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Research article

Kawí Tamiruyé: A permanent research forest plot in the *Sierra Tarahumara*

Kawí Tamiruyé: Una parcela permanente de investigación forestal en la Sierra Tarahumara

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Abstract

Periodic and continuous monitoring is an appropriate strategy to identify information needs for the planning and management of forest resources. The aim of this work was to characterizes the dasometric and structural parameters of a permanent research plot in Northern Mexico. From a census-based methodology, 2 165 trees (*n*) were recorded in an area of 1.4 ha^{-1} and, through the application of various sampling schemes, dasometric variables, and diversity indices were estimated for comparison with the census of a reference plot. As result, we estimated the following dasometric measurements: Quadratic Mean Diameter (*QMD*)=12.16 cm, Crown Area (*CA*)=61.6 %, Reineke's Stand Density Index (*SDI*)=668 individuals, Basimetric Area (*BA*)=25.16 m^2, Total Volume (*Vol*)=158.83 m^3 ha^{-1}, aboveground biomass (*AGB*)=142.78 Mg ha^{-1}, and Carbon (*C*)=71.39 Mg ha^{-1}. Ecologically, the species with the highest Importance Value Index (*IVI*) were *P. engelmannii* and *J. deppeana* (50.8 and 35 %, respectively). The Simpson's dominance index (δ)=0.39 and diversity (λ)=0.61 were low, as was the Shannon-Wiener index of diversity (*H'*)=1.3, which is in agreement with the Margalef index (*DMG*)=1.04. The value of Pielou's evenness (*J'*)=0.53 confirmed low abundance. Equidistant systematic sampling at 40 m was closer to the reference census, presenting lower values in the mean and variance estimators compared to the other sampling methods. This plot represents an important source of information for develop adaptative strategies in management portfolios to improve decision-making, in the face of forest stand dynamics. Although further studies on site size, inclusion of additive indices, and operational costs are required.

Key words: Diversity indices, ecosystem structure, forest monitoring, permanent plots, sampling strategies, UAV monitoring.

Resumen

El monitoreo periódico y continuo es una estrategia apropiada para identificar información necesaria para la planeación y manejo de los recursos forestales. El objetivo de este trabajo fue caracterizar los parámetros dasométricos y estructurales de una parcela permanente de investigación en el norte de México. A partir de un censo total, se registraron 2 165 árboles (*n*) en una superficie de 1.4 ha^{-1}, y mediante la aplicación de diversos esquemas de muestreo se estimaron variables dasométricas e índices de diversidad para su comparación con el censo de una parcela de referencia. Se estimaron las siguientes variables dasométricas: Diámetro Medio Cuadrático (*DMC*) = 12.16 cm, Área de Copa (*AC*) = 61.6 %, Índice de Densidad de Rodal de *Reineke* (*IDRR*) = 668 individuos, Área Basal (*AB*) = 25.16 m^2, Volumen Total (*Vol*) = 158.83 m^3 ha^{-1}, Biomasa Aérea (*BA*) = 142.78 Mg ha^{-1} y Carbono (*C*) = 71.39 Mg ha^{-1}. Las especies con mayor Índice de Valor de Importancia (*IVI*) fueron *Pinus engelmannii* y *Juniperus deppeana* (50.8 y 35 %, respectivamente). El Índice de Dominancia de *Simpson* (δ) = 0.39 y la diversidad (λ) = 0.61 fueron bajos; al igual que el Índice de Diversidad de *Shannon-Wiener* (*H'*) = 1.3, que concuerda con el Índice de *Margalef* (*DMG*) = 1.04. El valor de la Uniformidad de *Pielou* (*J'*) = 0.53 confirmó la escasa abundancia. El muestreo sistemático equidistante a 40 m se aproximó más al censo de referencia, con valores inferiores en los estimadores de la media y la varianza, en comparación con los otros métodos de muestreo. Esta parcela representa una importante fuente de información para desarrollar estrategias adaptativas de manejo para mejorar la toma de decisiones, ante la dinámica del rodal. No obstante, se requieren estudios adicionales sobre el tamaño del sitio, la inclusión de índices aditivos y de los costos operativos.

Palabras clave: Índices de diversidad, estructura del ecosistema, monitoreo forestal, parcelas permanentes, estrategias de muestreo, monitoreo con UAV.

Introduction

Periodic and continuous monitoring is an appropriate strategy to identify information needs for the planning and management of forest resources; it propitiates the beginning of new paradigms that lead to decision-making in biodiversity and involves metrics of multiple resources that amplify its expansion towards extended variables, not only in the area of timber production (Kakkar *et al.*, 2021).

Currently, forest monitoring in permanent plots has gained ground over traditional procedures (Laine *et al.*, 2013), towards non-traditional metrics that try to adhere to international commitments. In addition, the inventory is intended to be multipurpose and the debate on the role of ecological monitoring associated with forest management remains open (Magagnotti *et al.*, 2023). This linkage is strategic to expand the variables related to timber production with the assessment of ecosystem composition, structure, and function, which provides a better understanding of the roles of biodiversity components in the provision of multiple forest ecosystem functions.

Since tree populations in the forests of the *Sierra Tarahumara* in Mexico varies widely in their species composition, site requirements, age, and growth rates (Graciano-Ávila *et al.*, 2020), they are strategic for establishing monitoring protocols. Thus, the forest manager should seek the appropriate selection of inventory techniques, in terms of economically viable and statistically reliable alternatives. Under these premises, the forests of the *Sierra Tarahumara* are strategic for establishing monitoring protocols, given their floristic complexity and the provision of a wide range of environmental goods and services.

Since permanent ecological forest plots represent an adaptive strategy to generate knowledge, this paper provides dasometric estimates and structural indices to improve the relevance of forest metrics to enhance the scope of forest monitoring. For example, accurate estimations of composition, species diversity, and stand growth dynamics are crucial tools with which to modify traditional monitoring strategies (Linder, 2000). Thus, the conjunction of forest inventories with structural indices has the potential to make a valuable contribution to forest monitoring. We aimed to characterizes the dasometric and structural parameters of a permanent research plot in Northern Mexico.

To generate metrics that contribute to an improved understanding of the structural, compositional, and forest diversity indicators of the studied plot, our specific research questions were: What are the indicators of the structure and diversity of the studied plot?, Do differences arise when using different sampling schemes? We hypothesized that this monitoring strategy improves the knowledge of ecosystem components, which would promote better management policies according to the requirements of the latest protocols.

Materials and Methods

The study area, known as *Kawí Tamiruyé* (meaning "Forest, teach me about you" in the indigenous *Rarámuri* language), corresponds to a continuous and permanent research plot located in the *Sierra Tarahumara* in the Southeast of *Chihuahua* state, Mexico (Figure 1). A total census of the experimental permanent plot was conducted in January 2022.

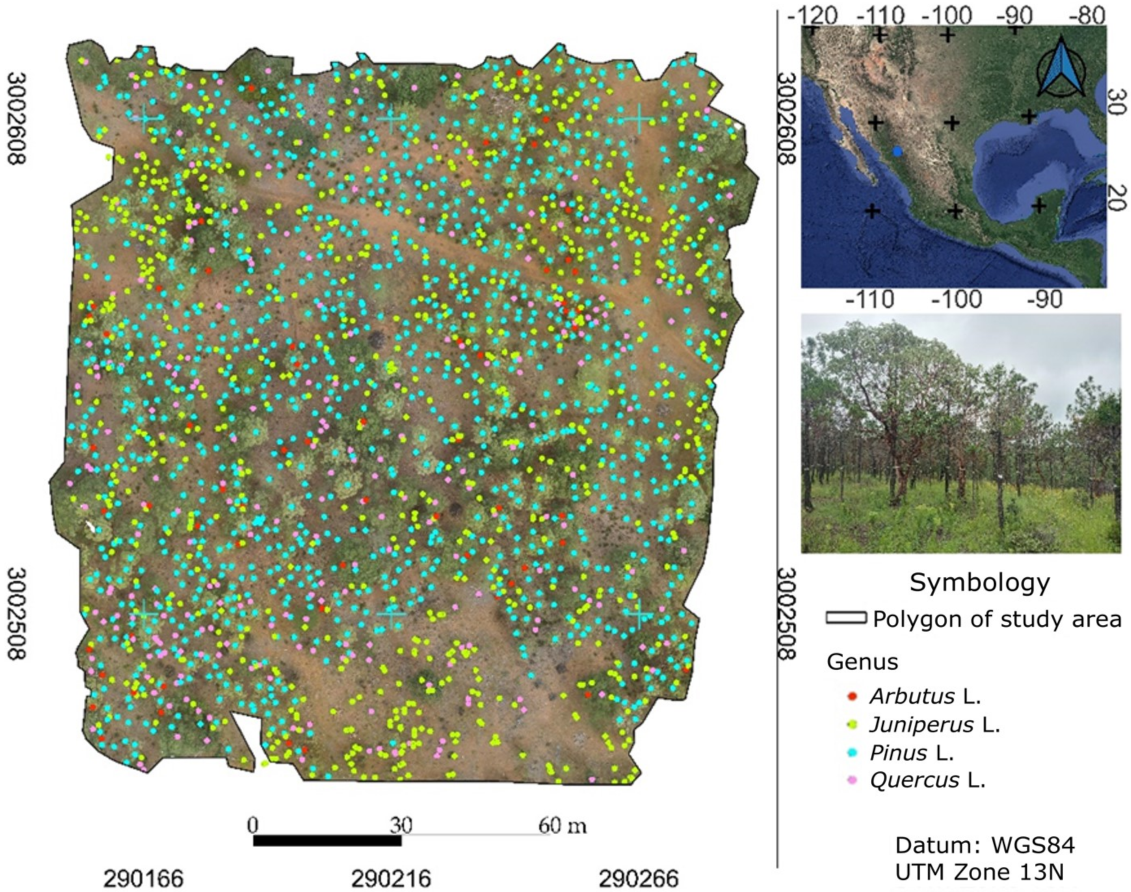

Figure 1. The study area *Kawí Tamiruyé*, in the *Sierra Madre Occidental* of Mexico.

All trees included in the census were labeled, and the species identified, with diameter at breast height (*DBH*, cm) and basal diameter (*BD*, cm) determined using a diametric tape (model 283D/5D Forestry Suppliers® Metric Fabric Diameter Tape 160 cm), commercial height (*CH*, m) and total height (*TH*, m) measured directly by climbing the trees and using a length meter (model TFC-30ME Truper®). To compare the implications of different sampling strategies with respect to the census conducted within the area, three sampling types were adopted: (1) Simple random sampling (ten sites), (2) Stratified random sampling (three strata according to tree density [three and four sites]), and (3) Systematic sampling with three distances

(30 m [14 circular sites], 40 m [nine sites] and 50 m [four sites]). With the flight conducted in August (summer), the crown area (m^2) was digitized individually and as a percentage.

Circular sites of 1 000 m^2 in area (17.84 m in diameter) were established, from which the dasometric information of all individuals within the site was obtained. The dasometric variables calculated were: basimetric area (*BA*), total volume (*Vol*) (Graciano-Ávila *et al.*, 2019; Rascón-Solano *et al.*, 2022), aboveground biomass (*AGB*) (Návar, 2009), Carbon content (*C*) (García *et al.*, 2021), site density (*QMD* and *SDI*) (Tamarit-Urias *et al.*, 2020) and biodiversity indices (Simpson's dominance and diversity index [δ and λ], Shannon-Wiener index of diversity [H'], Margalef index [*DMG*] and Pielou's evenness [J']) (Thukral, 2017).

Results

Table 1 shows the descriptive statistics of the trees present in *Kawí Tamiruyé*. The order of the genera with the highest number of individuals was *Pinus* L., *Juniperus* L., *Quercus* L., and *Arbutus* L. (1 105, 758, 243, and 59 individuals, respectively). The highest average *DBH* and *TH* were recorded in the genus *Quercus* (28.5 cm and 7.2 m, respectively) (Table 1). The highest *TH* recorded was in the genus *Pinus* (21.4 m), while the highest *DBH* was recorded in the genus *Quercus* (62.3 cm), as well as the greatest crown area (123.4 m^2) (Table 1).

Table 1. Descriptive statistics of the dasometric variables per tree genus sampled in *Kawí Tamiruyé*, *Chihuahua*, Mexico.

Genus	Var	*n*	Min	Max	*Avg*	*q1*	*q3*	*SD*	*SE*
Pinus L.	*BD*	1 105	3.0	66.4	14.8	10.1	17.4	7.5	0.2
	DBH		0.0	56.4	11.1	7.1	13.2	6.5	0.2
	CH		0.0	12.6	3.1	2.3	3.5	1.5	0.0
	TH		0.0	21.4	6.8	4.6	8.4	3.2	0.1
	CA		0.0	59.8	4.3	1.5	4.7	5.4	0.2
Juniperus L.	*BD*	758	2.4	39.6	9.0	5.3	11.6	4.9	0.2
	DBH		0.0	28.5	5.5	2.7	8.0	4.1	0.2
	CH		0.0	3.4	1.6	1.3	2.0	0.5	0.0
	TH		0.9	9.7	3.3	2.3	4.2	1.3	0.1
	CA		0.0	14.9	1.5	0.4	1.8	1.8	0.1
Quercus L.	*BD*	243	2.5	69.5	22.6	8.9	33.3	16.9	1.1
	DBH		0.0	62.3	16.6	5.0	26.0	14.3	1.0
	CH		0.0	9.2	2.0	1.4	2.5	1.2	0.1
	TH		1.2	16.8	7.2	3.9	10.3	3.9	0.3
	CA		0.0	123.4	14.6	1.1	16.4	22.1	1.5
Arbutus L.	*BD*	59	6.1	50.7	19.0	13.9	22.2	9.0	1.5
	DBH		0.0	36.3	12.6	8.0	15.0	7.4	1.3
	CH		0.4	3.0	1.6	1.3	1.8	0.6	0.1
	TH		1.9	9.6	5.2	4.1	5.9	1.7	0.3
	CA		0.2	54.9	6.3	2.2	5.3	9.8	1.6

Var = Variable; *BD* = Basimetric diameter (cm); *DBH* = Diameter at breast height (cm); *CH* = Commercial height (m); *TH* = Total height (m); *CA* = Crown area (m^2); *n* = Number of trees; Min = Minimum; Max = Maximum; *Avg* = Average; *q1* = First quartile; *q3* = Third quartile; *SD* = Standard deviation; *SE* = Standard error.

The diameter distribution of the trees showed a negative exponential trend in the form of a Liocourt curve or "inverted J" (Figure 2), showing that most of the individuals present in the area were within the first diameter categories. The tree stratum is therefore in a state of development from regeneration to juvenile, with some individuals present in the higher diameter classes.

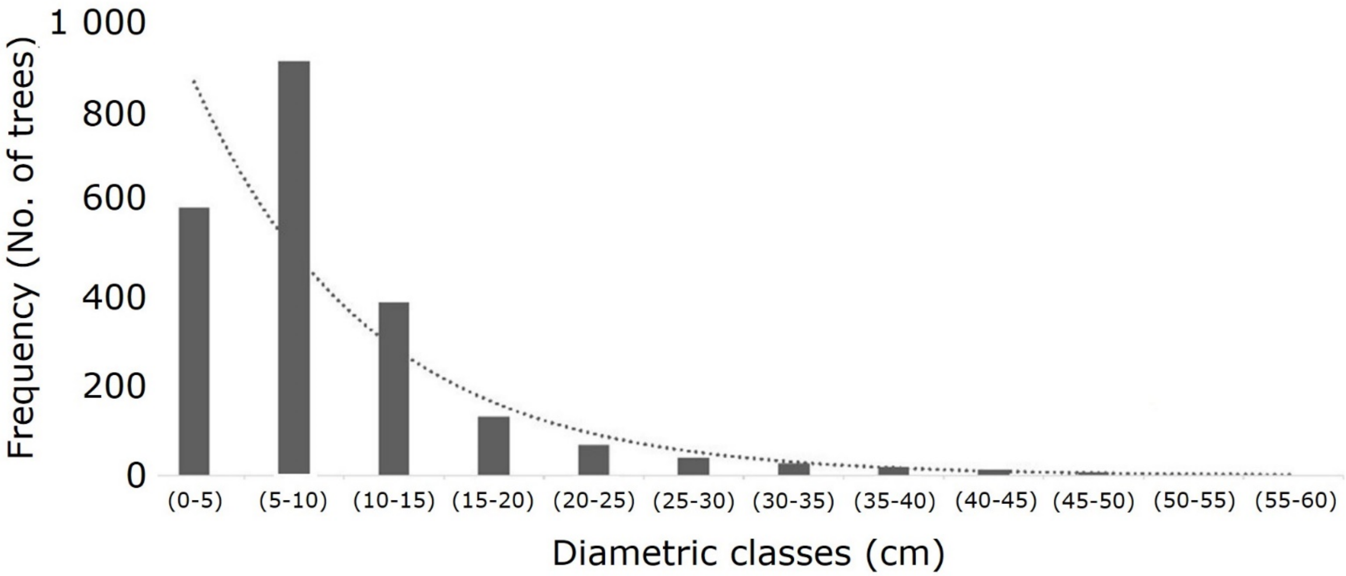

Figure 2. Diametric density of individuals of the permanent plot *Kawí Tamiruyé*, *Chihuahua*, Mexico.

The systematic sampling at 50 m presented minimum variance; however, it underestimated the variables *BA*, *Vol*, *AGB*, *C*, and *SDI*. The sampling that most underestimated the real existences are the stratified random sampling. The sampling type that most closely approached the true total results was systematic sampling at 40 m (Table 2).

Table 2. Dasometric characteristics of the census and sampling types in *Kawí Tamiruyé*, *Chihuahua*, Mexico.

Sampling type	*BA*	*SD*	*SE*	*Vol*	*SD*	*SE*	*AGB*	*SD*	*SE*	*C*	*SD*	*SE*	Ind. ha^{-1}	*SD*	*SE*	*QMD*	*SD*	*SE*	*SDI*	*SD*	*SE*

Census		25.2	0.6	0.5	158.9	0.0	0.0	142.8	24.7	0.34	71.4	6.18	0.17	2 165	2 533.52	76.43	12.2	3.3	0.6	668	1 713	41
Random sampling		17.7	4.1	2.0	112.6	273.7	16.5	86.1	314.0	17.7	43.8	155.6	12.5	1 599	5 001.14	70.72	11.7	3.9	0.6	472	2 076	46
Systematic sampling	30 m	19.1	5.7	2.0	123.1	392.7	16.7	97.1	539.5	19.6	49.5	147.5	11.6	1 632	6 103.20	66.03	12.1	6.4	0.7	501	2 517	42
	40 m	20.4	3.8	2.1	133.5	321.0	18.9	108.6	599.2	25.8	54.2	165.2	12.3	1 658	6 398.80	84.32	12.5	4.8	0.7	530	1 637	43
	50 m	18.9	1.3	1.8	124.9	108.2	16.4	103.1	63.1	12.6	51.3	15.3	6.2	1 656	3 825.68	97.80	12.1	2.6	0.8	500	491	35
Stratified sampling	3 strata	17.6	4.5	2.1	111.9	348.6	18.7	103.0	575.5	24.0	51.3	148.1	12.2	1 604	4 006.44	63.30	11.5	6.0	0.7	465	1 844	41

BA = Basimetric area; *Vol* = Total volume; *AGB* = Aboveground biomass; *C* = Carbon; Ind. ha^{-1} = Number of individuals per hectare; *QMD* = Quadratic mean diameter; *SDI* = Reineke's Stand Density Index; *SD* and *SE* = Standard Deviation and Standard Error, respectively, of different variables. The color ranges from green to red denotes the values closest to and furthest from the census reference, respectively. *SDI* was underestimated by up to 203 individuals in the stratified sampling. However, systematic sampling at 40 m distance (530 individuals) was closest to the true values of the total census.

The real existences in *BA* and *Vol* of the study area were 25.2 m^2 and 158.8 m^3 ha^{-1}, respectively (Table 2). On the other hand, when extrapolating the results of the samples to the total surface of the area, it was found that all the samples underestimated the total *BA* by up to 8 m^2, such as in the random stratified sampling. *Vol* was also underestimated by up to 46 and 47 m^3, as was the case for random and stratified sampling, respectively, relative to the census total (Table 2).

For aboveground biomass (*AGB*), the sample that most underestimated the real value was the random sample (86.1<142.78 Mg ha^{-1}). Carbon (*C*) was also underestimated with up to 52.0 Mg ha^{-1} in the random sampling (<71.4 Mg ha^{-1}) (Table 2). Meanwhile, *QMD* showed the worst underestimation with 11.50<12.2 cm with stratified sampling. The number of individuals per hectare was underestimated in the random sampling by up to 566 individuals (1 599<2 165) (Table 2).

The total census of *Kawí Tamiruyé* recorded 2 165 individuals (*n*), distributed in nine taxa in the arboreal stratum, belonging to four genera and represented by four families. The families Pinaceae and Fagaceae had three taxa, while Ericaceae had two and Cupressaceae had one (51.03, 11.22, 2.75, and 35.01 %, respectively).

According to the results obtained, the maximum number of species (nine) was only recorded in the systematic sampling at 30 m distance between sites after seven sites, while in the 50 m distance sampling, this was achieved after four sites. The sampling that most closely resembled the percentage per species found in the census was systematic sampling at 30 m since all nine species were recorded and in the same proportions.

A Simpson's diversity index (λ) value similar to that of the total census (0.61) was obtained after eight sites in the systematic sampling at 40 m while, in the stratified sampling, this was achieved after three sites per stratum, as was the case for Simpson's dominance index (δ).

The Simpson's dominance and diversity indices indicated a 39 % probability that, when selecting two different species, they will be of the same species, while there is a 61 % probability that when selecting two random species, they will be of different species. In other words, dominance was low.

The Shannon-Wiener index of diversity for the total census was 1.16 and the sampling types that came closest to this value were systematic sampling at 30, 40, and 50 m, after 12, seven, and two sites, respectively, while the stratified sampling achieved this after three sites per stratum (Table 3). The Margalef index was 1.04 for the total census, while the sampling that came closest was systematic sampling at 40 m.

Table 3. Indices of biodiversity in the sampling types and the total census.

Sampling type		***ns***	**Spp.**	***n***	**Simpson**		***H'***	***DMG***	***J'***
					λ	**δ**			
Census		--	9	2 165	0.61	0.39	1.16	1.04	0.53
Random sampling		1	5	122	0.60	0.39	1.08	0.83	0.67
		2	7	234	0.56	0.43	1.01	1.1	0.52
		3	7	340	0.55	0.44	0.96	1.02	0.49
		4	7	464	0.54	0.45	0.95	0.97	0.49
		5	7	589	0.56	0.43	1.01	0.94	0.52
		6	7	697	0.57	0.42	1.03	0.91	0.53
		7	7	804	0.56	0.43	1.01	0.89	0.51
		8	8	954	0.58	0.41	1.07	1.0	0.51
		9	8	1 045	0.59	0.40	1.07	1.00	0.51
		10	8	1 142	0.59	0.40	1.09	0.99	0.52
Systematic sampling	30 m	1	5	136	0.57	0.42	1.0	0.81	0.64
		2	6	240	0.57	0.42	1.00	0.91	0.55
		3	7	384	0.57	0.42	1.04	1.0	0.53
		4	7	479	0.57	0.42	1.03	0.97	0.53
		5	7	599	0.58	0.41	1.07	0.93	0.55
		6	7	740	0.58	0.41	1.0	0.90	0.55
		7	9	857	0.57	0.42	1.0	1.18	0.49
		8	9	975	0.57	0.42	1.0	1.16	0.49
		9	9	1 100	0.58	0.41	1.09	1.14	0.49
		10	9	1 187	0.58	0.41	1.11	1.13	0.50
		11	9	1 294	0.59	0.40	1.12	1.11	0.51
		12	9	1 444	0.60	0.39	1.14	1.0	0.53
		13	9	1 541	0.60	0.39	1.14	1.0	0.52
		14	9	1 632	0.607	0.39	1.15	1.08	0.52
	40 m	1	6	128	0.59	0.40	1.0	1.0	0.60
		2	7	249	0.56	0.43	0.98	1.08	0.50
		3	7	394	0.59	0.40	1.08	1.00	0.55
		4	8	519	0.59	0.40	1.11	1.12	0.53
		5	8	621	0.61	0.38	1.14	1.08	0.54

		6	8	719	0.59	0.40	1.11	1.06	0.53
		7	8	865	0.60	0.39	1.14	1.03	0.55
		8	8	966	0.61	0.38	1.14	1.01	0.55
		9	8	1 066	0.61	0.38	1.15	1.00	0.55
	50 m	1	6	113	0.51	0.48	0.95	1.05	0.53
		2	8	255	0.59	0.40	1.17	1.26	0.56
		3	8	367	0.58	0.41	1.15	1.18	0.55
		4	9	473	0.59	0.40	1.17	1.29	0.53
Stratified sampling	3 strata	1×1×1	7	360	0.56	0.43	1.05	1.01	0.54
		2×2×2	8	691	0.59	0.40	1.09	1.07	0.52
		3×3×3	8	999	0.60	0.39	1.12	1.01	0.53
		4×3×4	8	1 260	0.61	0.38	1.14	0.98	0.55

ns = Number of sites; Spp. = Number of species; *n* = Number of individuals; *λ* = Simpson's diversity index; *δ* = Simpson's dominance index; *H′* = Shannon-Wiener index of diversity; *DMG* = Margalef index; *J′* = Pielou's evenness. The color ranges from green to red denotes the values nearest to and furthest from the reference of the census, respectively.

The Pielou's evenness (*J'*) was 0.53; the samples that came closest to this value were the systematic sampling at 30 m after 12 sites, at 40 m after 4-6 sites, and at 50 m after two sites, while the stratified sampling achieved this after 3×3×3 sites per stratum (Table 3).

Discussion

This study documents the structure and composition of a representative mixed forest plot in Northern Mexico by monitoring 2 165 individual trees and comparing their metrics using different sampling strategies. Trees undergo changes throughout their lives dictated by the intensity, frequency, and duration of their responses to the context in which they develop; thus, having this ecological diagnostic is important for subsequent studies.

The studied plot presents a diameter distribution typical of juvenile stands in development, which is attributed to irregular forest management, with a cutting of regeneration by parent trees (Maciel-Nájera *et al.*, 2020). This strategy has allowed regeneration to become established, laying the foundations for a desirable future stand structure. However, care is required to avoid disturbance by fire events that could be catastrophic.

The dasometric parameters are in line with those reported in studies from neighboring areas (García *et al.*, 2021; Rascón-Solano *et al.*, 2022) and represent metrics that allow multi-temporal repeated measurements to monitor the stand dynamics. For example, the true existences of *BA* and *Vol* (25.16 m^2 and 158.86 m^3, respectively) agree with those reported by García *et al.* (2021) (18.72 m^2 ha^{-1} and 168.58 m^3 ha^{-1}, respectively), but are lower than that described by Rascón-Solano *et al.* (2022) (217.13 m^2 ha^{-1} and 1 810.38 m^3 ha^{-1}, respectively). The number of families recorded (four) agrees with that reported by García *et al.* (2021) for a temperate forest in the South of the state (four families), although it is lower than that reported by Rascón-Solano *et al.* (2022) in a temperate forest in *Guachochi*, *Chihuahua* (five families). These differences could be attributed to differences in plot size. The basimetric area (*BA*, m^2) was higher than that reported by other studies in temperate forests (Hernández-Salas *et al.*, 2013; Hernández-Salas *et al.*, 2018; Villela-Suárez *et al.*, 2022). We assumed that intra-specific variability at site level, including climatic and management factors, may play a specific role in these differences.

The number of trees presented (2 165) is higher than other values reported for temperate forests in Mexico (Graciano-Ávila *et al.*, 2020 [715, 685, and 714]). Perhaps, the different regime management and soil conditions are plausible explanations. The aboveground biomass and Carbon values (*AGB*=142.78 Mg ha^{-1} and *C*=71.39 Mg ha^{-1}) are within the ranges described by Martínez *et al.* (2016) in pine-oak forests in the state of *Durango* (75.43 to 176.06 Mg ha^{-1}). The *SDI* values (668 ind.) are in agreement with the maximum density line described by Tamarit-Urias *et al.* (2020) for stand density management diagrams based on the Reineke index (937-230 ind.).

The monitoring strategy in *Kawí Tamiruyé* assumes long-term viability since it brings together the most important aspects with which to structurally describe the vegetation, in accordance with Storch *et al.* (2018). For example, the identification of diametric classes, true existences of Carbon contents, aboveground biomass, and total volume provide valuable elements for decision-making in forest management. In turn, the indices of richness, abundance, and importance of vegetation are feasible as a parameter for comparison in large-scale inventories and with neighboring ecosystems.

The census revealed that the forests of the region tend towards juvenile stands, with a change in species composition with *Pinus*-*Juniperus* forests, where species of the latter seem to take advantage of the others. It appears that the ecology of *Juniperus* presents comparative advantages over the rest of the species, including resistance to fire (Blanco-Sacristán *et al.*, 2023), adaptations to long periods of drought stress (Zhao *et al.*, 2022), and the ability to resprout in response to browsing by herbivores or mechanical damage (Gill, 1992).

Regarding sampling strategies, there were differences expected with respect to the census reference values. The results for this area show that the choice to apply will be influenced by the desired precision, as well as the field efforts, including costs (not evaluated here). Although systematic sampling proved to be the sampling type with the closest adherence to the reference values, the results are not definitive. Further sampling, including different site sizes, sampling intensities, etc., remains to be evaluated. The advantage is that the plot itself represents a natural laboratory in which such procedures can be refined.

Although random sampling has been commonly used in inference due to its simplicity of design and the fact that it is generally conservative (Scott and Gove, 2002), our results showed marked differences in estimations in favor of systematic sampling. The latter showed error reduction, producing more efficient estimators as a result of its balanced spatial effect in the face of population heterogeneity (Räty *et al.*, 2020). Thus, the spatial distribution of the grid in terms of distance and size of the sites is important, as is evident in the results from the systematic sampling itself. Although stratified sampling produced the worst result, as a simple alternative, experts recommend the inclusion of more stratification information to build homogeneous strata to reduce variance prior to field sampling. While these efforts must be made as part of future research, the plot established here represents an ideal laboratory in which to optimize different sampling schemes.

While the results are useful for describing the structural diversity of the studied forest, more can be done to simplify the effort and to replicate it at larger geographic scales. For example, the inclusion of additive indices, which combine the different variables into an individual index (Storch *et al.*, 2018) can provide an objective assessment of the status of structural diversity across different forest types that are sensitive to temporal changes. This implies a requirement for future research in the plot under study, including cost analysis, inclusion of remote sensing, xylogenesis studies, and ecophysiology, etc. For example, changing the size and shape of sites in different seasons is now possible thanks to the records of the trees included in the census, without the higher field costs and efforts that temporary sites entail. Moreover, risk assessments should be incorporated given the uncertainty in the results found, and it is necessary to consider that trees are multi-connected, and their development variables are multifactorial.

In terms of the composition and structure in the study area we observed that the ecological indices recorded are like that reported from related studies (Graciano-Ávila *et al.*, 2020; García *et al.*, 2021; Rascón-Solano *et al.*, 2022). However, the marginal differences can be attributed to the sampling criteria. It is evident that modified community structure have resulted in loss of biodiversity, which could be related to disturbances from anthropogenic activities, including logging, drought and fires. Even though, the stand structure deserves further research.

Conclusions

This study contributes to increasing the scope of permanent monitoring of forest plots, which has traditionally focused on categorizing timber production in quantitative terms (growing stock, species, products, size, mortality, etc.). The collection of other variables, such as structural indices, provides knowledge of ecosystem components necessary to promote management policies in accordance with the requirements of new ecologically orientated protocols. The structural characterization was a feasible measure of forest integrity condition, showing that *Kawí Tamiruyé* is ecologically complex; however more research is needed.

The use of different sampling schemes allows us to conclude that sampling strategy does affect the precision of the results, although a cost analysis is lacking. Systematic sampling made it evident that spatial balance is a factor that increases the precision of inferences, for both structural indices and dasometric variables.

The systematization of these variables and the feasibility of the proposed methodology mean that it represents an important source of information for the development of tools for decision-making in forest management, in the face of forest stand dynamics.

It also remains important to explore variations in sampling intensity, or even the combination of sampling designs and scales, including the incorporation of UAV-based remote sensing, as well as the replication of this approach in other regions.

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Conflict of interest

The authors declare that they have no conflict of interest.

Contribution by author

Marín Pompa-García: conceptualization, research, resources and writing-preparation of the original draft; Sergio Romero-Rocha: research and formal analysis; José Alexis Martínez-Rivas: methodology and software; Eduardo Daniel Vivar-Vivar: methodology, field data gathering; Felipa de Jesús Rodríguez-Flores: resources and writing-preparation of the original draft; José Israel Yerena-Yamallel: revision and correction. All authors read and accepted the published version of the manuscript.

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