

Impact on the leaf moisture and chlorophyll content in *Bursera bipinnata* (DC.) Engl. from the extraction of resin

Martínez-Galván, Fredy¹; Buendía-Espinoza, Julio C.^{1*}; Martínez-Ochoa, Elisa d. C.²; Arrazate-Jiménez, Selene d. C.³; García-Núñez, Rosa M.²

¹ Universidad Autónoma Chapingo. Maestría en Agroforestería para el Desarrollo Sostenible, Departamento de Suelos. Carretera México-Texcoco Km 38.5, Texcoco, Estado de México. C. P. 56230.

² Universidad Autónoma Chapingo. Área de Agronomía. Departamento de Preparatoria Agrícola., Carretera México-Texcoco Km 38.5, Texcoco, Estado de México, C. P. 56230.

³ Universidad Autónoma Chapingo. Departamento de Fitotecnia, Carretera México-Texcoco Km 38.5, Texcoco, Estado de México, C. P. 56230.

* Correspondence: jbuendiae@chapingo.mx

ABSTRACT

Objective: To establish the variables of the resin extraction method that have the greatest influence on the leaf moisture and chlorophyll content in *Bursera bipinnata*, through correlation analysis and multiple linear regression, to determine the physiological impact.

Design/methodology/approach: The experimental site was developed in the Los Sauces micro watershed, in Morelos, Mexico, with a random sample of n=70 trees. The explicative variables corresponded to the extraction method. The response variables were the Normalized Difference Moisture Index (NDMI) and the Green Chlorophyll Index (GCI).

Results: The resin production is correlated with the NDMI in October ($r=-0.287$; $p=0.016$). The incision depth was correlated with the GCI in August ($r=-0.438$; $p=0.001$) and October ($r=-0.300$; $p=0.012$). The resin production and the incision depth were factors associated with the NDMI in October ($R^2=0.09$; $p=0.041$). Meanwhile, the incision depth and the total number of resin tapping faces were factors associated with the CGI in August ($R^2=0.204$; $p=0.05$) and October ($R^2=0.106$; $p=0.023$).

Limitations on study/implications: The results are limited to the period and sampling site; it is recommended to replicate the study in other ecological conditions.

Findings/conclusions: Finally, it is necessary to limit the incision depth, as well as the number of resin tapping faces, especially under drought conditions, since this would favor their sustainable exploitation.

Keywords: Copal, non-timber forest products, physiological impact, NDMI, GCI.

Citation: Martínez-Galván, F., Buendía-Espinoza, J. C., Martínez-Ochoa, E. del C., Arrazate-Jiménez, S. del C., García-Núñez, R. M. (2025). Impact on the leaf moisture and chlorophyll content in *Bursera bipinnata* (DC.) Engl. from the extraction of resin. *Agro Productividad*. <https://doi.org/10.32854/afscgt08>

Academic Editor: Jorge Cadena Iñiguez

Associate Editor: Dra. Lucero del Mar Ruiz Posadas

Guest Editor: Juan Francisco Aguirre Medina

Received: May 3, 2025.

Accepted: September 11, 2025.

Published on-line: November 20, 2025.

Agro Productividad, 18(10). October. 2025. pp: 97-110.

This work is licensed under a Creative Commons Attribution-Non-Commercial 4.0 International license.



INTRODUCTION

The collection of non-timber forest products (NTFP) is an activity of economic, social and ecological importance in Mexico, especially in dry tropical forests. Among NTFP, resins obtained from the genus *Bursera*, such as copal, represent a strategic resource for rural communities. *Bursera bipinnata* (DC.) Engl. stands out from this group because of the volume and quality of the resin it produces (Medina-Lemos, 2008).



The species of *Bursera* present the capacity to exude resin immediately after tissue damage, phenomenon that constitutes a compositional defense mechanism against herbivores and pathogens (Becerra *et al.*, 2001). This resin contains bioactive compounds such as terpenoids and lignans, whose biosynthesis implies a high energetic cost for the plant (Marcotullio *et al.*, 2018; Pallardy, 2008). On the other hand, resin production as a defense mechanism is activated by stress signals in face of tissue damage, induced by reactive oxygen species (ROS), electrical signals, calcium (Ca²⁺), and jasmonic acid (Choi *et al.*, 2017).

The traditional extraction of resin from *B. bipinnata* is conducted during the rainy season, through repeated incisions in trunks or branches, with metallic tools, and collected through in maguey leaves or plastic bottles (Montúfar-López, 2016). Although this practice has cultural and economic importance, its intensive execution can compromise key processes such as growth, reproduction and regeneration of the tree, in addition to exposing the plant to exogenous stress factors (Huot *et al.*, 2014).

Various studies have documented negative physiological effects in resin-producing species subjected to frequent extraction, including reductions in nutrient content, carbohydrate reserves, and leaf area, as well as in the reproductive capacity (Abad-Fitz *et al.*, 2022; Khan *et al.*, 2018; Mengistu *et al.*, 2012; Montúfar-López, 2016).

In *B. bipinnata*, the frequency and depth of the damage during extraction could affect vascular tissues, altering water and nutrient transport, which could generate physiological stress that limits photosynthesis, post-stress recovery, as well as growth. In face of this scenario, the objective was to determine how the variables of the resin extraction method impact the leaf moisture and chlorophyll content in *Bursera bipinnata* using multiple linear regression models. The results will allow optimizing the collection practices, reducing the physiological impact on the trees, and fostering a sustainable management of this resource in dry tropical ecosystems.

MATERIALS AND METHODS

Study area

The study was carried out in the Los Sauces micro watershed, located in the Cuautla River sub watershed, in the southeast of the state of Morelos, Mexico. This micro watershed covers a surface of 384 ha, with an altitudinal range of 1230 to 1580 meters, subhumid semi-warm climate [(A)C(w1)], mean annual temperature of 22.8 °C, and average precipitation of 819.2 mm (Servicio Meteorológico Nacional, 2024). The predominant soils are haplic Phaeozem, with a dark superficial horizon rich in organic matter, clayey subsoil, shallow depth, and high stoniness. The relief corresponds to volcanic mountain with steep slopes, where vegetation is dominated by secondary, shrubby and arboreal tropical dry forest, with dispersed agricultural areas (INEGI, 2015).

Experimental site. The study was conducted in the Los Sauces *ejido*, in Tepalcingo, Morelos, at an altitudinal range of 1368 to 1476 meters, covering 29.21 ha. The dominating vegetation corresponds to secondary shrubby tropical dry forest.

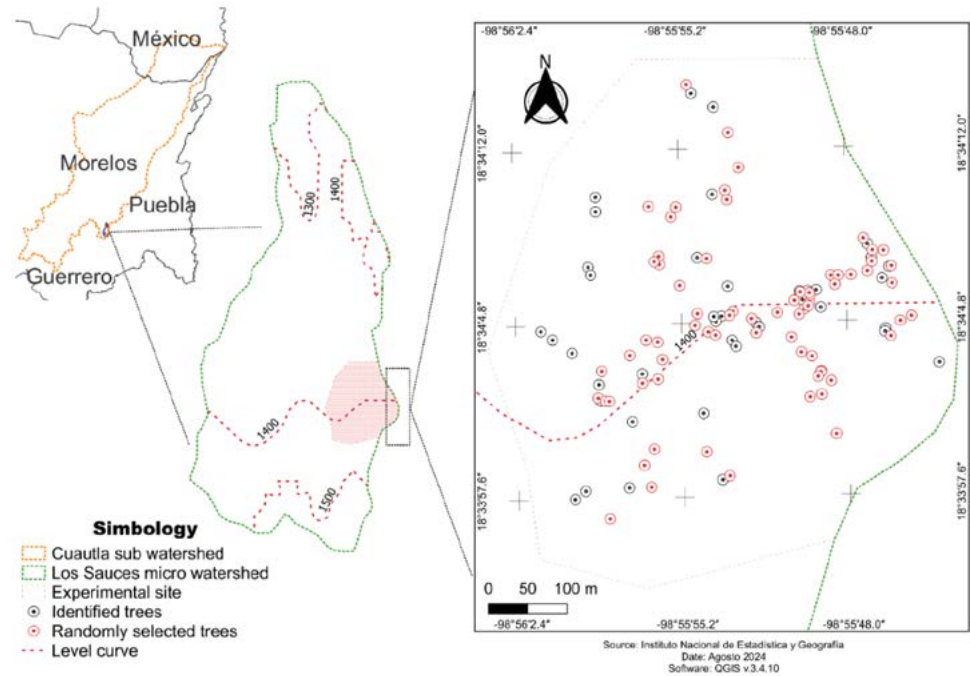


Figure 1. Location of the experimental site and the 70 sampling units (*Bursera bipinnata* trees) inside the Los Sauces micro watershed, Cuautla River sub watershed, state of Morelos.

Response variables

Two spectral indices were selected as indirect indicators of the physiological stress in *Bursera bipinnata* associated to resin extraction: the Normalized Difference Moisture Index (NDMI) and the Green Chlorophyll Index (GCI).

The NDMI, measured for August (NDMIA) and October (NDMIO), was calculated from near-infrared (band 8) and shortwave infrared (band 11) reflectance. This index is sensitive to changes in the hydration of foliage and cell structure of the mesophyll (Gao, 1996), allowing the detection of variations related to water stress induced by tissue damage. In *B. bipinnata*, resin extraction can compromise the functioning of vascular tissues, affecting the transport of water and nutrients to the canopy, as well as the photosynthetic capacity (Bhattacharya, 2021).

The GCI, recorded in the same months (GCIA and GCIO), was used as a proxy of the chlorophyll content and, therefore, of the photosynthetic capacity of the leaves (Gitelson *et al.*, 2005). Reduced levels of chlorophyll reflect a reallocation of resources towards the production of defense compounds after tissue damage, which can jeopardize light harvesting and carbon fixation (Guo *et al.*, 2012; Huot *et al.*, 2014; Khan *et al.*, 2018). Therefore, a decrease in GCI values can be interpreted as a physiological response to stress induced from resin extraction.

Explicative variables

The explicative variables considered in the model are directly related to the resin extraction technique in *B. bipinnata*:

- **Resin tapping faces:** The number of resin tapping faces on the stem (NFS), the branches (NFB), and the total from both (NFT). Each face represents a set of incisions carried out alternately throughout the period of exploitation. These incisions immediately release resin, at the same time triggering a stress response involving calcium, reactive oxygen species, and electrical signals (Choi *et al.*, 2017). These signals induce the biosynthesis of more resin.
- **Resin tapping face height (RFH):** It is the height at which each resin tapping face is made on the tree. Previous studies have shown that the location of the incisions can influence the amount and quality of resin produced (Cheremet *et al.*, 2020), as well as the physiological response to tissue damage.
- **Incision length and depth:** They were recorded as mean length (MIL) and mean depth (MID). These dimensions define the degree of impact on the tissues, from the peridermis, the phloem and the xylem, responsible for the transport of water, nutrients and photo assimilates (García-Pineda, 1988). Deeper and more extensive incisions can induce more intense defensive responses but also jeopardize the vitality of the tree.
- **Mean face area (MFA):** Calculated as indicator of the average size of the resin tapping zones. A higher MFA is associated with an increase in the flow and quality of resin, but also with greater damage of the vascular tissues and reallocation of resources for recovery (Sabo *et al.*, 2022).
- **Total resin tapping area (RTA):** It represents the sum of the areas of all the faces made on the tree during the extraction cycle. This variable quantifies the intensity of use and accumulated damage, which can affect processes such as growth, tissue regeneration, adaptation and survival (Huot *et al.*, 2014).
- **Total resin production (PROD):** Resins are complex mixtures; in the case of *B. bipinnata* they contain mainly terpenoid and lignan compounds, of high metabolic cost (Pallardy, 2008). This variable reflects the defense ability of trees in the presence of tissue damage. Its intensive extraction is related to the reduction in population observed in the region of the High Balsas (Abad-Fitz *et al.*, 2022; Montúfar-López, 2016).

Database and variable measurement

In the experimental site, *B. bipinnata* trees were georeferenced, selected for their use by copal extractors during the period of August to October 2023. Each tree was considered as a sampling unit. Initially, 111 trees were recorded, from which a simple random sample of 70 units was selected, using the sample function of the R software (R Core Team, 2024).

The geographical coordinates of each tree were obtained through a global positioning system (GPS) device. The *resin tapping face height* was measured from the ground level with a measuring tape, averaging the height of each face in the tree. The *incision length* was determined with the same measuring tape, taking the average of the incisions located in the center of each face. The *incision depth* was measured with calipers, considering the average of the incisions also located in the middle of each face.

The *area of each resin tapping face* was calculated through the trapezoid formula, using the measurements of the bases and the height of the faces, obtained with measuring tape. The mean value of these areas was used to calculate the *total resin tapping area per tree*, by multiplying the average by the total number of faces found. The *total production* of resin was weighed at the end of the exploitation cycle with a triple beam balance, recording the total weight of resin collected per tree.

The *physiological variables*, corresponding to the NDMI and the GCI, were estimated from Sentinel-2 L2A satellite images. Calculation of the indices was carried out in the QGIS 3.10 software with a raster calculator. The NDMI was calculated with the formula:

$$NDMI = NIR - SWIR1 / NIR + SWIR1$$

where: *NIR* corresponds to the near-infrared reflectance band (band 8) and *SWIR1* to the shortwave infrared band (band 11). The index results in values between -1 and 1 : values close to -1 indicate bare soils or without plant cover; values close to 0 (-0.2 to 0.4) reflect possible water stress; while values higher than 0.4 indicate a dense and healthy canopy (EOS Data Analytics, 2024; Sentinelhub, 2024).

The GCI was calculated through the formula:

$$GCI = NIR / Green - 1$$

where: *NIR* represents the near-infrared band (band 8) and *Green* the reflectance of the green band (band 3). This index presents values between 0 and 10 ; high values indicate higher content of chlorophyll and greater photosynthetic capacity, while low values can be indication of physiological stress and low photosynthetic activity.

Data analysis

To identify the best explicative model of physiological stress in *B. bipinnata*, a two-stage statistical analysis was conducted: linear correlation and multiple linear regression, using the R software (R Core Team, 2024). The variables related to the extraction methods were treated as explicative, while the NDMI and GCI indices evaluated in August and October were used as response variables.

In the first stage, the Pearson correlation coefficient (r_{xy}) was applied to determine the linear relationship between pairs of variables. The magnitude of the correlation was classified in function of its absolute value, from very weak (<0.25) to very strong (≥ 0.75), evaluating the significance with a confidence level of 95% and contrasting the hypothesis of independence through the *t*-Student distribution with $n-2$ degrees of freedom (McGibney, 2023).

Then, multiple linear regression (MLR) models were adjusted to evaluate the joint effect of the explicative variables on the physiological indices. The model was structured according to:

$$Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \dots + \beta_p X_{pi} + \varepsilon_i$$

where: Y_i is the response variable, β_p the model's coefficients, X_{pi} the explicative variables, and ε_i the random error (Cohen *et al.*, 2003). Standardized coefficients (β) were calculated to estimate the relative importance of each predictor and the adjusted determination coefficient ($R_{adjusted}^2$) was used as a measure of goodness of fit. In addition, the assumptions of the model were verified through graphic analysis and statistical tests: linearity, independence, normality (Shapiro-Wilk and Q-Q graphs), and homoscedasticity (Breusch-Pagan test and residue graphs) (Cohen *et al.*, 2003).

To avoid problems of multicollinearity, correlations between the explicative variables ($|r| > 0.70$) and the variance inflation factor ($VIF > 4$) (Schober *et al.*, 2018) were analyzed. The redundant variables were rejected to improve the accuracy of the model (Akinwande *et al.*, 2015). These measurements were evaluated through corrplot (Wei and Simko, 2021) and usdm (Naimi *et al.*, 2014) packages in R.

RESULTS AND DISCUSSION

Database and variable selection

The database was established by 70 *Bursera bipinnata* trees, whose geographic location was georeferenced. As predicting variables, the following were considered: resin tapping faces on the stem, resin tapping faces on the branches, total resin tapping faces, face height, incision length, incision depth, mean area of the face, total resin tapping area, and resin yield. The response variables were: $NDMI_{August}$, $NDMI_{October}$, GCI_{August} and $GCI_{October}$.

Table 1 shows that the median number of resin tapping faces on the stem was 0, and the number of resin tapping faces on the branches and number of total resin tapping faces was 1. On average, the face height was 1.56 ± 0.66 m, the incision length was 15.64 ± 3.57 cm, and the depth 5.97 ± 2.40 mm. The mean face area was 56.77 ± 20.15 cm², while total resin tapping area reached 90.72 ± 52.69 cm². The mean resin production per tree was 38.56 ± 50.44 g.

Table 1. Descriptive statistics of the resin tapping method.

Variable	Units	Median	Minimum	Maximum	Range
Resin tapping faces on the stem	Amount	0.00	0.00	2.00	2.00
Resin tapping faces on branches	Amount	1.00	0.00	4.00	4.00
Total resin tapping faces	Amount	1.00	1.00	4.00	3.00
Variable	Units	Mean	Minimum	Maximum	Standar deviation
Resin tapping face height	m	1.56	0.40	3.72	0.66
Incision length	cm	15.64	5.00	25.00	3.57
Incision depth	mm	5.97	3.00	19.00	2.40
Mean resin tapping face area	cm ²	56.77	18.00	109.25	20.15
Total resin tapping area	cm ²	90.72	18.00	285.00	52.69
Resin yield	g	38.56	0	190	50.44

Table 2 shows that the NDMI decreased from 0.30 ± 0.02 in August to 0.11 ± 0.05 in October, and the GCI went from 4.76 ± 0.46 to 3.79 ± 0.47 , which suggests a progressive reduction in the moisture content and the photosynthetic capacity of the foliage.

Correlation coefficient

The Pearson correlation coefficient analysis indicated that no productive variable presented a significant association with the NDMI in August (Table 3). However, in October, resin production showed a weak negative correlation, although significant, with this index ($r = -0.287$; $p = 0.016$), suggesting that a higher extraction could be related to a lower availability of water in the canopy (Table 4).

Regarding the GCI, incision depth was the only variable that presented a significant negative correlation in August ($r = -0.438$; $p = 0.001$) and October ($r = -0.300$; $p = 0.012$). This finding shows that deeper incisions can be associated with a reduction in the photosynthetic capacity, possibly due to a greater allotment of resources to defense mechanisms (Table 5 and Table 6).

Multiple linear regression model

Two multiple linear regression (MLR) models were constructed to analyze the effect of the productive variables on the physiological indices NDMI and GCI in *Bursera bipinnata*. Both models were defined from the results of the correlation analysis and fulfilled the

Table 2. Descriptive statistics of physiological variables.

Variable	Units	Mean	Minimum	Maximum	Standar deviation
<i>NDMI</i> _{August}	Dimensionless	0.30	0.25	0.35	0.02
<i>NDMI</i> _{October}	Dimensionless	0.11	-0.004	0.24	0.05
<i>GCI</i> _{August}	Dimensionless	4.76	3.71	5.86	0.46
<i>GCI</i> _{October}	Dimensionless	3.79	2.39	4.80	0.47

Table 3. Correlation between productive parameters and NDMI in August.

Variable	Pearson Correlation Coefficient	Sig.
Resin tapping faces on the stem	-0.055	0.652
Resin tapping faces on branches	-0.057	0.639
Total resin tapping faces	-0.113	0.353
Resin tapping face height	0.014	0.906
Incision length	0.006	0.964
Incision depth	-0.085	0.485
Mean resin tapping face area	-0.006	0.963
Total resin tapping area	-0.013	0.915
Resin yield	-0.179	0.139

** Correlation is significant at the 0.01 level (two-tailed).

* Correlation is significant at the 0.05 level (two-tailed).

Table 4. Correlation between productive parameters and NDMI in October.

Variable	Pearson Correlation Coefficient	Sig.
Resin tapping faces on the stem	0.030	0.788
Resin tapping faces on branches	-0.169	0.163
Total resin tapping faces	-0.211	0.080
Resin tapping face height	-0.051	0.674
Incision length	0.047	0.698
Incision depth	-0.90	0.457
Mean resin tapping face area	-0.010	0.937
Total resin tapping area	-0.103	0.398
Resin yield	-0.287*	0.016

** Correlation is significant at the 0.01 level (two-tailed).

* Correlation is significant at the 0.05 level (two-tailed).

Table 5. Correlation between productive parameters and GCI in August.

Variable	Pearson Correlation Coefficient	Sig.
Resin tapping faces on the stem	-0.094	0.438
Resin tapping faces on branches	0.150	0.214
Total resin tapping faces	0.147	0.225
Resin tapping face height	0.057	0.641
Incision length	-0.192	0.112
Incision depth	-0.438**	<0.001
Mean resin tapping face area	-0.226	0.060
Total resin tapping area	-0.021	0.861
Resin yield	0.079	0.513

** Correlation is significant at the 0.01 level (two-tailed).

* Correlation is significant at the 0.05 level (two-tailed).

Table 6. Correlation between productive parameters and GCI in October.

Variable	Pearson Correlation Coefficient	Sig.
Resin tapping faces on the stem	-0.111	0.365
Resin tapping faces on branches	0.161	0.184
Total resin tapping faces	0.151	0.213
Resin tapping face height	0.023	0.850
Incision length	-0.065	0.594
Incision depth	-0.300*	0.012
Mean resin tapping face area	-0.173	0.152
Total resin tapping area	0.018	0.881
Resin yield	0.153	0.207

** Correlation is significant at the 0.01 level (two-tailed).

* Correlation is significant at the 0.05 level (two-tailed).

statistical assumptions of normality, homoscedasticity and independence of the residues, guaranteeing the validity of the inferences.

Normalized Difference Moisture Index (NDMI). In the month of October, the model included the following predictors: resin production (PROD) and incision depth (MID). Only the resin production showed a significant effect ($p=0.016$), which explains 9% of the variability in the canopy moisture (adjusted $R^2=0.063$). The negative coefficient indicates that a greater extraction of resin is associated with a decrease in the leaf moisture content ($\hat{\beta}_1 = -0.287$), suggesting a relationship between intensive exploitation and water stress in the canopy (Table 7).

Green Chlorophyll Index (GCI). For the month of August, the model incorporated the incision depth (MID) and the total number of resin tapping faces (NFT). The incision depth was the only significant predictor ($p<0.05$), explaining 20.4% of the variation observed (adjusted $R^2=0.180$). A negative effect was identified ($\hat{\beta}_1 = -0.420$), which means that deeper incisions negatively affect the chlorophyll content, probably due to a higher allotment of resources to defense mechanisms, as well as from the damage to vascular tissues (Table 8).

For the month of October, only the incision depth showed a statistically significant effect ($p=0.014$), with negative coefficient ($\hat{\beta}_1 = -0.289$). The model explained 10.6% of the index variability (adjusted $R^2=0.079$), which suggests that deep incisions carried out at the end of the season also compromise the photosynthetic activity (Table 9).

Table 7. Model on the effects of the productive parameters on NDMI in October.

	Estimate	Standard Error	T-Value	Pr> t
INTERCEPT	0.000	0.115	0.000	1.000
PROD	-0.287	0.116	-2.463*	0.016
MID	-0.089	0.116	-0.772	0.443

Residual standard error: 0.967 on 67 degrees of freedom.

Multiple R-squared: 0.090 and adjusted R-squared: 0.063.

F-statistic: 3.334 on 2 and 67 degrees of freedom, p -value: 0.041.

Variance Inflation Factor (VIF): PROD: 1.000; MID: 1.000.

*** Correlation is significant at the 0.001 level (two-tailed).

** Correlation is significant at the 0.01 level (two-tailed).

* Correlation is significant at the 0.05 level (two-tailed).

Table 8. Model on the effects of productive parameters on GCI in August.

	Estimate	Standard Error	T-Value	Pr> t
INTERCEPT	0.000	0.108	0.000	1.000
MID	-0.428	0.109	-3.925***	<0.05
NFT	0.114	0.109	1.051	0.297

Residual standard error: 0.905 on 67 degrees of freedom.

Multiple R-squared: 0.204, and adjusted R-squared: 0.180.

F-statistic: 8.614 on 2 and 67 degrees of freedom, p -value: 0.05.

Variance Inflation Factor (VIF): MID: 1.005; NFT: 1.005.

*** Correlation is significant at the 0.001 level (two-tailed).

** Correlation is significant at the 0.01 level (two-tailed).

* Correlation is significant at the 0.05 level (two-tailed).

Table 9. Model on the effects of productive parameters on GCI in October.

	Estimate	Standard Error	T-Value	Pr > t
INTERCEPT	-0.000	0.114	0.000	1.000
MID	-0.289	0.115	-2.502*	0.014
NFT	0.129	0.115	1.114	0.269

Residual standard error: 0.959 on 67 degrees of freedom.

Multiple R-squared: 0.106, and adjusted R-squared: 0.079.

F-statistic: 3.98 on 2 and 67 degrees of freedom, *p*-value: 0.023.

Variance Inflation Factor (VIF): MID: 1.005; NFT: 1.005.

*** Correlation is significant at the 0.001 level (two-tailed).

** Correlation is significant at the 0.01 level (two-tailed).

* Correlation is significant at the 0.05 level (two-tailed).

The results indicate that resin tapping in *B. bipinnata* has important physiological effects on moisture and chlorophyll content in the canopy, estimated from the NDMI and GCI indices.

Relationship between NDMI and resin yield

The correlation analysis and the multiple linear regression model evidenced a negative relationship between the NDMI and resin production during the month of October. As resin production increases, the moisture content in the canopy decreases, which suggests that the intensity of tissue damage from extraction affects the water supply, from the root system to the leaves. In previous studies in *Boswellia* and *Acacia* have proven that the increase in intensity of tissue damage generates an increase in the yield of resin or gum (Negussie *et al.*, 2021; Sabo *et al.*, 2022), but the physiological effect from the damage is not established. In this study, the average incision depth, which was 5.97 ± 2.40 mm, showed impacts on peridermis, conducting and non-conducting phloem, which is where the resin producing channels are located (García-Pineda, 1988). Likewise, the damage from incision depth reached the xylem, tissue responsible for the ascending transport of water to satisfy the demand for transpiration and cell expansion (Couvreur *et al.*, 2018).

In addition to this, the tissue damage generated by resin extraction could contribute to the loss of water in the main stem and the branches. As exposed by Oliva-Carrasco *et al.* (2015), since the water stored in the trunks can contribute between 6% and 28% to the daily water budget of large trees. In extreme cases, the water stored in the main stems can supply up to 50% of the total daily transpiration (Scholz *et al.*, 2008). Therefore, the reduction in the supply from loss can contribute to the water deficit of the canopy leaves.

This water stress was worsened under conditions of low water availability in the soil, as happened in the sampling period, characterized by a deficit in precipitation. The mean value recorded of NDMI (0.11 ± 0.05) indicated severe stress as consequence of the low volume of accumulated rainfall, which was 26.6 mm between July and October of 2023, in contrast with the 417.48 mm expected for the same period (Servicio Meteorológico Nacional, 2024). This water deficit, combined with the damage in vascular tissues and the loss of water from tissue damage, reduces both the content and the water potential in the plant, which makes the adequate distribution of water

in the tissues difficult (Zhao *et al.*, 2021). In addition this compromises fundamental processes such as cell growth, photosynthesis, respiration rate and other key enzyme processes (Bhattacharya, 2021).

Relationship between GCI and incision depth

The chlorophyll content (GCI) showed a significant negative correlation with the incision depth in both periods evaluated. This evidence shows that an increase in incision depth causes a decrease in canopy chlorophyll content. On the other hand, if it is considered that GCI is a reliable estimator of the green leaf area index (LAI), which is related to the proportion of photosynthetically active leaf area by surface unit of the soil (Nguy-Robertson *et al.*, 2014), it is deduced that the GCI also reflects a leaf area reduction as the incision depth increases. Therefore, if an incision affects the vascular tissues and the transport of water and mineral nutrients through the xylem is altered, as in the case of nitrogen, the composition and function of chloroplasts is collaterally disturbed, specifically the primary reactions of photosynthesis and carbon fixation reactions (Evans and Clarke, 2019).

In addition to this, the tissue damage generated from resin extraction is marked by reactive oxygen species (ROS), calcium (Ca^{2+}), and electrical signals, known as trio signaling (Choi *et al.*, 2017). These signals activate chemical messengers such as jasmonic acid (JA, Koo, 2018), which performs a crucial role in the reallocation of resources, including carbon, hydrogen and nitrogen, towards defense, which contributes to the reduction of essential components for photosynthesis, such as the light harvesting and carbon fixation complexes (Guo *et al.*, 2012; Huot *et al.*, 2014). This contributes to senescence and reduction of the leaf area, as indicated by the GCI values of this study in both periods. This has been proven in *Boswellia papyrifera*, where the continuous and intensive extraction of resin caused a significant decrease in the levels of essential nutrients like nitrogen, carbon and nitrogen, as well as a reduction in the leaf area of the crown, favoring the defensive capacity in detriment of growth and development (Khan *et al.*, 2018; Mengistu *et al.*, 2012).

Physiological effects of the accumulated damage

The multiple linear regression showed that resin production explained 9% of the variation in NDMI, while the incision depth explained 20% and 10.6% of the variability in GCI in August and October, respectively. These results evidenced that intensive exploitation has cumulative physiological impacts in *B. bipinnata*, by jeopardizing water availability and photosynthetic activity in the canopy.

Thus, the reduction in leaf area, consequence of the decrease in water supply and reallocation of resources towards defense, negatively affects the productivity of *B. bipinnata*, since the leaves carry out a crucial role in carbon fixation through photosynthesis and respiration (Binkley *et al.*, 2013). Similarly, the senescence of leaves leads to lower production and storage of non-structural carbohydrates (NSC), which are fundamental for transport of resources, energetic metabolism, cellular osmoregulation, and synthesis of defense compounds, as well as post-stress recovery (Piper and Paula, 2020). In the study by Mengistu *et al.* (2013) for species of the genus *Boswellia*, it has been proven that the continuous and intensive extraction of resin decreases the concentration of non-structural

carbohydrates, leading them to possible exhaustion. In addition to this, the recovery of NSC can take several years due to the continuous extraction of resin, since it compromises the defensive capacity of trees in the presence of conditions of biotic or abiotic stress (Wang *et al.*, 2021). This could contribute directly to the mortality of the *B. bipinnata* trees used if resin tapping is not conducted in a sustainable manner.

CONCLUSIONS

The intensity of resin extraction from *Bursera bipinnata* directly impacts the physiological stress of the trees. The incision depths affect the conducting tissues (xylem and phloem) that reduce the moisture content in the canopy, situation that can be aggravated in contexts of environmental water deficit. The decrease in chlorophyll content, associated with the loss of leaf area and the reallocation of resources towards defense mechanisms, compromises the photosynthetic capacity of the trees. Both effects alter the reserves of non-structural carbohydrates (NSC), fundamental for post-stress recovery, thus increasing the vulnerability of individuals in the presence of adverse biotic and abiotic factors. To promote sustainable management of *B. bipinnata*, the recommendation is to limit the depth of incisions to less than 6 mm, decrease the frequency of extraction, establish rest periods between seasons of exploitation, and reduce or avoid extraction under restrictive environmental conditions (drought). The implementation of these practices will favor the physiological health of the trees, allow keeping their productivity in the long term, strengthen the resilience of dry tropical ecosystems facing the effects of climate change, and contribute to the design of sustainable forest management strategies in local communities.

ACKNOWLEDGEMENTS

The authors wish to thank the Los Sauces Morelos Ejido, especially the families of Don Margarito and Don Joaquín for their willingness to help in this research study.

REFERENCES

- Abad-Fitz, I., Vázquez-Lobo, A., Blancas, J., Casas, A., Sierra-Huelsz, J. A., Martínez-Garza, C., Alcalá, R. A., y Beltrán-Rodríguez, L. (2022). Can Resin Extraction Have an Effect on the Reproductive Biology in Burseraceae Species?: A Global Analysis. *Trees, Forests and People*, 10. <https://doi.org/10.1016/j.tfp.2022.100353>
- Akinwande, M. O., Dikko, H. G., & Samson, A. (2015). Variance inflation factor: as a condition for the inclusion of suppressor variable (s) in regression analysis. *Open journal of statistics*, 5(07), 754. <https://doi.org/10.4236/ojs.2015.57075>
- Allen, C. D., Macalady, A. K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D. D., Hogg E. H., Gonzáles, P., Fensham, R., Zhang, Z., Castro, J., Deminova, N., Lim, J. H., Allard, G., Running, S. T., Semerci, A., & Cobb, N. (2010). A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management*, 259, 660-684. <https://doi.org/10.1016/j.foreco.2009.09.001>
- Becerra, J. X., Venable, D. L., Evans, P. H., & Bowers, W. S. (2001). Interactions between chemical and mechanical defenses in the plant genus *Bursera* and their implications for herbivores. *American Zoologist*, 41(4), 865-876. <https://doi.org/10.1093/ich/41.4.865>
- Bhattacharya, A. (2021). Soil water deficit and physiological issues in plants. Springer. <https://doi.org/10.1007/978-981-33-6276-5>
- Binkley, D., Campoe, O. C., Gspaldt, M., & Forrester, D. I. (2013). Light absorption and use efficiency in forests: Why patterns differ for trees and stands. *Forest ecology and management*, 288, 5-13. <https://doi.org/10.1016/j.foreco.2011.11.002>

- Cherenet, E., Abiyu, A., Ambachew, G., Kibruyesfa, S., & Tatek, D. (2020). Tapping height and season affect frankincense yield and wound recovery of *Boswellia papyrifera* trees. *Journal of Arid Environments*, 179, 1-5. <https://doi.org/10.1016/j.jaridenv.2020.104176>
- Choi, W. G., Miller, G., Wallace, I., Harper, J., Mittler, R. & Gilroy, S. (2017). Orchestrating rapid long-distance signaling in plants with Ca²⁺, ROS and electrical signals. *Plant J*, 90, 698-707. <https://doi.org/10.1111/tpj.13492>
- Cohen, J., Cohen, P., West, S. G., & Aiken, L. S. (2003). Applied Multiple Regression/Correlation Analysis for the Behavioral Sciences. LAWRENCE ERLBAUM ASOCIATES, PUBLISHERS.
- Couvreur, V., Ledder, G., Manzoni, S., Way, D. A., Muller, E. B., & Russo, S. E. (2018). Water transport through tall trees: a vertically explicit, analytical model of xylem hydraulic conductance in stems. *Plant, Cell & Environment*, 41(8), 1821-1839. <https://doi.org/10.1111/pce.13322>
- EOS Data Analytics. (2024). NDMI: Índice de Humedad de Diferencia Normalizada. <https://eos.com/es/make-an-analysis/ndmi/#:~:text=El%20C3%8Dndice%20de%20Humedad%20de,estr%C3%A9s%20h%C3%ADdrico%20en%20los%20cultivos>
- Evans, J. R., & Clarke, V. C. (2019). The nitrogen cost of photosynthesis. *Journal of Experimental Botany*, 70(1), 7-15. <https://doi.org/10.1093/jxb/ery366>
- Gao, B. C. (1996). NDWI-A normalized difference water index for remote sensing of vegetation liquid water from space. *Remote sensing of environment*, 58(3), 257-266. [https://doi.org/10.1016/S0034-4257\(96\)00067-3](https://doi.org/10.1016/S0034-4257(96)00067-3)
- García-Pineda, M. O. (1988). Descripción anatómica de la corteza de seis especies del género *Bursera*. [Tesis Profesional, Universidad Autónoma de México]. Repositorio Institucional de la UNAM. <https://repositorio.unam.mx/>
- Gitelson, A. A., Viña, A., Ciganda, V., Rundquist, D. C., & Arkebauer, T. J. (2005). Remote estimation of canopy chlorophyll content in crops. *Geophys. Res. Lett.*, 32(8), L08403. <https://doi.org/10.1029/2005GL022688>
- Guo, J., Pang, Q., Wang, L., Yu, P., Li, N., & Yan, X. (2012). Proteomic identification of MYC2-dependent jasmonate-regulated proteins in *Arabidopsis thaliana*. *Proteome Sci* 10(57). <https://doi.org/10.1186/1477-5956-10-57>
- Huot, B., Yao, J., Montgomery, B. L., & He, S. Y. (2014). Growth–defense tradeoffs in plants: A balancing act to optimize fitness. *Molecular plant*, 7(8), 1267-1287. <https://doi.org/10.1093/mp/ssu049>
- Instituto Nacional de Estadística y Geografía. INEGI. (2015). Guía para la interpretación de cartografía: Uso del suelo y vegetación: Escala 1:250 000 Serie V. INEGI. México.
- Khan, A. L., Al-Harrasi, A., Shahzad, R., Imran, Q. M., Yun, B. W., Kim, Y. H., Kang, S. M., Al-Rawahi, A., & Lee, I. J. (2018). Regulation of endogenous phytohormones and essential metabolites in frankincense-producing *Boswellia sacra* under wounding stress. *Acta Physiologiae Plantarum*, 40(113), 1-11. <https://doi.org/10.1007/s11738-018-2688-6>
- Koo, A. J. (2018). Metabolism of the plant hormone jasmonate: a sentinel for tissue damage and master regulator of stress response. *Phytochem Rev.*, 17, 51-80 <https://doi.org/10.1007/s11101-017-9510-8>
- Marcotullio, M. C., Curini, M., & Becerra, J. X. (2018). An ethnopharmacological, phytochemical and pharmacological review on lignans from mexican *Bursera* spp. *Molecules*, 23(8), 1-20. <https://doi.org/10.3390/molecules23081976>
- McGibney, D. P. (2023). Applied Linear Regression for Business Analytics with R. A practical Guide to Data Science with Case Studies. Springer. <https://doi.org/10.1007/978-3-031-21480-6>
- Medina-Lemos, R. (2008). Fascículo 66. Burseraceae. En Flora del valle de Tehuacán-Cuicatlán (pp. 1-76). Universidad Nacional Autónoma de México. ISBN 970-32-5083-7
- Mengistu, T., Sterck, F. J., Anten, N. P. A., & Bongers, F. (2012). Frankincense tapping reduced photosynthetic carbon gain in *Boswellia papyrifera* (Burseraceae) trees. *Forest Ecology and Management*, 278, 1-8. <https://doi.org/10.1016/j.foreco.2012.04.029>
- Mengistu, T., Sterck, F. J., Fetene, M., & Bongers, F. (2013). Frankincense tapping reduces the carbohydrate storage of *Boswellia* trees. *Tree physiology*, 33(6), 601-608. <https://doi.org/10.1093/treephys/tppt035>
- Montúfar-López, A. (2016). Copal de *Bursera bipinnata*. Una resina mesoamericana de uso ritual. *Trace*, 70, 45-78.
- Naimi, B., Hamm, N. A., Groen, T. A., Skidmore, A. K., & Toxopeus, A. G. (2014). Where is positional uncertainty a problem for species distribution modelling? *Ecography*, 37(2), 191-203. <https://doi.org/10.1111/j.1600-0587.2013.00205.x>
- Negussie, A., Gebrehiwot, K., Yohannes, M., Norgrove, L., & Aynekulu, E. (2021). Continuous resin tapping for frankincense harvest increases susceptibility of *Boswellia papyrifera* (Del.) Hochst trees to longhorn beetle damage. *Heliyon*, 7(2), 1-7. <https://doi.org/10.1016/j.heliyon.2021.e06250>

- Nguy-Robertson, A. L., Peng, Y., Gitelson, A. A., Arkebauer, T. J., Pimstein, A., Herrmann, I., Karnieli, A., Rundquist, D. C., & Bonfil, D. J. (2014). Estimating green LAI in four crops: Potential of determining optimal spectral bands for a universal algorithm. *Agricultural and forest meteorology*, 192, 140-148. <https://doi.org/10.1016/j.agrformet.2014.03.004>
- Oliva-Carrasco, L., Bucci, S. J., Di-Francescantonio, D., Lezcano, O. A., Campanello, P. I., Scholz, F. G., Rodríguez, S., Madanes, N., Cristiano, P. M., Hao, G. Y., Holbrook, N. M., & Goldstein, G. (2015). Water storage dynamics in the main stem of subtropical tree species differing in wood density, growth rate and life history traits. *Tree physiology*, 35(4), 354-365. <https://doi.org/10.1093/treephys/tpu087>
- Pallardy, S. G. (2008). Physiology of Woody plants. *Science Direct*. ISBN: 978-0-12-088765-1
- Piper, F. I., & Paula, S. (2020). The role of nonstructural carbohydrates storage in forest resilience under climate change. *Current Forestry Reports*, 6, 1-13. <https://doi.org/10.1007/s40725-019-00109-z>
- R Core Team. (2024). R: A language and environment for statistical computing (Versión 4.4.1) [Software]. R Foundation for Statistical Computing. <https://www.r-project.org/>
- Sabo, P., Salako, K. V., Kakai, R. G., & Trees, A. O. (2022). Combined effects of tree size and tapping techniques on resin production of *Boswellia dalzielii* Hutch., an African frankincense tree. *Trees*, 36, 1697-1710. <https://doi.org/10.1007/s00468-022-02320-1>
- Schober, P., Boer, C., & Schwarte, L. A. (2018). Correlation coefficients: appropriate use and interpretation. *Anesthesia & analgesia*, 126(5), 1763-1768. <https://doi.org/10.1213/ANE.0000000000002864>
- Scholz, F. C., Bucci, S. J., Goldstein, G., Meinzer, F. C., Franco, A. C., & Miralles-Wilhelm, F. (2008). Temporal dynamics of stem expansion and contraction in savanna trees: withdrawal and recharge of stored water. *Tree Physiology*, 28(3), 469-480. <https://doi.org/10.1093/treephys/28.3.469>
- Sentinelhub. (2024). Normalized Difference Moisture Index (NDMI). <https://custom-scripts.sentinel-hub.com/sentinel-2/ndmi/>
- Servicio Meteorológico Nacional (SMN). (2024). Estación Meteorológica Automatizada El Limón, Tepalcingo. Datos climáticos. México.
- Wang, Z., Zhou, Z., & Wang, C. (2021). Defoliation-induced tree growth declines are jointly limited by carbon source and sink activities. *Science of The Total Environment*, 762, 1-9. <https://doi.org/10.1016/j.scitotenv.2020.143077>
- Wei, T., & Simko, V. (2021). R Package “Corrplot”: Visualization of a Correlation Matrix.
- Zhao, J., Lu, Z., Wang, L., & Jin, B. (2021). Plant Responses to Heat Stress: Physiology, Transcription, Noncoding RNAs, and Epigenetics. *International Journal of Molecular Sciences*, 22(1), 117. <https://doi.org/10.3390/ijms22010117>