origin.

This proposal assumes the following concepts:

- Regulation 488/2014 is for processed products.
- Mass Cd concentration is similar to cocoa liqueur (first derivative of processing).
- The % mass in chocolate is known
- The butter contains minimum levels of Cd (criterion not applied in its formula)
- Proportionality

The calculation formula is:

$$MLCM = \frac{MLEU \cdot P}{X\,\%P} \qquad (1)$$

Where:

$MLCM$ = Maximum Cd level in the cocoa mass (μg g^{-1})
$MLEU \cdot P$ = EU maximum level in final P product (μg g^{-1})
$X\,\%P$ = Mass percent in finished product P

Using dark chocolate with 70 % mass as an example (dry cocoa solids), and 0.8 μg g^{-1} of Cd set by the EU in the finished product, the maximum Cd level will be:

$$MLCM = \frac{0{,}8}{0{,}7} = 1{,}14\ \mu\text{g g}^{-1} \qquad (2)$$

It can be seen that the EU maximum levels are for finished products and not for raw materials. The equation estimates a maximum Cd level at the mass of 1.14 μg g^{-1} that will ensure that the final product remains below the level set by the EU.

Table 2. Per capita consumption of chocolate in Europe and Latin America

Continent	Country	Annual consumption per person (kg)	Annual bars (bar / 70g)	Bars/month
Europe	Switzerland	11.9	170	14
	Ireland	9.9	141	12
	United Kindom	9.5	136	11
	Austria	8.8	126	10
	Belgium	8.3	119	10
	Germani	8.2	117	10
Mean		9.43 ± 1.38	134.8 ± 19.61	11.17 ± 1.6
America	Uruguay	3.1	44	3.7
	Argentina	2.9	41	3.5
	Chile	2.2	31	2.6
	Brazil	1.7	24	2
	Mexico	0.7	10	0.8
	Peru	0.6	9	0.7
Mean		1.87 ± 1.07	26.5 ± 15	2.22 ± 1.3

Source: Jiménez (2015)

Table 3. Regulation 488/2014 for tolerable limits

Product	**Dry matter (%)**	**Maximum limit Permitted (μg g^{-1})***
Milk chocolate	<30	0.1
Milk chocolate	≥30	0.3
Chocolate	<50	0.3
Chocolate	≥50	0.8
Cocoa powder sold to the final consumer or as an ingredient in cocoa in sweetened powder sold to the final consumer (chocolate for drinking)		0.6

* They entered into force since January 2019
Source: European Union-EU (2014); Zug et al. (2019); Abt and Lauren (2020)

b) Author's proposal

The proposal is based on the calculations of Meter et al. (2019), the conclusions of Pastor and Gutierrez (2016) and Pastor (2017) and the general concepts of the average bromatological composition of chocolate and raw beans (Table 4); therefore, the proposal assumes the following concepts:

- Chemically, cocoa consists of 53.05 % cocoa fat or butter used for chocolate and the difference is cocoa cake used for sweetened cocoa powder for drinks (Morales et al., 2012), and it takes the 0.5 factor (% TA).
- Bitter chocolates have cocoa butter which normally do not exceed 50 % (Sánchez et al., 2016).
- In chocolates with 70 % of cocoa butter, the Cd content is reduced to less than half in chocolate compared to grain, so a 0.5 factor of (RP) is applied (Pastor and Gutierrez, 2016).
- The butter contains minimum Cd levels (Meter et al., 2019), which was not considered in its formula and it confirms what was stated by Pastor and Gutierrez (2016).
- Beans bioaccumulate cadmium in varying concentrations according to the cocoa genotype (Table 5), with a variation of approximately 30 %, a proportion that must be removed by applying a 0.7 factor (VG) to the partial results of cocoa butter and cake.

According to Table 5, the primary processing products for beans are approximately 50 % of cocoa cake used for chocolate sweetened powder for drinks and with an EU tolerable limit of 0.6 μg g^{-1} and cocoa butter in similar proportions 50 %, used for chocolates with a maximum level of 0.8 μg g^{-1} (Sánchez et al., 2016). The proposal suggests that butter (Formula 4) and cake (Formula 5) should be calculated separately, and in both cases genotype variation should be incorporated (Table 5), to reduce this partial result by 30 % by applying a 0.7 factor; finally, it must be averaged to obtain a maximum limit (Formula 3). Hence, the formula for the calculation is:

$$LCP = \frac{LCMC + LCTC}{2} \quad (3)$$

$$LCMC = \frac{FM}{RP} \times VG \quad (4)$$

$$LCTC = \frac{MCP}{\%TA} \times VG \quad (5)$$

Where:

LCP = Proposed Cd Limit
$LCMC$ = Cd Limit in cacao butter
$LCTC$ = Cd Limit in cacao cake
FM = Formula by Meter et al. (2019), gets a maximum limit of 1.14 μg g^{-1}
RP = Reduction of Cd reported by Pastor and Gutierrez (2016)
VG = Variability by genotype, 30 % was eliminated (applying a 0.7 factor to the Cd content in cocoa butter and cake)

MCP = maximum limit for cocoa powder according to EU (0.6 μg g^{-1})
$\%TA$ = % of cake in raw beans 50% (0.5 factor)

Dark chocolate with 70% cocoa mass (0.8 μg g^{-1}), is used and calculated in the formula of Meter et al. (2019):

$$LCMC = \frac{1{,}14}{0{,}5} \times 0{,}7 = 1{,}6\,\mu\text{g g}^{-1} \quad (6)$$

$$LCTC = \frac{0{,}6}{0{,}5} \times 0{,}7 = 0{,}84\,\mu\text{g g}^{-1} \quad (7)$$

$$LCP = \frac{1{,}6 + 0{,}84}{2} = 1{,}22\,\mu\text{g g}^{-1} \quad (8)$$

The proposed equation estimates a maximum Cd level in raw beans of 1.22 μg g^{-1} (Formula 8) ensuring that the processed end product is below the limit set by the EU (0.8 μg g^{-1}). Therefore, in accordance with the proposal of Meter et al. (2019) the categorization of scientific reports (Table 6) varies reasonably.

Table 6 shows that the author's proposal is a little different from Meter et al. (2019) but is similar to the one established in Indonesia, which sets maximum limits of 1 μg g^{-1} for cocoa mass. In addition, the percentage of results that would exceed the limits are similar when comparing available reports, however, in comparison with Regulation 488/2014, the levels categorized as high fall from 70.59 to 23.53%, which is more reasonable and consistent. In addition, concepts of metal bioavailability are not yet being incorporated in this analysis since research reveals a great dynamic in concentration and availability in soils (Prieto et al., 2009; Kabata, 2010; Sánchez et al., 2011; Bravo et al., 2014; Gramlich et al., 2017; Díaz et al., 2018; Gramlich et al., 2018; Zug et al., 2019), which may contribute or limit the mobilization and uptake of cadmium by cocoa. Therefore, appropriate actions need to be taken to fill the regulatory gap in health protection and the millions of cocoa producers in Latin American and the world.

Table 4. Physical-chemical characterization in cocoa beans (*Theobroma cacao* L.)

Parameters	Origin of the crop	Average content
Physical		
Husk %		11 – 12
Grain thickness (g)		1.05 – 1.2
Humidity (%)		7 – 8
Chemicals*		
Fat (%)	Mountain Cocoa	55
	Tropical Wet Forest	54
	Dry inter-Andean valleys	54
Protein (%)	Mountain Cocoa	14
	Tropical Wet Forest	13
	Dry inter-Andean valleys	13
pH	Mountain Cocoa	5.07
	Tropical Wet Forest	4.97
	Dry inter-Andean valleys	5.54
Fiber (%)	Mountain Cocoa	3
	Tropical Wet Forest	3
	Dry inter-Andean valleys	3
Calories (kcal/100 g)	Mountain Cocoa	629
	Tropical Wet Forest	629
	Dry inter-Andean valleys	625

* Calculated from the study of 15 cocoa genotypes
Source: Ministry of Agriculture and Rural Development- MINAGRICULTURA (2004)

Table 5. Cd levels in different cocoa genotypes (*Theobroma cacao* L.)

Reference	Genotype	Cd beans (μg g^{-1})
Barraza et al. (2017)	CCN-51	1.21
	National Ecuatorian	0.89
Lanza et al. (2016)	HNF	2.09
	PNF	1.9
	PF	1.82
	PFC	1.76
	HF	1.74
	PFM	1.57
	HFC	1.1
	HFM	0.95
Florida et al. (2018)	CCN-51	0.98
Average concentration		$1.45 + 0.43$
CV (%)		29.65

CV Variation coefficient

Table 6. Comparison of Cadmium classification levels

References	Country	Cd average (μg g^{-1})	Level according to Regulation No 488/2014	Level according to Meter et al. (2019)[a]	Level proposed by the Author[b]
Furcal and Torres (2020)	Costa Rica	0.44*	Nb	Nb	Nb
		2.25***	Na	Na	Na
Argüello et al. (2019)	Ecuador	0.90	Na	Nb	Nb
Barraza et al. (2019)		1.26	Na	Na	Na
Barraza et al. (2017)		1.12	Na	Nb	Nb
Chávez et al. (2015)		0.94	Na	Nb	Nb
Mite et al. (2010)		0.84	Na	Nb	Nb
Romero et al. (2019)		0.75	Nb	Nb	Nb
Lanza et al. (2016)	Venezuela	1.62	Na	Na	Na
Oliveira et al. (2019)	Brazil	0.13	Nb	Nb	Nb
Gramlich et al. (2018)	Honduras	1.10	Na	Nb	Nb
Arévalo et al. (2017a)	Peru	1.13*	Na	Nb	Nb
		0.45**	Nb	Nb	Nb
		0.20***	Nb	Nb	Nb
Florida et al. (2018)		0.98	Na	Nb	Nb
Tantalean and Huauya (2017)		1.08	Na	Nb	Nb
Zug et al. (2019)		2.46	Na	Na	Na
Results that exceed limits based on criteria (%)			70.59	23.53	23.53

[a]Max: 1.14 μg g^{-1}, [b]Max: 1.22 μg g^{-1}, Na: high level, Nb: low level

6 Implications of the regulatory gap in the producer and the substitution of illicit crops

In the last decade, cocoa was the second alternative crop to substitute coca production in Peru (INEI, 2017). Cocoa is the most successful cultivation to substitute illegal coca cultivation, and thousands of small family farmers have been rescued from coca cultivation thanks to the cultivation of cocoa (Pastor and Gutierrez, 2016). In Peru, it is cultivated in 16 regions, 57 provinces and 259 districts (MINAGRI, 2019) and similarly Colombia, Bolivia and Ecuador show sustained growth in cocoa production and a reduction in illicit crops (Celis et al., 2020).

In general, the sustainability of cocoa production is threatened in these countries of the region (Argüello et al., 2019; Abt and Lauren, 2020) and some influential aspects can be identified, including:

1. **Regulation 488/2014;** the EU's regulatory imposition with high limits on cocoa derivatives, whereas more than 60% of Latin American production volume is exported to the EU (MINAGRI, 2016; Meter et al., 2019).

2. **Forced eradication;** countries such as Peru, through the National Commission for Development and Life without Drugs - DEVIDA and the United States Agency for International Development - USAID, carry out forced eradication, eliminating the illicit cultivation of coca in its entirety, causing greater socio-economic imbalances (Chocce, 2015).

3. **Inefficiency of public investment;** caused by individual and institutional factors, alternative projects (cocoa) to illicit coca cultivation and rural development projects do not generate socio-economic improvements expected by the producer; this was observed in Peru (Alvarado et al., 2020) and Ecuador (Viteri, 2013) and is very likely to occur in other producing countries of the region.

The critical aspect is that both forced eradication and inefficiency in public investment are problems our region has faced for decades, and the emergence and enforcement of Regulation 488/2014 plays a trigger role to the previous ones, which is unfavorable to the producer and may discourage families who have replaced coca cultivation with cocoa (Pastor, 2017; Abt and Lauren, 2020). Therefore, the tolerable levels of Cd in processed cocoa set by the EU to classify the levels in raw beans represent an error (Pastor, 2017; Meter et al., 2019) and it requires agencies such as Codex and the EU to consider evaluating these levels in order to recalculate and record tolerable limits of Cd in raw cocoa beans to avoid oversizing the problem that represents the presence of this metal in cocoa in Latin America.

In order to contextualize the implications, cultivation has spread commercially in 23 countries in Latin American and The Caribbean until 2016, with a volume of more than 675 000 t and about 1 700 000 ha, where Brazil, Ecuador, Dominican Republic, Peru, Colombia and Mexico account for more than 90% of production (Arvelo et al., 2017), and in 2018 it accounts for more than 18% of the world's imports of cocoa beans (836 000 t in the period 2017 - 2018) and in cases such as Peru, 54.3% of the total exported in 2018 corresponds to raw cocoa beans (López et al., 2020). In addition, countries such as Ecuador, Peru and Colombia have shown an average growth of more than 9% per year in the last decade (MINAGRI, 2016; Meter et al., 2019), and in the case of Ecuador, it rose from 3 to 6% of the world's production, reaching fourth among the producing countries, surpassing Brazil (Cunha, 2018).

Finally, the lack of maximum limits on raw cocoa is considered as a threat to the sustainability of cocoa production (Argüello et al., 2019; Abt and Lauren, 2020) and has caused some confusion and speculation, including: a) confusion in the scientific community in classifying raw cocoa, applying the limits of the European standard for processed cocoa; b) concern to the cocoa sector throughout Latin America and c) market distortions at the time of negotiations since the producer is hardly in a position to counter and buyers prefer low Cd content to ensure its use in any recipe, with the consequent negative effect on the price for the grain (Pastor, 2017; Meter et al., 2019).

7 Conclusions

Scientific reports reveal important advances of Cd in cacao beans. In the region, the highest average values reported are Peru, Costa Rica, Venezuela and Ecuador. In addition, European Union Regulation No 488/2014 establishes maximum limits for processed cocoa, and is being used as a basis for classifying the cadmium concentration in raw beans, generating confusion in the scientific community and concern to the cocoa sector.

There are calculation proposals to determine a reasonable and scientific limit, incorporating criteria of proportionality, genetic variability and bromatological aspects of cocoa, on the basis of the limits established in the European Union regulation. The calculation proposals determine a maximum cadmium limit in raw beans of 1.14 (Meter) y 1.22 $\mu g\ g^{-1}$ (author), by reducing the levels categorized as high (according to the EU), from 70.59 % to only 23.53 %, a reasonable and consistent figure that will contribute to maintaining the quality of the product for the final consumer, avoid market distortions by protecting the producer and the substitution efforts of illegal coca cultivation in Peru, Colombia, Bolivia and other countries of the region.

References

Abt, E. and Lauren, P. (2020). Perspective on cadmium and lead in cocoa and chocolate. *Journal of Agricultural and Food Chemistry*, 68(46):13008–13015. Online: https://bit.ly/3xIThQf.

Alvarado, Y., Ferrer, R., and Florida, N. (2020). Evaluación ex post al proyecto productivo alternativo de bella bajo monzón. *Ciencia Unemi*, 13(34):47–58. Online: https://bit.ly/3ubF2kM.

Antoine, J., Leslie, A., Hoo, F., and Grant, N. (2017). Assessment of the potential health risks associated with the aluminium, arsenic, cadmium and lead content in selected fruits and vegetables grown in jamaica. *Toxicology Reports*, 4:181–187. Online: https://bit.ly/3xIuPhS.

Antolinez, E., Almanza, P., Baraona, A., Polanco, E., and Serrano, P. (2020). Estado actual de la cacaocultura: una revisión de sus principales limitantes. *Ciencia y Agricultura*, 17(2):1–11. Online: https://bit.ly/3eLlxch.

Arévalo, E., Arévalo, C., Baligar, C., and He, L. (2017a). Heavy metal accumulation in leaves and beans of cacao (theobroma cacao l.) in major cacao growing regions in peru. *Science of The Total Environment*, 605-606:792–800. Online: https://bit.ly/33fbPt3.

Arévalo, H., Arévalo, G., Farfán, P., Baligar, V., and He, Z. (2017b). Metales pesados en suelos, hojas y granos de zonas cacaoteras del perú. In *International Symposium on Cocoa Research (ISCR) 2017*, pages 1–6. Online: https://bit.ly/33AeRbJ.

Argüello, D., Chavez, E., Lauryssen, F., Vanderschueren, R., Smolders, ., and Montalvo, D. (2019). Soil properties and agronomic factors affecting cadmium concentrations in cacao beans: A nationwide survey in ecuador. *Science of The Total Environment*, 649:120–127. Online: https://bit.ly/2Re36Vs.

Arvelo, S., González, L., Delgado, L., Maroto, A., and Montoya, R. (2017). *Estado actual sobre la producción, el comercio y cultivo del cacao en américa*. IICA-bba. Online: https://bit.ly/3ecahXm.

Barraza, F., Moore, R., Rehkämper, M., Schreck, E., Lefeuvre, G., Kreissig, K., Coles, B., and Maurice, L. (2019). Cadmium isotope fractionation in the soil cacao systems of ecuador: a pilot field study. *The Royal Society of Chemistry*, 9(58):34011–34022. Online: https://rsc.li/3vBUS8x.

Barraza, F., Schreck, E., Lévêque, T., Uzu, G., López, F., Ruales, J., Prunier, J., Marquet, A., and Maurice, L. (2017). Cadmium bioaccumulation and gastric bioaccessibility in cacao: A field study in areas impacted by oil activities in ecuador. *Environmental Pollution*, 229:950–963. Online: https://bit.ly/3tDWPA2.

Bravo, I., Arboleda, C., and Martin, F. (2014). Efecto de la calidad de la materia orgánica asociada con el uso y manejo de suelos en la retención de cadmio en sistemas altoandinos de colombia. *Acta Agronómica*, 63(2):164–174. Online: https://bit.ly/3ePtXPD.

Casteblanco, J. (2018). Heavy metals remediation with potential application in cocoa cultivation. *La Granja*, 27(1):21–35. Online: https://bit.ly/33ffMhn.

Celis, R., Florida, N., and Rengifo, A. (2020). Impacto sobre indicadores físicos y químicos del suelo con manejo convencional de coca y cacao. *CIENCIA UNEMI*, 13(33):1–9. Online: https://bit.ly/3vyOZJe.

Chávez, E., He, Z., Stoffella, P., Mylavarapu, R., Li, Y., Moyano, B., and Baligar, V. (2015). Concentration of cadmium in cacao beans and its relationship with soil cadmium in southern ecuador. *Science of The Total Environment*, 533:205–214. Online: https://bit.ly/3eMSDIF.

Chocce, D. (2015). Funciones de la hoja de coca durante el proceso de violencia política en el centro poblado de san josé de villa vista, distrito de chungui, provincia la mar, región ayacucho. tesis de grado, Facultad de Antropología-Universidad Nacional del Centro del Perú. Online: https://bit.ly/3taqe4j.

Cunha, L. (2018). *Estudo de competitividade do cacau e chocolate no Brasil: desafios na produção e comércio global*. Ministério do Desenvolvimento, Indústria e Comércio Exterior-MDIC. Brasil. Online: https://bit.ly/3gSHicM.

Díaz, U., Mendoza, H., Bravo, B., and Dominguez, V. (2018). Determinación de cadmio y plomo en almendras de cacao (theobroma cacao), proveniente de fincas de productores orgánicos del cantón vinces. *Espirales*, 12(15):77–92. Online: https://bit.ly/3ebPZgv.

Engbersen, N., Gramlich, A., Lopez, M., Schwarz, G., Hattendorf, B., Gutierrez, O., and Schulin, R. (2019). Cadmium accumulation and allocation in different cacao cultivars. *Science of The Total Environment*, 678(678):660–670. Online: https://bit.ly/3edGmOc.

European Union-EU (2014). Regulation no. 488/2014. they modify ec regulation no 1881/2006 regarding the maximum content of cadmium in food products. Technical report, Official Journal of the European Union. Online: https://bit.ly/3uvfOxT.

Florida, N., Paucar, H., Jacobo, S., Escobar, F., and Torres, J. (2019). Efecto de compost y npk sobre los niveles de microorganismos y cadmio en suelo y almendra de cacao. *Journal of High Andean Research*, 21(4):264–273. Online: https://bit.ly/3nLIHDm.

Florida, R., Claudio, M., and Gómez, B. (2018). El ph y la absorción de cadmio en almendras de cacao orgánico (theobroma cacao l.) en leoncio prado, huánuco, perú. *Folia Amazónica*, 27(1):1–8. Online: https://bit.ly/3nNNxjx.

Furcal, P. and Torres, J. (2020). Determinación de concentraciones de cadmio en plantaciones de theobroma cacao l. en costa rica. *Tecnología en Marcha*, 33(1):122–137. Online: https://bit.ly/3eXdysN.

Gramlich, A., Tandy, S., Andres, C., Paniagua, J., Armengot, L., Schneider, M., and Schulin, R. (2017). Cadmium uptake by cocoa trees in agroforestry and monoculture systems under conventional and organic management. *Science of The Total Environment*, 580:677–686. Online: https://bit.ly/3nXXJGp.

Gramlich, A., Tandy, S., Gauggel, C., López, M., Perla, D., Gonzalez, V., and Schulin, R. (2018). Soil cadmium uptake by cocoa in honduras. *Science of The Total Environment*, 612(580):370–378. Online: https://bit.ly/2SsNYEj.

Gunnar, N. (2013). *Encyclopaedia of health and safety at work*, volume 63, chapter Metals: chemical properties and toxicity. Ministerio de Trabajo y Asuntos Sociales de España. Online: https://bit.ly/3b0UCrP.

He, S., He, Z., Yang, X., Stoffella, P., and Baligar, V. (2015). Soil biogeochemistry, plant physiology, and phytoremediation of cadmium-contaminated soils. *Advances in Agronomy*, 134:135–225. Online: https://bit.ly/3gZEIll.

Hernández, C., Arévalo, G., Farfán, P., Baligar, V., and He, Z. (2017). Metales pesados en suelos, hojas y granos de zonas cacaoteras del perú. In *International Symposium on Cocoa Research (ISCR) 2017*, pages 13–17. Online: https://bit.ly/3ok4tP3.

INEI (2017). *Encuesta nacional Agropecuaria 2017 - Principales resultados pequeñas, medianas y grandes unidades agropecuarias*. Instituto Nacional de Estadística e Informática. Online: https://bit.ly/3xZloe9.

Jiménez, C. (2015). Global legal status of cadmium in cacao (theobroma cacao): a fantasy or a reality. *Producción+ Limpia*, 10(1):89–104. Online: https://bit.ly/2QTDltM.

Kabata, A. (2010). *Trace elements in soils and plants*. Taylor Francis Group. Online: https://bit.ly/3uH0y0L.

Kruszewski, B., Wiesław, O., and Kowalska, J. (2018). Nickel, cadmium and lead levels in raw cocoa and processed chocolate mass materials from three different manufacturers. *Journal of Food Composition and Analysis*, 66:127–135. Online: https://bit.ly/3ejjDAE.

Lanza, J., Churión, P., Liendo, N., and López, V. (2016). Evaluación del contenido de metales pesados en cacao (teobroma cacao l.) de santa bárbara del zulia, venezuela. *Saber*, 28(1):106–115. Online: https://bit.ly/3h9OsJD.

López, Y., Cunias, M., and Carrasco, Y. (2020). El cacao peruano y su impacto en la economía nacional. *Revista Universidad y Sociedad*, 12(3):344–352. Online: https://bit.ly/3tqF9rj.

Meter, A., Atkinson, R., and Laliberte, B. (2019). *admio en el cacao de América Latina y el Caribe. Análisis de la investigación y soluciones potenciales para la mitigación*. Bioversity International, Roma. 84pp. Online: https://bit.ly/3baFnwA.

MINAGRI (2016). *Estudio del cacao en el Perú y en el mundo; Situación Actual y Perspectivas en el Mercado Nacional e Internacional al 2015*. MINAGRI-DGPA-DEEIA. Online: https://bit.ly/3bb7DyY.

MINAGRI (2019). Ministerio de agricultura y riego-dirección general de políticas agrarias; dirección de estudios económicos e información agraria. observatorio del cacao. Online: https://bit.ly/33sWhCl.

MINAGRICULTURA (2004). Ministerio de agricultura y desarrollo rural. el beneficio y características fisicoquímicas del cacao (theobroma cacao l.). Technical report, MINAGRICULTURA-FEDECACAO Colombia. Online: https://bit.ly/3etUHX7.

Mite, F., Carrillo, M., and Durango, W. (2010). Avances del monitoreo de presencia de cadmio en almendras de cacao, suelos y aguas en ecuador. In *2010 Actas XII Congreso Ecuatoriano de la Ciencia del Suelo*, pages 1–21. Online: https://bit.ly/3uwZk8l.

Morales, J., García, A., and Méndez, E. (2012). ¿qué sabe usted acerca de... cacao? *Revista Mexicana de Ciencias Farmacéuticas*, 43(4):79–81. Online: https://bit.ly/3vHJBDI.

Oliveira, A., Milani, R., Melo, L., Efraim, P., Morgano, M., and Tfouni, S. (2019). Cádmio e chumbo em amêndoa de cacau do brasil. In *2019 Anais do 13º Simpósio Latino Americano de Ciência de Alimentos (SLACA)*, pages 1–2. Online: https://bit.ly/3nXtoaM.

Pastor, S. (2017). Niveles de cadmio en el chocolate: Nm y eca, sí; otc, no. In *International Symposium on Cocoa Research (ISCR) 2017*, pages 1–5.

Pastor, S. and Gutierrez, M. (2016). Sobre los fundamentos de una norma que regula el cadmio en los alimentos y presume del mismo en el suelo. In *Memorias del XXI Congreso Latinoamericano de la Ciencia del Suelo*, pages 24–28. Online: https://bit.ly/3bbe4SE.

Pérez, G. and Azcona, C. (2012). The effects of cadmium on health. *Magazine of Specialties Médico-Quirúrgicas*, 17(3):199–205. Online: https://bit.ly/3bbiSHA.

Prieto, J., González, C., Román, A., and Prieto, F. (2009). Contaminación y fitotoxicidad en plantas por metales pesados provenientes de suelos y agua. *Tropical and subtropical Agroecosystems*, 10(1):29–44. Online: https://bit.ly/3o4Y7CP.

Raju, M., Dhatri, K., García, C., Chakraborty, S., Venkateswarlu, K., and Megharaj, M. (2020). Cocoa-laden cadmium threatens human health and cacao economy: A critical view. *Science of The Total Environment*, 720(10):137645. Online: https://bit.ly/3trMbfl.

Reyes, Y., Vergara, I., Torres, O., Díaz, M., and González, E. (2016). Contaminación por metales pesados: Implicaciones en salud, ambiente y seguridad alimentaria. *Ingeniería Investigación y Desarrollo*, 16(2):66–77. Online: https://bit.ly/3uEHhgD.

Romero, D., Yánez, G., Simbaña, K., and Navarrete, H. (2019). Content and the relationship between cadmium, nickel, and lead concentrations in ecuadorian cocoa beans from nine provinces. *Food control*, 106(106750):1–8. Online: https://bit.ly/3fdW9fd.

Sánchez, Á., Naranjo, J., Córdova, V., Ávalos, D., and Zaldívar, J. (2016). Caracterización bromatológica de los productos derivados de cacao (theobroma cacao l.) en la chontalpa, tabasco, méxico. *Revista mexicana de ciencias agrícolas*, 7(1):2817–2830. Online: https://bit.ly/3eXHCnY.

Sánchez, N., Rivero, C., and Martínez, Y. (2011). Cadmio disponible en dos suelos de venezuela: efecto del fósforo. *Revista Ingeniería UC*, 18(2):7–14. Online: https://bit.ly/3vHNYyC.

Tantalean, E. and Huauya, M. (2017). Distribución del contenido de cadmio en los diferentes órganos del cacao ccn-51 en suelo aluvial y residual en las localidades de jacintillo y ramal de aspuzana. *Revista de Investigación de Agroproducción Sustentable*, 1(2):69–78. Online: https://bit.ly/3hb07rN.

Viteri, O. (2013). *Evaluación de la Sostenibilidad de los cultivos café y cacao en las provincias Orellana y Sucumbíos-Ecuador*. Tesis doctoral, Universidad Autónoma de Barcelona. Online: https://bit.ly/3nZY3o4.

Zug, K., Huamaní, H., Meyberg, F., Cierjacks, J., and Cierjacks, A. (2019). Cadmium accumulation in peruvian cacao (theobroma cacao l.) and opportunities for mitigation. *Water, Air, Soil Pollution*, 230(3):72–80. Online: https://bit.ly/3to8x1q.

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IN VITRO INDUCTION OF CALLUS FROM FOLIAR EXPLANTS IN ROCOTO (*CAPSICUM PUBESCENS RUIZ & PAV.*)

INDUCCIÓN *IN VITRO* DE CALLOS A PARTIR DE EXPLANTES FOLIARES EN ROCOTO (*CAPSICUM PUBESCENS RUIZ & PAV.*)

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Abstract

Rocoto (*Capsicum pubescens* Ruiz & Pav.) is a native plant of Peru, used in the national gastronomy with great nutritional value; it has pharmaceutical and medicinal properties. The crop is susceptible to diseases caused by phytopathogens, which are spread by seeds of infected cultivars or seedlings. Through the use of biotechnological tools such as *in vitro* plant tissue culture, it is possible to obtain plants free of pathogens, of good quality and great agronomic potential. Therefore, the present work aimed to develop a methodology for the *in vitro* induction of callus from hot pepper leaves. *In vitro* germinated rocoto seedlings were used, from which the first true leaves were selected, which were sectioned into 1 cm explants and placed in different MS culture media added with 2,4-dichlorophenoxyacetic acid (2,4-D). The induction response to calllogenesis was evaluated in five treatments with different concentrations of 2,4-D (0, 0.25, 0.5, 0.75 and 1 mg l^{-1}), under conditions of 25 °C in the dark for 35 days. The culture media added with 0.75 and 1 mg l^{-1} of 2.4-D allowed to obtain 100% induction of calluses in the hot pepper leaves with 81% and 86%, respectively of grade 3 callus formation. This study, pioneer for the species, is good for the potential use of breeding programs.

Keywords: Biotechnology, plant tissue, callogenesis, leaves, germination.

Resumen

El rocoto (*Capsicum pubescens* Ruiz & Pav.) es una planta oriunda de Perú, empleada en la gastronomía nacional, tiene un gran valor nutricional, y presenta propiedades farmacéuticas y medicinales. El cultivo es susceptible a enfermedades causada por fitopatógenos, los cuales son diseminados por semillas de cultivares o almácigos infectados. Mediante el uso de herramientas biotecnológicas como el cultivo de tejidos vegetales *in vitro* se puede obtener plantas libres de patógenos, de buena calidad y de gran potencial agronómico. Por lo tanto, el presente trabajo se planteó como objetivo desarrollar una metodología para la inducción *in vitro* de callos a partir de hojas en rocoto. Se emplearon plántulas de rocoto germinadas *in vitro*, de las cuales se seleccionaron las primeras hojas verdaderas que fueron seccionadas en explantes de 1 cm y colocadas en diferentes medios de cultivo MS adicionadas con ácido 2,4-diclorofenoxiacético (2,4-D). Se evaluó la respuesta de inducción a callogénesis en cinco tratamientos con diferentes concentraciones de 2,4-D (0; 0,25; 0,5; 0,75 y 1 mg l^{-1}), en condiciones de 25 °C en oscuridad durante 35 días. Los medios de cultivo adicionados con 0,75 y 1 mg l^{-1} de 2,4-D permitieron obtener 100 % de inducción de callos en las hojas de rocoto con 81 % y 86 % respectivamente de formación de callos de grado 3. Este estudio, pionero para la especie, abre expectativas en programas de mejoramiento para su potencial uso.

Palabras clave: Biotecnología, tejido vegetal, callogénesis, hojas, germinación.

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1 Introduction

Rocoto pepper (*Capsicum pubescens* Ruiz & Pav.) is a herbaceous plant with a perennial life cycle belonging to the *Solanaceae* family. It is originary from the Andean region of Peru, but it is also found in its wild form in the mountains and high jungle. This species differs from the other species belonging to the *Capsicum* genus by presenting purple flowers and by its black seeds. The fruit can vary in shape, size and color, but it is characterized by being spicy and for this reason it is very used in the Peruvian gastronomy. In addition, rocoto pepper presents pharmaceutical and medicinal properties related to capsaicin (Caballero et al., 2017).

Two varieties of rocoto have been defined in Peru, forest rocoto (*rocoto de monte*) and orchard rocoto (*rocoto de huerta or serrano*). It is known as forest rocoto because it is cropped in the central forest; it has a larger fruit size, so there is a greater demand of this variety for the preparation of the filled rocoto. The other variety is orchard rocoto and it is cropped in all the areas of the country, mainly in the Andean valleys. The fruit of this variety is smaller and it is very spicy, reason for which it is used for sauces (Valdez, 2017).

The national production of rocoto has increased at an annual rate of 5% mainly because of the great gastronomic demand developed in the country; for this reason it is currently considered a product of national importance (Sardón, 2015). However, this crop is sensitive to wilt, root decay and other diseases caused by *Fusarium oxysporum, Phytoptora capsici, Risotonia solanacearum* among other phytopathogens. It is also sensitive to damage caused by viruses that can provoke yellowing in the nerves, deformations in leaves and fruits, enanism, lack of vigor and fall of the leaves. These diseases are normally spread through seeds from infected cultivars or seedbeds, because seeds from previous crops are normally used in new crops; and some viruses are spread with the contact among plants (Lucana, 2012; Hernández et al., 2019b).

It is important to strengthen the value chain of rocoto, and the idea is to obtain qualified and certified seeds or pathogen-free seedlings in order to maintain more uniform crops with higher quality and production. Biotechnology tools are considered as alternatives for the production of aseptic plant material with *in vitro* plant tissue culture techniques (Robledo and Carrillo, 2004; Sanatombi and Sharma, 2007; Orlinska and Nowaczyk, 2015). These techniques allow the proliferation of cells from an explant (plant fragment that can be meristems, axillary buds, leaves, roots, anthers and even microspores) in a culture medium equipped with nutrients, vitamins, and in some cases with hormones (Levitus et al., 2010; Vélez et al., 2010; Venkataiah et al., 2016). Under appropriate conditions, these explants will induce the formation of calluses, which are amorphous or disorganized masses of undifferentiated cells. The importance of the callus lies in its irregular growth functionality with the potential to form organs or embryos under appropriate conditions (Alayón et al., 2006; Pérez et al., 2009; Terra et al., 2009; Smith, 2012; Rashmi and Trivedi, 2014).

The potential of calluses as a pathway for organogenesis and indirect embryogenesis is an alternative for breeding programs in rocoto, because these methods in some species or genotypes when introduced *in vitro* culture media with different concentrations of phyto-hormones or combinations may induce somaclonal variation, allowing new characteristics to be obtained or the elimination of some unwanted trait (Sala and Labra, 2003; Rodríguez et al., 2014). But without these somaclonal variations, promising genotypes of good performance and good quality can be multiplied, as is being developed in the *in vitro* cultivation of plant tissues in different species of the genus *Capsicum* (Marín, 2012; Gómez, 2016; Gutierrez-Rosati and Vega, 2017; Izquierdo et al., 2017).

Therefore, the aim of this research is to develop a methodology for inducing calluses *in vitro* from rocoto leaf segments.

2 Materials and methods

This research was carried out at the facilities of the Plant Biotechnology Laboratory of the Professional School of Biology with the specialization on Biotechnology, located at the National University José Faustino Sánchez Carrión, Huacho, Lima, Peru.

2.1 Disinfection of the vegetal material

Rocoto seeds obtained from mature fruits present in the laboratory were used. The seeds were washed with water and commercial detergent for 5 minutes, and then the disinfection process was conducted in laminar flow chamber using the protocol established by Hernández et al. (2019a). The seeds were first immersed in 70 % of ethanol for 1 minute, then were immersed in a 2 % sodium hypochlorite solution for 15 minutes in constant agitation. After that time, three rinses were made with sterile distiled water, then seeds were placed on filter paper and three seeds were placed per test tube using MS culture medium (Murashige and Skoog, 1962).

All treatments were kept in the growth chamber (Plant Growth Chamber, LGC-5201 G, LabTech) in total darkness conditions at 25 °C, with relative humidity of 75 ± 2%. When germination began, they were switched to a photoperiod of 16 hours of light and 8 hours of darkness.

MS culture medium consisted of salts described by Murashige and Skoog (1962), with myoinositol (100 mg l^{-1}), nicotinic acid (0.5 mg l^{-1}), pyridoxine HCL (0.5 mg l^{-1}), thiamine HCL (0.1 mg l^{-1}), glycine (2 mg l^{-1}) and sucrose (30 g l^{-1}). Before adding agar agar (7 g l^{-1}) the pH was adjusted to 5.7 ± 0.1 using the Lab 850 potentiometer (SI Analytics). Subsequently, autoclave (BKM-Z18N, Biobase) was sterilized at 1.2 Bar of pressure and 121°C for 20 minutes.

2.2 Induction of calluses

The first two green leaves were selected from the seedlings germinated *in vitro*; these were segmented into 1-cm explants and five segments were introduced by MS culture with myoinositol (100 mg l^{-1}), nicotinic acid (0.5 mg l^{-1}), pyridoxine HCL (0.5 mg l^{-1}), thiamine HCL (0.1 mg l^{-1}), glycine (2 mg l^{-1}), sucrose (30 g l^{-1}) and auxin 2.4-D at different concentrations (Table 1). Then pH was adjusted to 5.7 ± 0.1 and agar (7 g l^{-1}) was added. It was then autoclaved at 1.2 Bar pressure and 121°C for 20 minutes.

All treatments were kept in the growth chamber (Plant Growth Chamber, LGC-5201 G, LabTech) in total darkness conditions at 25°C and with relative humidity of 75 ± 2 % for 35 days, with observations every seven days to differentiate the induction progress.

Table 1. Treatments for inducing calluses in rocoto leaves.

Treatment	2.4-D (mg l^{-1})
T1	0
T2	0.25
T3	0.5
T4	0.75
T5	1

2.4-D = Dichlorophenoxyacetic acid 2.4

2.3 Experimental design and statistical analysis

It was a completely randomized design (CRD) with five treatments, using 15 replications per treatment, and the experimental unit was made up of each segment of rocoto leaf. The percentage of callus induction in rocoto leaves and the callus grade on the Santana scale Santana (1982) were evaluated (Table 2). The data obtained were submitted to Analysis of Variance (ANOVA) and mean comparison was made with Tukey test ($p \leq 0.05$), using the statistical package of the R program (version 4.0.3 for Windows).

3 Results

The methodology used for the disinfection of rocoto seeds allowed to obtain 100 % of contamination-free seeds in the culture media, permitting the germination by bacteria or fungi to compete with the growing seedlings.

The induction of calluses from foliar explants in rocoto was observed from the seventh day in the treatments with 0.75 and 1 mg l^{-1} of 2.4-D (T4 and T5, respectively) forming grade 1 calluses. The treatments with 0.25 and 0.5 mg l^{-1} of 2.4-D showed the formation of calluses in rocoto leaves during the second week in the induction medium. After 35 days, MS culture medium with 0.75 and 1 mg l^{-1} of 2.4-D presented the highest percentages of callus formation with 100 % callus induction in rocoto leaves (Figure 1), showing significant differences with the other treatments (Figure 2).

Table 2. Description of the scale used by Santana (1982)

Grade	Callus induction	Observation
0	None formation of callus	-
1	Slight formation of callus	Slight enhancement in the edge of the explant
2	Formation of callus	Proliferation of cells in the edge of the explant, without creating a mass
3	Significant formation of callus	Formation of a callus mass

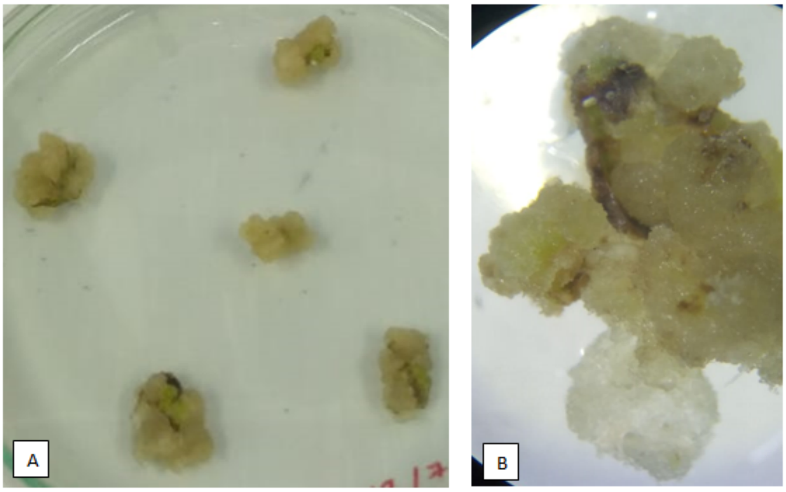

Figure 1. A. Calluses at 35 days formed from rocoto leaves in basal medium MS with 0.75 mg l^{-1} of 2.4-D. B. Callus induced at 35 days with treatment 1 mg l^{-1} of 2.4-D with yellowish coloring, translucid zones and friable consistency.

The treatments with higher percentages of grade 3 calluses were 0.75 and 1 mg l^{-1} culture medium of 2.4-D with 81 % and 86 %, respectively; however, there were no significant differences between the two treatments (Table 3). Also treatment 0.5 mg l^{-1} of 2.4-D with 57 %, while treatment 0.25 mg l^{-1} of 2.4-D showed a higher percentage of grade 2 calluses.

The morphological characteristics of calluses were: light yellow coloring and bleaching or translucid zones in some explants, and friable consistency of the callus. Calluses began their formation at the cutting sites (edges) of the explants until completely covering the surface of the explants in the T3 and T4 treatments. Hence, it can be indicated that rocoto has good response to callus induction, rapid formation and growth (Figure 3).

Table 3. Percentage of the formation degree of calluses in rocoto leaves.

Treatment	Callus formation by scale degree (%)			
	0	1	2	3
T1	100 a	0 c	0 c	0 d
T2	0 b	18 a	58 a	24 c
T3	0 b	7 b	46 a	57 b
T4	0 b	0 c	19 b	81 a
T5	0 b	0 c	14 b	86 a

Means with different letters differ significantly according to Tukey´s test p<0,05

4 Discussion

In vitro callus formation was induced in rocoto foliar explants with MS culture medium with the presen-

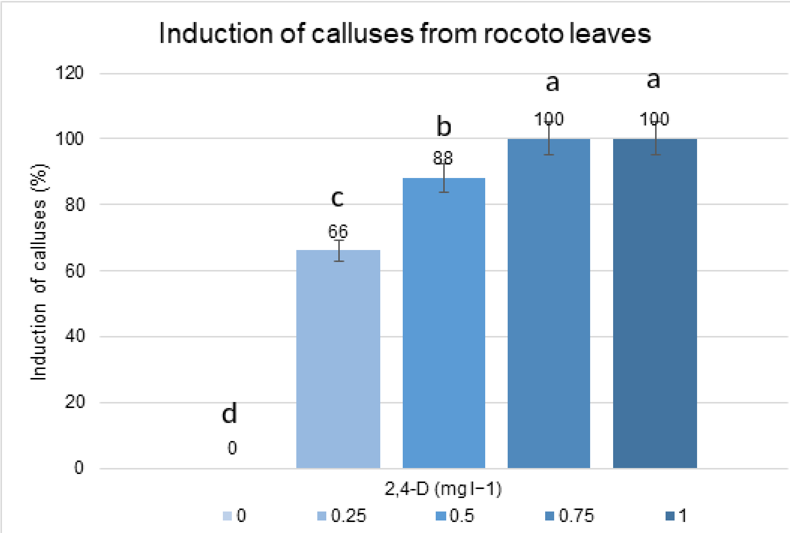

Figure 2. Percentage of *in vitro* callus induction from rocoto leaves. Means with different letters differ significantly according to Tukey's test for $p<0.05$.

ce of 2.4-D; the appearance of calluses was translucent and compact. The induction of calluses in *Capsicum* leaves is very favorable compared with other types of explants (Solís-Ramos et al., 2010; Alva-Guzmán et al., 2014; Argüelles et al., 2020). As mentioned by Rodríguez et al. (2014) and Espinosa et al. (2012) the induction of callus in leaves mostly depends on the type of explant and hormone used, unlike other explants. An evident increase of callus is seen when the concentration of 2.4-D is increased, in addition, this type of hormone influences the appearance of calluses.

The addition of auxins and their concentration in the culture medium may generate a higher percentage of callus induction depending on the species or genotype used, but the action of auxins is related to the presence of compounds present in the culture medium that have a greater influence on cell development and differentiation (Feeney et al., 2007; Meiners et al., 2007). This is because these endogenous compounds in *in vitro* culture have drastic changes in the cellular environment, which generate stress effect that can cause cell reorganization and form a mass of undifferentiated cells (Feher et al., 2003; Shriram et al., 2008).

Calluses that generated in the first weeks started at the edges of the explants, and gradually progressed in the explant over the course of the days. On day 35 the explants were covered and there was an increase in the size of the callus. Smith (2012), states that calluses are generated from the cutting zone of explants, an area that is in direct contact with the growth regulators that influence an accumulation of auxins, stimulating a continuous mitotic division that generates the gradual formation of small tissue until covering the explant largely or completely.

The effect of auxin 2.4-D on rocoto foliar explants resulted in callus induction, which could be related to physiological actions that are activated in the explant by exogenous auxin in the culture medium. Taiz and Zeiger (1998) determined that induction is expressed by genes encoding protein factors by binding auxins to external and internal receptors. Azcón-Bieto (2008), discovered that protein factors allow increasing plasticity and softening the cell wall, resulting in dilatation of the cell by turgor pressure, increasing in size until the cell wall opposes resistance. Additionally, the induction of calluses is influenced by enzymes that activate or repress gene transcription by the physiological actions of the cytokines; these enzymes are the histidine phosphotransferases, which are activated by the binding of the cytokines to histidine kinase receptors (Müller and Sheen, 2007).

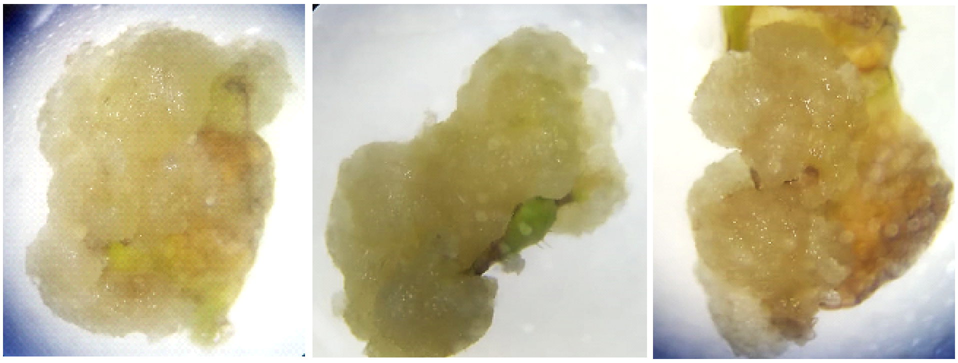

Figure 3. Calluses obtained in foliar rocoto explants, induced in MS culture medium with 2.4-D (0,75 mg l^{-1}).

The formation of rocoto callus in the first week can be an important finding because it provides information of having a sort of rapid induction effect. who generated calluses in Alva-Guzmán et al. (2014), quienes generaron callos en *Capsicum chinensis* from the tenth day in the induction medium, using 0.5 and 1 mg l^{-1} of 2,4-D.

The importance of auxin 2.4-D, being the main phytohormone used in *in vitro* conditions for the induction of calluses, is highlighted with a large number of reports of its addition in the culture medium for species of the same genus as rocoto, as well as for other genera (Larson et al., 2006; Terra et al., 2009; Hernández and Díaz, 2019; Hernández et al., 2020).

The age of the explants used should also be taken into account, since the first true leaves of rocoto were the ones influencing the study with a higher induction potential as stated by Alleweldt and Radler (1962), indicating that the physiological age of explants is inversely proportional to their organogenic potential.

These results represent an important advance in the application of biotechnological techniques in genetic improvement programs of rocoto, providing information for the potential use of calluses of this species in cell cultures to obtain secondary metabolites of pharmacological interest. It is a basis for future research in the induction of indirect somatic embryogenesis, indirect organogenesis, rhizogenesis, isolation of protoplasts, among others.

5 Conclusions

A methodology was developed for the *in vitro* induction of calluses from rocoto leaves, obtaining the highest induction percentage and formation of calluses in grade 3, using MS culture medium with 0.75 and 1 mg l^{-1} of 2,4-D.

References

Alayón, P., Tarragó, J., Mroginski, L., Pagano, E., and Sozzi, G. (2006.). Obtención de callos por cultivo in vitro de pulpa de manzana cv 'anna': Detección de actividad de alfa-l-arabinofuranosidasa. Master's thesis, Universidad Nacional del NORDESTE. Comunicaciones Científicas y Tecnológicas, Resumen: A-044.

Alleweldt, G. and Radler, F. (1962). Interrelationship between photoperiodic behavior of grapes & growth of plant tissue cultures. *Plant physiology*, 37(3):376–379. Online:https://bit.ly/3jkvsaH.

Alva-Guzmán, B., Cerna-Rebaza, L., and Chico-Ruíz, J. (2014). Inducción de embriones somáticos a partir de hojas Capsicum chinensis utilizando diferentes concentraciones de 2, 4 Diclorofenoxiacético y 6 Bencilaminopurina. *Scéndo*, 16(2. Online:https://bit.ly/2MHonCh).

Argüelles, A., Hernández, A., Cortez, A., and Díaz, H. (2020). Callogénesis in vitro de paprika (Capsicum annuum L.) cv. Papri King a partir de tallos. *Big Bang Faustiniano*, 9(1):4–7. Online:https://bit.ly/3nQdy0y.

Azcón-Bieto, J. y Talon, M. (2008). *Fisiología y Bioquíminca Vegetal*. Hill - Interamericana, Madrid, 2da ed edition.

Caballero, B., Márquez, C., and Rojano, B. (2017). Efecto de la liofilización sobre las propiedades funcionales del ají rocoto (Capsicum pubescens). *Revista U.D.C.A. Actualidad & Divulgación Científica*, 20(1):111–119. Online:https://bit.ly/2V5qwZI.

Espinosa, A., Silva, J., Sariego, S., and Cholo, L.and Delgado, H. (2012). Efecto del tipo de explante y la concentración de ácido 2, 4-diclorofenoxiacético en la formación de callos en Morus alba L. *Pastos y Forrajes*, 35(4):407–416. Online:https://bit.ly/3oQXStG.

Feeney, M., Bhagwat, B., Mitchell, J., and Lane, W. (2007). Shoot regeneration from organogenic callus of sweet cherry (Prunus avium L.). *Plant cell, tissue and organ culture*, 90(2):201–214. Online:https://bit.ly/3cKuUcT.

Feher, A., Pasternak, T., and Dudits, D. (2003). Transition of somatic plant cells to an embryogenic state. *Plant cell, tissue and organ culture*, 74(3):201–228. Online:https://bit.ly/2Od2ZrJ.

Gómez, L. (2016). Establecimiento de un protocolo para la inducción de la androgénesis en Capsicum chinense Jacq. Tesis de maestría, Centro de Investigación Científica de Yucatán, Mérida, Yucatán, México. Online:https://bit.ly/2Pd2vjO.

Gutierrez-Rosati, A. and Vega, B. (2017). Micropropagación in vitro de "ají mirasol", Capsicum baccatum var. Pendulum. *The biologist*, 14(2):171–181. Online:https://bit.ly/3pPkUTc.

Hernández, A. and Díaz, H. (2019). Inducción in vitro de callo embriogénico a partir del cultivo de anteras en "papa amarilla" Solanum goniocalyx Juz. & Bukasov (Solanaceae). *Arnaldoa*, 26(1):277–286. Online:https://bit.ly/2YPyNFi.

Hernández, A., Pineda, A., and Díaz, H. (2019a). Efecto de la luz y del ácido giberélico en la germinación *in vitro* de Capsicum annuum L. cv. "papri king". *Biotecnología Vegetal*, 19(3):165–170. Online: https://bit.ly/3ez5U5W.

Hernández, A., Pineda, A., and Noriega, H. (2019b). Aislamiento e identificación de fusarium oxysporum obtenidos de zonas productoras de "ají paprika" Capsicum annumm L.(Solanaceae) en el distrito de Barranca, perú. *Arnaldoa*, 26(2):689–698. Online:https://bit.ly/2YOy9HR.

Hernández, A., Argüelles, A., Cortez, A., and Díaz, H. (2020). Efecto de la concentración de 2,4-diclorofenoxiactico en la inducción de callos in vitro utilizando cotiledones de rocoto (Capsicum pubescens Ruiz & Pav.). *The Biologist*, 17(2):327–334. Online:https://bit.ly/3kXv5BM.

Izquierdo, H., Alcaraz, L., and Rodríguez-Álvarez, M. (2017). Micropropagación de chiltepín (Capsicum annuum L. cv.'glabriusculum') mediante el empleo de una oligosacarina de origen péctico. *Acta universitaria*, 27(5):34–43. Online:https://bit.ly/2p9bTdE.

Larson, C., Gómez, C.and Sánchez, M., and Ríos, D. (2006). Inducción de caulogénesis indirecta en Eucalyptus globulus. *Bosque*, 27(3):250–257. Online:https://bit.ly/3jriGXJ.

Levitus, G., Echenique, V., Rubinstein, C., Hopp, E., and Mroginski, L. (2010). Biotecnología y mejoramiento vegetal ii. Master's thesis, Instituto Nacional de Tecnología Agropecuaria, Argentina.

Lucana, C. (2012). Respuesta de 5 especies de capsicum spp. a phytophthora capsici leon, bajo condiciones de invernadero, en los laboratorios de fitopatologia de la unalm-lima. Tesis de ingeniera, Universidad Nacional de San Antonio Abad del Cusco, Cusco. Perú. Online:https://bit.ly/31J3taa.

Marín, E. (2012). Embriogénesis somática del género Capsicum: Validación de un protocolo de regeneración in vitro en Capsicum annuum. Tesis de maestría, Centro de Investigación Científica de Yucatán, Mérida, Yucatán, México. Online:https://bit.ly/2BHB7Ck.

Meiners, J., Schwab, M., and Szankowski, I. (2007). Efficient in vitro regeneration systems for vaccinium species. *Plant Cell, Tissue and Organ Culture*, 89(2):169–176. Online:https://bit.ly/3cKCST3.

Müller, B. and Sheen, J. (2007). Advances in cytokinin signaling. *Science*, 318(5847):68–69. Online:https://bit.ly/3jutEvO.

Murashige, T. and Skoog, F. (1962). A revised medium for rapid growth and bio agsays with tohaoco tissue cultures. *Physiology Plant*, 15(3):473–497. Online:https://bit.ly/2MK33w2.

Orlinska, M. and Nowaczyk, P. (2015). In vitro plant regeneration of 4 Capsicum spp. genotypes using different explant types. *Turkish Journal of Biology*, 39(1):60–68. Online:https://bit.ly/2MD8AHm.

Pérez, M., Hernández, C., Teresa, M., and Delgado, M. (2009). Expresión transitoria gus en callos de arroz (var. j-104) mediante la optimización de las condiciones de cultivo in vitro. *Rev. Colomb. Biotecnol.*, 9(2):75–84. Online:https://bit.ly/2MIrERD.

Rashmi, R. and Trivedi, M. (2014). Effect of various growth hormone concentration and combination on callus induction, nature of callus and callogenic response of nerium odorum. *Applied biochemistry and biotechnology*, 172(5):2562–2570. Online:https://bit.ly/3cPoAkb.

Robledo, A. and Carrillo, G. (2004). Regeneración in vitro de plantas de Chile (Capsicum annuum L.) mediante cultivo de cotiledones e hipocótilos. *Revista Fitotecnia Mexicana*, 27(2):121–126. Online:https://bit.ly/2pPgu4w.

Rodríguez, M., Latsague, M., Chacón, M., and Astorga, P. (2014). Inducción in vitro de callogénesis y organogénesis indirecta a partir de explantes de cotiledón, hipocótilo y hoja en ugni molinae. *Bosque*, 35(1):111–118. Online:https://bit.ly/2WdJDCD.

Sala, F. and Labra, M. (2003). *Encyclopedia Appl. Plant Sci.*, chapter Somaclonal variation, pages 1417–1422. Academic Press Elsevier, Oxford, UK.

Sanatombi, K. and Sharma, G. (2007). Micropropagation of capsicum annuum l. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, 35(1):57–64. Online:https://bit.ly/3cJKYeT.

Santana, N. (1982). Determinacín de un medio adecuado para la obtención de callus en variedades de caña de azúcar (Saccharum species) in vitro. *Cultivos Tropicales*, 4(3):48–52. Online:https://bit.ly/3jmosdf.

Sardón, E. (2015). Fortalecimiento de la cadena de valor del rocoto fresco (Capsicum pubescens) de la selva central para el mercado de lima. Tesis de maestría, Universidad Nacional Agraria La Molina, Lima, Perú. Online:https://bit.ly/3gFCJ2Y.

Shriram, V., Kumar, V., and Shitole, M. (2008). Indirect organogenesis and plant regeneration in Helicteres isora L., an important medicinal plant. *In Vitro Cellular and Developmental Biology-Plant*, 44(3):186–193. Online:https://bit.ly/31Go4vL.

Smith, R. (2012). *Plant tissue culture: techniques and experiments*. Academic Press Elsevier, Londres, UK. Online:https://bit.ly/2qyukbU.

Solís-Ramos, L., Nahuath, S., Andrade, A., Barredo, F., González, T., and Castañ0, E. (2010). Indirect somatic embryogenesis and morphohistological analysis in Capsicum chinense. *Biologia*, 65(3):504–511. Online:https://bit.ly/2MBI80E.

Taiz, L. and Zeiger, E. (1998). *Plant Physiology*. Sinauer Associates, Inc., Sunderland, Massachusetts. Online:Online: https://bit.ly/35XfUTb, 2nd edition.

Terra, E., Faustini, G., Vilas, K., Pinto, F., and Almeida, J. (2009). Controle da calogênese do paubrasil in vitro. *Revista Árvore*, 33(6):987–996. Online:https://bit.ly/2YSqBnD.

Valdez, I. (2017). Caracterización fenotípica de quince accesiones de germoplasma de rocoto (Capsicum pubescens Ruiz & Pavón.) en la estación inia santa rita arequipa. Tesis de ingeniera, Universidad Nacional de San Agustín,, Arequipa Perú. Online:https://bit.ly/362Wo7K.

Vélez, M., Robledo, A., Corona, T., Aguilar, V. H., Ramírez, P., and Suárez, J. (2010). Obtención de plantas haploides en chile miahuateco (Capsicum annuum L.). *Revista mexicana de ciencias agrícolas*, 1(2):189–201. Online:https://bit.ly/3q6MoDO.

Venkataiah, P., Bhanuprakash, P., Kalyan, S., and Subhash, K. (2016). Somatic embryogenesis and plant regeneration of Capsicum baccatum L. *Journal of Genetic Engineering and Biotechnology*, 14(1):55–60. Online:https://bit.ly/2JjhZyR.

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Scientific paper/ Artículo científico
Sustainable Development

Systemic analysis of the economic sustainability of family agricultural production units in a peasant community of Lebrija, Colombia

Análisis sistémico de la sostenibilidad económica de unidades de producción agropecuaria familiar en una comunidad campesina de Lebrija, Colombia

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Abstract

The complexity of the current problems in the Colombian countryside puts at risk the sustainability of family Agricultural Production Units (UPA for its acronym in Spanish). Consequently, it becomes a fundamental study area for the improvement of the rural economy. For this reason, a documentary, field investigation was developed on a case study located in Lebrija, Colombia, for the systemic analysis of economic sustainability in 10 UPAS promoters of sustainable agriculture. The results allowed to establish the effectiveness of the ES in the Characterization of UPAs. It was identified that the lack of investment in infrastructure and appropriate technologies has made the UPAs to allocate 50% of its total area for inadequate grazing. This distribution of land threatens the sustainability of the economy of local families, given that the production and profitability of livestock are not enough for their livelihood and the maintenance of pastures. The inadequate grazing generates large amounts of manure that pollutes the environment. The above affects the congruence between the productive activities and the philosophical principles of the UPAs.

Keywords: Rural development, systemic approach, organic surpluses, economic sustainability, compost.

Resumen

La complejidad de los problemas actuales del campo colombiano pone en riesgo la sostenibilidad de las Unidades de Producción Agropecuaria (UPA) familiares. En consecuencia, se convierte en un área de estudio fundamental para el mejoramiento de la economía rural. Debido a ello, se desarrolló una investigación documental y de campo sobre un caso de estudio ubicado en Lebrija, Colombia, para el análisis sistémico de la sostenibilidad económica en 10 UPAS promotoras de la agricultura sostenible. Los resultados permitieron establecer la efectividad del ES en la caracterización de UPAs. Se identificó que la falta de inversión en infraestructura y tecnologías apropiadas han hecho que las UPAs destinen más del 50 % de su área total para el inadecuado pastoreo de bovinos. Esta distribución de la tierra amenaza la sostenibilidad de la economía de las familias locales, dado que la producción y rentabilidad de la ganadería no son suficientes para su sustento y el mantenimiento de los potreros. El inadecuado pastoreo genera grandes cantidades de estiércol que contamina el medio ambiente. Lo anterior afecta la congruencia entre las actividades productivas y los principios filosóficos de las UPAs.

Palabras clave: Desarrollo rural, enfoque sistémico, excedentes orgánicos, sostenibilidad económica, compost.

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1 Introduction

Farms located in La Cuchilla, municipality of Lebrija Santander, represent a group of family farm units (UPA by its acronym in Spanish), beloging to an association of peasant women called AMMUCALE (Díaz et al., 2011). Its owners promote protection of water, forests, ancestral knowledge, native seeds and food sovereignty, closely related to the principles of biocentrism, alternative economies (barter) and simple life expressed by the objectives of good living (Cubillo and Hidalgo, 2019; Huanacuni, 2010). Although they are a local example of responsible agriculture aligned with some Sustainable Development Goals - SDGs (UN, 2015) according to different studies (ONU, 2015) según diferentes estudios (Díaz et al., 2011; Amaya et al., 2018; Cruz et al., 2018), they experience the problems of the Colombian rural sector.

The distribution and possession of the land shows that 70 % of Colombian UPA have less than 5 ha (DANE, 2015), limiting the production capacity of farms (Kalmanovitz and López, 2003). Similarly, issues such as investment in machinery, infrastructure, irrigation systems and technical assistance remain below 15 % (DANE, 2015), while the use of artificial fertilizers is 2.83 times higher than the South American average (Banco Mundial, 2019a).This makes it difficult for farmers to keep their production costs stable and puts their economic sustainability at risk.

Since 1950s efforts have been made to improve the conditions of agriculture through development plans (Kalmanovitz and López, 2003), but the results have shown an increase in the inequality gap between the countryside and the city with a Gini (Banco Mundial, 2019b) of 0.45 (DANE, 2019). Some research (Arias et al., 2008; Ruiz and Oregui, 2001), state that one of the main reasons is that agro has traditionally been observed from a reductionist approach, which results in a limited view of the problems. In response, some authors (Bistagnino, 2011; Capra, 1996; Meadows, 2008; Rovaletti, 1989) point to the need to change to a systemic approach – SA for the analysis of complex situations, where different applied research has validated SA for the design of decision-making models (Stamberg, 2015) and sustainable production (Barbero and Toso, 2006).

According to the above, the main objective of the study is to carry out an economic systemic analysis of sustainability in 10 UPA which promote sustainable agriculture. To this end, the specific objectives are proposed: (1) to carry out a systemic analysis of the UPA in relation to the territory based on Bistagnino (2009) Sistemic Desing methodology, (2) to carry out a detailed review of the economic results in terms of production and profitability and (3) to identify systemic problems and their potential opportunities for improvement.

2 Materials and Methods

The data collection through primary and secondary sources, systemic analysis and data interpretation was carried out between May and December 2019 on the basis of a case study, using a qualitative and quantitative analysis.

2.1 Case study

The study area is located in the rural area of the municipality of Lebrija-Santander, north-west of Colombia. In this region, 80 % of its inhabitants depend on agricultural activities, mainly from pineapple, Tahiti lemon and cocoa crops. 84.27 % of UPA have less than 20 ha (Alcaldía de Lebrija, 2016), as shown in Figure 1. The farms of the territory have approximately 20 ha, whose productive activities are specially based on the cultivation of citrus fruits, vegetables, cocoa and cattle grazing.

Criteria such as: Land extension, crop types, livestock activities, location and sustainability were used for the selection of the case study. 10 UPA located on La Cuchilla vereda were selected, headed by "Tierra Buena" farm. Its managers are women, who are head of the hosehold and belong to AMMUCALE and who are a representative sample of the association.

The selected UPA in this area conduct productive processes that add value to their products. 100 % of cocoa is transformed into chocolate and pig feces are used for generating gas from biodigesters. Its income is diversified through 5 livestock and 8 agricultural activities, traded under fair trade practices (Díaz et al., 2011; Amaya et al., 2018; Cruz et al., 2018). In addition, “Tierra Buena” farm leads the agroecological processes of the area, given its experience at AMMUCALE and the human vision of its owner.

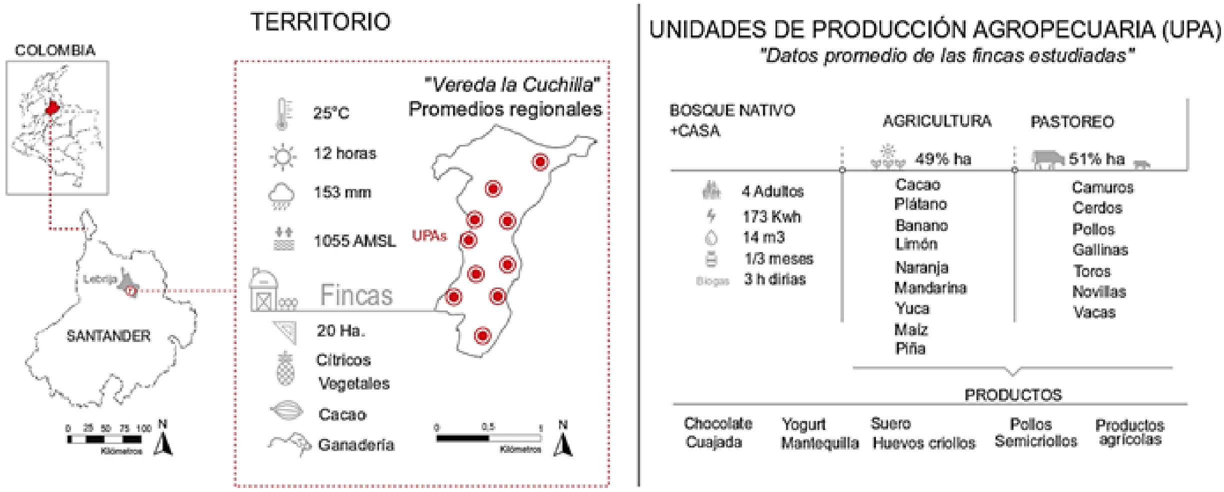

Figure 1. Territory averages and UPA based on Alcaldía de Lebrija (2016) mayor office data.

2.2 Methods

2.2.1 Systemic analysis

SA was applied according to the methodology suggested by Bistagnino (2011), which consists on the analysis of the territory, actors and systems at the different levels (Ceschin, 2014), seeking to identify and characterize quantitatively and qualitatively the inputs, processes, outputs, economic problems (Barbero and Toso, 2006; Bertalanffy, 1968; Bistagnino, 2011; Capra, 1996; Carrá, 1961; Garciandía, 2011; Johansen, 1993; Meadows, 2008; Stamberg, 2015; Rovaletti, 1989) and leverage points (Meadows, 1997) for the improvement of sustainability according to James (2015).

In the first stage, the analysis of the territory was carried out by reviewing secondary sources (articles, books, gray literature, official websites) to obtain data on the cultural, geographical and productive characteristics of the agro.

In the second stage, the analysis of the actors was carried out using a semistructured interview as an instrument of data collection, which was applied to 42 people directly involved in the agricultural activities of the case study, such as their owners, their children and their spouses. The analysis categories correspond to the economic dimension of sustainability based on James (2015), agricultural production, the family economy and transformation processes of raw matter.

In the third and final stage, observation was used as an instrument for the characterization of subsystems; and the system map was used as a tool for structuring and understanding the data (Vargas et al., 2020; Vezzoli et al., 2014). Finally, due to the heterogeneity of the data obtained by SA, three experts in responsible production, ethnobiology and fair trade were interviewed, who provided their interpretation of the results related to agroecology, social structure and informal agricultural trade in the case study.

2.2.2 Analysis of the economic dimension of sustainability

For the analysis of the economic dimension, the profile questionnaire designed by (James, 2015) was adapted, which consists of 49 questions distributed equally on seven topics related to: 1) production and allocation of resources, 2) exchange and transfer, 3) accounting and regulation, 4) consumption and use, 5) work and welfare, 6) technology and infrastructure, 7) wealth and distribution. The interview was applied to the owners of the farms, their spouses and their children older than 18, for a total of 42 people. The response options aimed to understand the interviewees' perception of each of the seven topics presented, who in each question chose a single answer that ranged from critical, bad, very dissatisfied, dissatisfied, basic, satisfactory, very satisfactory, good and excellent, which were tabulated in an Excel table and were assigned a value from 1 to 9, where 1 is critical and 9 is excellent. The answers were averaged to obtain the perception of the 49 questions. Subsequently, average satisfaction was calculated for each of the seven topics addressed. Finally, the overall perception of respondents about the economic sustainability of their families was calculated. The results were plotted to observe the levels of the seven themes.

2.2.3 Economic axis profitability analysis

A quantitative approach was applied, which focused on the economic value of goods produced in the UPA. To this end, information was collected on the production of microsystems based on money, and was registered in calculation tables. Economic capacity was assessed by means of net present value (NPV) (Stamberg, 2015), which was found by the formula (1).

$$\mathrm{VAN} = \mathrm{PB} - \mathrm{CI} - \mathrm{D} \tag{1}$$

Where PB is the gross production of UPA in Colombian pesos; CI is the intermediate consumption or the cost of the inputs acquired; D is the sum of the depreciation of the machines, equipment and facilities used in the production of goods and services.

In addition, the agricultural profitability (AP) was found, which allows to know the performance of the business after paying wages (S), bank interest (J), leases (T) and taxes (I) (Stamberg, 2015), thus having a realistic view of the final benefits received by families. For the calculation of AP, Stamberg (2015) formula was applied (2).

$$\mathrm{RA} = \mathrm{VAN} - \mathrm{S} - \mathrm{J} - \mathrm{T} - \mathrm{I} \tag{2}$$

Formulas were applied according to the two activities conducted in the UPA. The first covers all agricultural activities; the second covers livestock activities only. The data were tabulated and analyzed in Excel, where a descriptive analysis of the variables was performed, the formulas were applied and average totals were obtained by type of activity.

3 Results

3.1 Problems identified by SA

By using SA during field observations, it was observed how resources move through the productive systems of the UPA at the micro level; this allowed identifying five common problems in the farms studied, three of them related to inputs, one to processes and one to outputs, problems that are considered a threat for the achievement of a sustainable rural area (Figure 2).

In the inputs, three situations were found whose impacts are negative for the sustainability of the farms studied. The first is related to the lack of fertilizers. Although the owners do not use agrochemicals, the use of organic fertilizers was not evidenced, which in the long term could create agricultural production problems due to the decrease of nutrients in the soil. The second is related to the low profitability of farms, since economic income is not sufficient to cover costs and family needs. The third is based on income outside agricultural production. In 8 out of the 10 UPA studied, most of the economic income comes from urban employment of spouses and children. The latter is beneficial to the household economy, but in the long term it could displace these families into urban areas in search of better opportunities.

Problems related to the maintenance of UPA were identified during processes, specifically in paddocks. It was evidenced that in 7 of the 10 UPA studied, the use of the exclusive soil for cattle grazing is higher than 50 %; however, dairy production and the sale of animals do not generate sufficient income to cover the maintenance costs associated with the restoration of posts, fences, the payment of taxes, vaccines, food, among others. Although La Cuchilla is an area that combines agricultural activities with livestock, it was evidenced that the number of specimens corresponds to 1 animal per 1.5 ha in the farms studied.

In the outputs, a problem related to organic surpluses and the environment was evident. From field observations, it was identified that livestock manure, cocoa pods, household waste water and some wastes have inadequate disposal, thus being a source of environmental pollution. In the case of livestock manure, it was identified that approximately 219.55 t of manure is generated every seven months in the farms studied, which are distributed to the animals without any management. Similarly, during the months of surplus measurement, it was observed that cocoa production generated 53.9 t of pods, which accumulated in piles within the crop and did not receive adequate management. Similarly, it was identified that household wastewater is discharged into the environment without any type of decontamination treatment, the figure of which is unknown due to the lack of aqueduct, accountants and sewerage in the area; but considering the Colombian average consumption per family (EPM, 2020) it is estimated to be about 115.5 cubic meters per household monthly. Finally, it was evidenced that inorganic surpluses such as plastic bags, food wraps, toilet paper, among others, are incinerated by some families, because the urban garbage service does not provide its services in rural areas. Therefore, it was not possible to estimate the pollution level that this practice generates, however, it was considered as a relevant pollution source to be mentioned in the SA results.

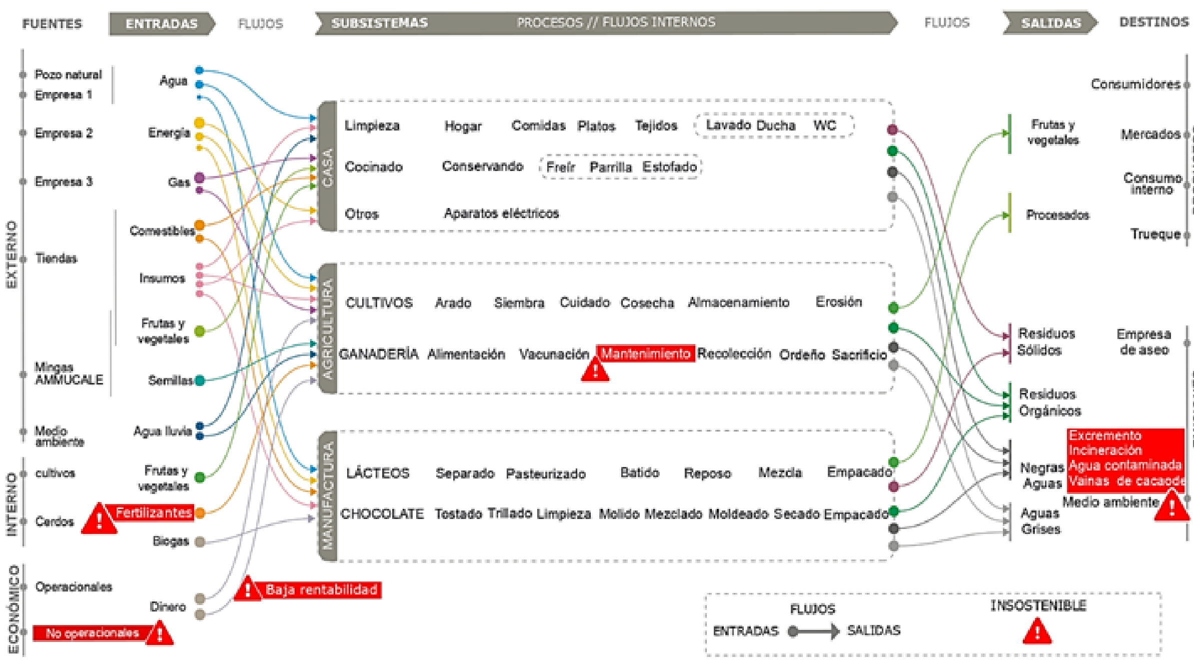

Figure 2. Analysis from the current UPA System Map. Alert symbols show identified sustainability issues.

3.2 Analysis of economic sustainability of UPA

By applying the adaptation of Profile Questionnaire by James James (2015), it was identified that the perception of families toward the economic sustainability is at a basic level. However, by looking at each of its edges, it is possible to note that some of the themes that make up this dimension are at lower levels. As shown in Figure 3, one of the main shortcomings of the UPAs studied and thais is found at a bad level is their lack of accounting strategies and regulation, a subject which, according to the interviewees, makes it difficult to know the amount of money of the family economy and the transparency in how it is used. Likewise, this lack of accounting knowledge prevents families from designing medium and long term plans, limiting them to short term economic exploitation. For its part, the technology and infrastructure edge has a very unsatisfactory level, mainly due to the lack of endowment and availability of these tools and the proper adaptation of the current infrastructure focused on sustainable development; in other words, the peasants surveyed believe that they have not been able to access new technology or improve the technology they currently possess.

Likewise, according to the results of the interview, edges 7 and 2 related to wealth and exchanges were placed at unsatisfactory level, which implies an informality of people about the opportunities for trading. Finally, edges 1, 4 and 5 related to production, consumption and employment were positioned between the basic and very satisfactory levels.

This means that interviewees have a normal to positive perception of these three issues, mainly because of the work that their owners have done with AMMUCALE for more than 20 year and that has promoted the diversification of production, responsible consumption and the commitment of young people to the countryside.

Figure 3. Profile of economic sustainability of UPA, adapted from (James, 2015).

3.3 Profitability of UPA

The calculation of the net value added and agricultural profitability of each of the UPA studied was carried out to know the economic dimension of sustainability. As can be seen in Figure 4, the results identified the most and least productive activities, as well as the profit generated according to the space required by each.

Although the municipality of Lebrija is not a cattle zone, about 56% of the soil in the UPA studied is used for breeding, in which few animals per hectare are maintained. The sale of cattle is not the most representative economic activity, as cattle are used mainly for the production of milk and dairy products such as yogurt, curd, butter and cottage cheese; instead, cattle is seen as a source of capital savings. Figure 4 shows that the most income-generating livestock activity is pig rearing, followed by the sale of chicken and the marketing of milk. On the other hand, livestock generates an average income of $480.000 per UPA per year, occupying the sixth place in livestock activities and eleventh in general.

In this area, manufacturing projects have been promoted to add value to raw materials, such as chocolate and dairy products. In this regard, chocolate contributes the most to the family economy, reason for which cocoa is transformed and only about 2.831 lbs are sold in grain. Although production by activity and land use makes it possible to understand some aspects of the local economy, it does not fully reflect the reality of households. Table 1 shows the profitability (AP) results, which after subtracting the costs associated with each production system allows identifying how much money the UPA receives and how much is the contribution per hectare according to its use.

The results shown in Table 1 correspond to the average values of the 10 UPA studied. As can be seen, the activities derived from agricultural production have an average NVA of $19'988.115 and an AP of $13'146.944, i.e. profitability per hectare of $4'537.427. However, livestock activities, including livestock and livestock derivatives have an average profitability per hectare of $497.365.

In 8 of the 10 UPA studied, the area used for breeding was greater than the area used for agricultural crops. Despite having more space, the economic benefit received by the family unit as a result of livestock activities is $3'098.579 pesos a year, much lower than the one generated by agricultural activities. This is mainly due to the livestock space and the costs related to food and vaccines that other animals require for their development. On the other hand, it is observed that agricultural activities, including the transformation of cocoa into chocolate, generate an average of $13'146.944 a year, being the main source of income of families in the area.

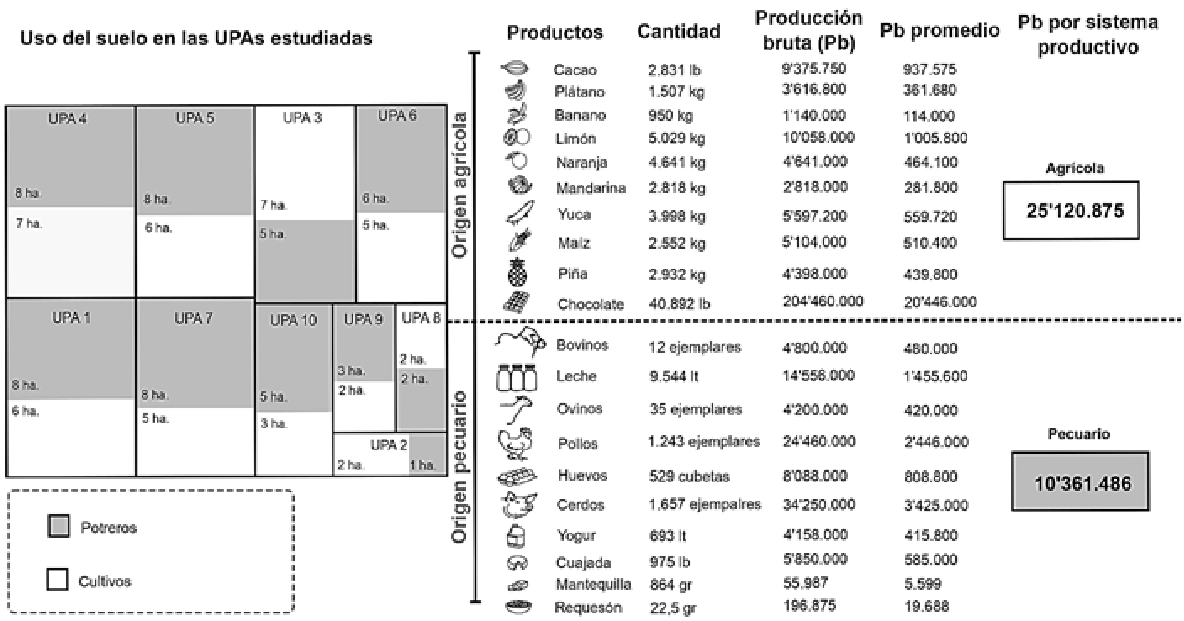

Figure 4. Use of the soil and gross production (Pb) in the UPA studied.

4 Discussion

4.1 SA for analyzing UPA

SA allowed a holistic understanding of the economic situation and the identification of problems associated with the incorrect management of cattle manure and cocoa pods in UPA. This information is based on other research such as Steinfeld et al. (2009) who say that these materials pollute the environment. In addition, Sosa and García (2019) claim that bovine manure produces greenhouse gases and Pinos et al. (2012) and Steinfeld et al. (2009) state that this surplus generates micro and macro nutrients that negatively affect soil and aquifers.

Likewise, SA allowed to identify philosophical differences between the activities carried out by the UPA studied and the principles they claim on sustainable agriculture and environmental protection. This is similar to the results published by Jagustović et al. (2019), in which a community of women farmers in Doggoh-Jirapa, northern Ghana, identified using SA transdisciplinary elements that contradicted their Climate-Smart Agriculture (CSA) principles and allowed them to design improvement strategies. SA also allowed to identify organic surpluses such as cattle manure, cocoa pods and other plant elements that can be exploited by the peasants of the region in the processing of vermicompost, which is rich in microorganisms (Asadu et al., 2019; Barbero and Toso, 2006; FAO, 2013).This is beneficial for crops because it contains large amounts of nitrogen-fixing bacteria that improves water retention, biological health and soil absorption capacity, stormwater use, enzymatic activity, presence of nutrients, among others (Agegnehu et al., 2016; Argaw, 2017; Rayen et al., 2006; Sharma et al., 2017; Wang et al., 2016), which could become an opportunity to identify pollution problems and to support the development of responsible and sustainable agriculture.

Table 1. VA and AP of the UPA studied

Productive system	Agriculture	Standard deviation	Livestock	Standard deviation	Total of agriculture and livestock
Average Area[1]	4.4	2.2	5.5	2.5	9.9
GP[2]($)	25’120.875	9’373.321	10’361.486	9’826.465	35’482.361
IC[3]($)	3’767.440	1’947.897	6’990.960	6’573.668	10’758.400
GVA[4]($)	21’353.435	7’730.943	3’530.526	3’654.294	24’883.961
DEP[5]($)	1’365.320	444.647	720.870	572.091	2’086.190
NVA[6]($)	19’988.115	7’775.486	2’809.656	3’192.752	22’797.771
DVA[7]($)	6’841.171	5’881.390	366.301	183.605	7’207.472
AP[8]($)	13’146.944	7’340.709	2’443.355	3’098.579	15’590.299
NVA/ha[9]($)	5’869.556	3’220.220	433.122	500.289	6’302.678
AP/ha[10]($)	4’537.427	3’659.267	368.037	497.365	4’905.464

[1] **Average area:** In hectares (ha).
[2] **GP:** Gross production
[3] **IC:** Internal consumption.
[4] **GVA:** Gross value added
[5] **DEP:** Depreciation
[6] **NVA:** Net value added
[7] **DVA:** Other topics related (wages(S), bank interests (J), leases (T), taxes (I)).
[8] **AP:** agriculture profitability
[9] **NVA/ha:** Net value added per hectare
[10] **AP/ha:** Agricultural profitability per hectare

4.2 Economic dimension of sustainability in rural communities

At this point, the study aims to open a debate based on land use and the values of NVA and AP, which suggest the potentialization of agricultural activity over some livestock activities such as cattle. This is similar to the proposal ofStamberg (2015), who advised the potentialization of one activity and the elimination of another based on the results of NVA and AP.

As can be seen, the AP of the livestock system, in the way livestock is currently developed in the UPA studied and compared to agricultural activities, does not generate sufficient income to benefit families; for this rason, it is suggested to continue researching on sustainable ways to use the soil in the rural area, considering topics such as crop diversification, the amount of cattle per hectare and the use of paddocks (Rojas et al., 2013). The latter is based on Fernández et al. (2016) proposal on suitable paddocks that facilitate the management of excreta.

The above also suggests the need to create a complete system of organic surplus management that allows the use of bovine manure, cocoa pods and other plant surpluses through composting processes. For this reason, it is necessary to conduct studies focused on the design of adequate infrastructure and advice on the handling of these materials.

This research is expected to be a tool for the decision-making of the owners of the UPA studied to improve their net income, boost their economic independence, empower them, strengthen their identity and their commitment as peasant women (Botello and Guerrero, 2017); it also serves as the basis for future research related to sustainable rural development and economy.

5 Conclusions

The research provides information on the application of SA to analyze UPA, because this approach concentrates in the flows and their interaction with the actors involved, which allowed to identify the lack of advice on sustainable practices. Also, some limitations inherent in this approach are recognized, since it requires the collection of large amounts of information, and therefore it needs a lot of time, resources and expert advice in multiple disciplines.

The lack of organization and accounting records do not allow the owners of the UPA to know the way the money flows in their businesses, and it is considered a constraint to design improvement plans and strategies, since it normally requires the economic resources that peasant families do not have; moreover, the lack of public investment and the difficult access to credit reduce the possibilities of peasants in obtaining technology, appropriate advice and infrastructure.

Finally, it is concluded that land use in Colombia is a problem observed in the productive distribution applied by the family UPAs, where most of the area is used for cattle grazing, which may have 1.5 ha approximately per animal. The development of sustainable agriculture requires the promotion of efficient methods to improve the family economy and to reduce the gaps in inequality between the countryside and the city to guarantee the increase of agricultural land as a food security strategy for the sustainability of future generations.

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References

Agegnehu, G., Bass, A., Nelson, P., and Bird, M. (2016). Benefits of biochar, compost and biochar-compost for soil quality, maize yield and greenhouse gas emissions in a tropical agricultural soil. *Science of The Total Environment*, 543:295–306. Online: https://bit.ly/3uEIZyI.

Alcaldía de Lebrija (2016). Economía. Online: https://bit.ly/3vV8LPm.

Amaya, M., Mendez, R., and Hernández, A. (2018). Revisión documental sobre la experiencia de la asociacion municipal de mujeres campesinas de lebrija santander "ammucale". Tesis de grado, Universidad Industrial de Santander. Online: https://bit.ly/3tSr1Y3.

Argaw, A. (2017). Organic and inorganic fertilizer application enhances the effect of *Bradyrhizobium* on nodulation and yield of peanut (*Arachis hypogea* l.) in nutrient depleted and sandy soils of ethiopia. *International Journal of Recycling of Organic Waste in Agriculture*, 6(3):219–231. Online: https://bit.ly/3f8GXzZ.

Arias, R., Mader, T., and Escobar, P. (2008). Factores climáticos que afectan el desempeño productivo del ganado bovino de carne y leche. *Archivos de medicina veterinaria*, 40(1):7–22. Online: https://bit.ly/3tYFPVl.

Asadu, C., Egbuna, S., Chime, T., Eze, C., Kevin, D., Mbah, G. O., and Ezema, A. (2019). Survey on solid wastes management by composting: Optimization of key process parameters for biofertilizer synthesis from agro wastes using response surface methodology (rsm). *Artificial Intelligence in Agriculture*, 3:52–61. Online: https://bit.ly/2RzX8hQ.

Banco Mundial (2019a). Índice de gini - colombia. Online: https://bit.ly/3o0ndTe.

Banco Mundial (2019b). Uso de fertilizantes por país. Online: https://bit.ly/2R7yNzV.

Barbero, S. and Toso, D. (2006). Systemic design of a productive chain: reusing coffee waste as an input to agricultural production. *Environmental Quality Management*, pages 24–46. Online: https://bit.ly/3tSj70Y.

Bertalanffy, L. V. (1968). *General System Theory: Foundations, Development, Applications*. George Braziller.

Bistagnino, L. (2009). *Progettare la sostenibilità produttiva e ambientale in agricoltura, industria e comunità locali*, chapter Systemic Design sistemico. Slow Food Editore.

Bistagnino, L. (2011). *Systemic design: designing the productive and environmental sustainability*. Politecnico di Torino. Online: https://bit.ly/3y8Wt7R.

Botello, H. and Guerrero, I. (2017). Condiciones para el empoderamiento de la mujer rural en colombia. *Entramado*, 13(1):62–70. Online: https://bit.ly/3eG1PzH.

Capra, F. (1996). *The Web of Life: A New Scientific Understanding of Living Systems*. Anchor Books.

Carrá, J. C. (1961). Pensamiento sistémico. Online: https://bit.ly/2RSJ57l.

Ceschin, F. (2014). *Sustainable product-service systems: Between strategic design and transition studies*. Springer Science y Business Media.

Cruz, E., Monsalve, M., Loaiza, A., and Blanco, L. (2018). Mujeres por el buen vivir, perspectivas desde la investigación para la paz. asociación municipal de mujeres campesinas del municipio de lebrija "ammucale". Tesis de grado, Universidad Industrial de Santander. Online: https://bit.ly/2QooF5J.

Cubillo, A. and Hidalgo, A. (2019). Una propuesta para la construcción de un transdesarrollo global . los objetivos del buen vivir. Online: https://bit.ly/3ydVi6X.

DANE (2015). *Censo Nacional Agropecuario (CNA). Resultados Nacionales Con Resúmenes Provinciales CNA 2000*. Online: https://bit.ly/3w4DNnW.

DANE (2019). Boletín técnico pobreza monetaria en colombia año 2018. Technical report, Departamento Administrativo Nacional de Estadística. Online: https://bit.ly/3y99Qoy.

Díaz, L., Ortiz, J., and Rodríguez, D. (2011). Propuesta para el fortalecimiento de las condiciones socioeconómicas de la zona de influencia de ammucale" (sector rural del municipio de lebrija). Tesis de grado, Universidad Industrial de Santande. Online: https://bit.ly/33G9M1z.

EPM (2020). Tips para el uso inteligente. Online: https://bit.ly/3y9cyKK.

FAO (2013). *Manual de compostaje del agricultor*. Oficina Regional de la FAO para América Latina y el Caribe. Online: https://bit.ly/33IOb8y.

Fernández, C., Xercavins, A., Ribas, A., and Blanco, I. (2016). Establo sostenible. evaluación en granjas de vacuno de leche como estrategia para la mejora de la rentabilidad. Technical Report 122, Afriga. Online: https://bit.ly/3foKWIX.

Garciandía, J. (2011). *Pensar sistémico, una introducción al pensamiento sistémico*. Pontificia Universidad Javeriana. Online: https://bit.ly/3flcnn8.

Huanacuni, F. (2010). *Buen Vivir / Vivir Bien Filosoía, políticas, estrategias y experiencias regionales andinas*. Coordinadora Andina de Organizaciones Indígenas (CAOI). Online: https://bit.ly/3hx7muo.

Jagustović, R., Zougmoré, R., Kessler, A., Ritsema, C., Keesstra, S., and Reynolds, M. (2019). Contribution of systems thinking and complex adaptive system attributes to sustainable food production: Example from a climate-smart village. *Agricultural systems*, 171:65–75. Online: https://bit.ly/2SMmN7r.

James, P. (2015). *Urban sustainability in theory and practice: circles of sustainability*. Routledge. Online: https://bit.ly/3fDJcMj.

Johansen, O. (1993). *Introducción a la teoría general de sistemas*. Editorial Limusa. Online: https://bit.ly/2RWe2Yj.

Kalmanovitz, S. and López, E. (2003). La agricultura en colombia entre 1950 y 2000. *Revista del Banco de la República*, 76(912):1–45. Online: https://bit.ly/3fs2808.

Meadows, D. (1997). *Lugares donde intervenir en un sistema*. Whole Earth.

Meadows, D. (2008). *Thinking in systems: A primer*. Chelsea green publishing.

ONU (2015). Objetivos de desarrollo sostenible. Online: https://bit.ly/2SNQOnn.

Pinos, J., García, J., Peña, L., Rendón, J., González, C., and Tristán, F. (2012). Impactos y regulaciones ambientales del estiércol generado por los sistemas ganaderos de algunos países de américa. *Agrociencia*, 46(4):359–370. Online: https://bit.ly/3w7vN5B.

Rayen, M., Camila, M., Rosa, R., Aliro, C., and Fernando, B. (2006). Efecto de la adición de compost sobre propágulos micorrícicos arbusculares en un suelo volcánico del centro sur de chile. *Revista de la ciencia del suelo y nutrición vegetal*, 6(3):26–39. Online: https://bit.ly/3ycITQQ.

Rojas, D., Botero, J., and Osorio, O. (2013). Análisis técnico económico de sistemas de ganadería en confinamiento modelo establo invernadero en el departamento del quindío. *Sinapsis*, 5(5):127–136. Online: https://bit.ly/2QnUMm0.

Rovaletti, M. L. (1989). Teoría general de los sistemas. *Signo y Pensamiento*, 8(15):45 – 56. Online: https://bit.ly/3w9mXnR.

Ruiz, R. and Oregui, L. (2001). El enfoque sistémico en el análisis de la producción animal: revisión bibliográfica (revisión). *Invest. Agr.: Prod. Sanid. Anim*, 16(1):29–60. Online: https://bit.ly/3tR5teg.

Sharma, A., Saha, T., Arora, A., Shah, R., and Nain, L. (2017). Efficient microorganism compost benefits plant growth and improves soil health in calendula and marigold. *Horticultural Plant Journal*, 3(2):67–72. Online: https://bit.ly/3btYdic.

Sosa, B. and García, Y. (2019). Emisión de gases de efecto invernadero en el suelo bajo el uso de abonos verdes. *Agronomía Mesoamericana*, 30(3):767–782. Online: https://bit.ly/3yw9uZs.

Stamberg, A. R. P. (2015). Enfoque sistémico en administración rural: estudio de la unidad de producción familiar. *Ciencias Administrativas*, (5):23124–3738. Online: https://bit.ly/3flGB9p.

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M., and Haan, C. (2009). *La larga sombra del ganado: problemas ambientales y opciones*. FAO.

Vargas, A., Calderón, D., Mendoza, M., Rugeles, W., Fernández, O., and Álvarez, P. (2020). *Contribuciones académicas a los Diseños y Sostenibilidades en Colombia*. Unidad de Publicaciones Universidad de Investigación y Desarrollo – UDI. Online: https://bit.ly/3hrdZyh.

Vezzoli, C., Kohtala, C., Srinivasan, A., Diehl, J., Fusakul, S., Xin, L., and Sateesh, D. (2014). *Product-service system design for sustainability*. Routledge. Online: https://bit.ly/33RhENG.

Wang, X., Jia, Z., Liang, L., Yang, B., Ding, R., Nie, J., and Wang, J. (2016). Impacts of manure application on soil environment, rainfall use efficiency and crop biomass under dryland farming. *Scientific reports*, 6(1):1–8. Online: https://go.nature.com/3omgVNT.