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Tesis doctoral

CONSERVACIÓN, DOMESTICACIÓN DE "Juglans neotropica" DIELS. PARA USO COMERCIAL, MEJORAMIENTO GENÉTICO Y RESTAURACIÓN DE ECOSISTEMAS DEGRADADOS AL SUR DE ECUADOR

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DECLARACIÓN DE AUSENCIA DE CONFLICTO DE INTERESES

El doctorando declara no tener ningún conflicto de interés en relación con la Tesis Doctoral.

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RESUMEN

La presente Tesis Doctoral, desarrollada bajo la modalidad de compendio de publicaciones, aborda de manera integral el estudio ecológico, fenológico y fenotípico de *Juglans neotropica* Diels en ecosistemas montanos del sur de Ecuador. Esta especie nativa, clasificada como amenazada por la UICN, posee alto valor ecológico, económico y cultural, y representa un recurso estratégico para la restauración de paisajes forestales degradados en la Región Sur (Zona 7). La investigación se estructura en torno a tres objetivos específicos: (1) caracterizar la ocurrencia natural y artificial de la especie en distintos ecosistemas montanos; (2) analizar su comportamiento fenológico en función de gradientes edáficos y orográficos; (3) evaluar su variabilidad fenotípica en vivero y campo

El primer artículo caracteriza la estructura poblacional, distribución espacial y abundancia de *J. neotropica* en seis localidades de las provincias de Loja y Zamora Chinchipe, mediante inventarios forestales, análisis dasométricos e índices de agregación. Los resultados revelan una distribución agrupada, con densidades que oscilan entre 29 y 399 individuos por hectárea, y diferencias significativas en diámetro, altura y volumen entre sitios. Esta caracterización territorial proporciona la base ecológica sobre la cual se desarrollan los análisis fenotípicos y fenológicos posteriores.

El segundo artículo analiza la variación fenológica de poblaciones nativas y reforestadas, considerando gradientes ambientales como altitud, pendiente, tipo de suelo, temperatura y humedad relativa. Se monitorearon eventos estacionales clave (brotación, floración, fructificación y senescencia) durante cinco años, evidenciando que la expresión fenológica está modulada por el contexto ecológico y la edad de los individuos. Localidades como El Tundo y La Victoria presentan mayor sincronía fenológica y mejor desempeño reproductivo, mientras que La Argelia, aunque naturalizada, exhibe patrones diferenciados. Estos hallazgos permiten construir calendarios fenológicos representativos y adaptar las prácticas de manejo forestal a las condiciones locales.

El tercer artículo evalúa la variabilidad fenotípica de *J. neotropica* en vivero y campo, considerando tres procedencias locales (El Tundo, La Victoria y La Argelia) y cuatro tratamientos pregerminativos. Se analizaron parámetros como germinación, supervivencia, altura, diámetro basal y número de hojas en tres ambientes de plantación: bosque secundario, bosque ripario y pastizal. Los resultados demuestran que la aplicación de urea mejora la supervivencia (100%) y que el tratamiento de agua y sol favorece la germinación. El mayor diámetro basal se registró en el pastizal (13.2 mm/año), mientras que la mayor altura se alcanzó en el bosque secundario (54.8 cm/año), lo que confirma la plasticidad adaptativa de la especie y permite identificar combinaciones genotipo-ambiente con alto potencial para restauración ecológica y mejoramiento genético.

En conjunto, los tres estudios confirman la capacidad de *J. neotropica* para responder a condiciones ambientales contrastantes, y aportan evidencia técnica para su conservación activa, propagación *ex situ* y aprovechamiento sostenible. La Tesis Doctoral valida un enfoque metodológico multietapa, territorialmente contextualizado, que integra herramientas de georreferenciación, monitoreo fenológico, análisis estadístico bifactorial y evaluación estructural. Este enfoque puede ser replicado en otras regiones andinas con especies forestales de interés ecológico y económico.

Los hallazgos contribuyen al fortalecimiento de políticas públicas, viveros comunitarios y estrategias de restauración ecológica en zonas de alta fragilidad ambiental. Asimismo, promueven la valorización científica y territorial de *J. neotropica* como especie clave para la resiliencia ecosistémica, el desarrollo local y la conservación de la biodiversidad andina.

Palabras clave: Nogal, ecosistema forestal, especies nativas, plasticidad fenotípica, bosques montanos andinos, silvicultura tropical, mejoramiento forestal.

ABSTRACT

This Doctoral Thesis, developed under the modality of a compendium of publications, comprehensively addresses the ecological, phenological, and phenotypic study of *Juglans neotropica* Diels in montane ecosystems of southern Ecuador. This native species, classified as threatened by the IUCN, holds high ecological, economic, and cultural value, and represents a strategic resource for the restoration of degraded forest landscapes in the Southern Region (Zone 7). The research is structured around three specific objectives: (1) to characterize the natural and artificial occurrence of the species in different montane ecosystems; (2) to analyze its phenological behavior in relation to edaphic and orographic gradients; (3) to assess its phenotypic variability in nursery and field conditions.

The first article characterizes the population structure, spatial distribution, and abundance of *J. neotropica* in six localities across the provinces of Loja and Zamora Chinchipe, through forest inventories, dasometric analyses, and aggregation indices. The results reveal a clustered distribution, with densities ranging from 29 to 399 individuals per hectare, and significant differences in diameter, height, and volume among sites. This territorial characterization provides the ecological foundation for subsequent phenotypic and phenological analyses.

The second article analyzes the phenological variation of native and reforested populations, considering environmental gradients such as altitude, slope, soil type, temperature, and relative humidity. Key seasonal events (budburst, flowering, fruiting, and senescence) were monitored over five years, showing that phenological expression is modulated by ecological context and individual age. Localities such as The Tundo and The Victoria exhibit greater phenological synchrony and better reproductive performance, while The Argelia, although naturalized, displays differentiated patterns. These findings enable the construction of representative phenological calendars and the adaptation of forest management practices to local conditions.

The third article evaluates the phenotypic variability of *J. neotropica* in nursery and field conditions, considering three local provenances (The Tundo, The Victoria, and The Argelia) and four pregerminative treatments. Parameters such as germination, survival, height, basal diameter, and leaf number were analyzed across three planting environments: secondary forest, riparian forest, and pastureland. Results show that urea application improves survival (100%) and that the water and sun treatment favors germination. The highest basal diameter was recorded in pastureland (13.2 mm/year), while the greatest height was achieved in secondary forest (54.8 cm/year), confirming the species' adaptive plasticity and allowing the identification of genotype-environment combinations with high potential for ecological restoration and genetic improvement.

Taken together, the three studies confirm the ability of *J. neotropica* to respond to contrasting environmental conditions and provide technical evidence for its active conservation, *ex situ* propagation, and sustainable use. The Doctoral Thesis validates a multi-stage methodological approach, territorially contextualized, integrating tools such as georeferencing, phenological monitoring, bifactorial statistical analysis, and structural evaluation. This approach can be replicated in other Andean regions with forest species of ecological and economic interest.

The findings contribute to the strengthening of public policies, community nurseries, and ecological restoration strategies in areas of high environmental fragility. Furthermore, they promote the scientific and territorial valorization of *J. neotropica* as a key species for ecosystem resilience, local development, and the conservation of Andean biodiversity.

Keywords: Nogal, forest ecosystem, native species, phenotypic plasticity, Andean montane forests, tropical silviculture, forest improvement.

RESUMO

A presente Tese Doutoral, desenvolvida baixo a modalidade de compendio de publicacións, aborda de maneira integral o estudo ecolóxico, fenolóxico e fenotípico de *Juglans neotropica* Diels en ecosistemas montanos do sur de Ecuador. Esta especie nativa, clasificada como ameazada pola UICN, posúe un alto valor ecolóxico, económico e cultural, e representa un recurso estratéxico para a restauración de paisaxes forestais degradadas na Rexión Sur (Zona 7). A investigación estrutúrase arredor de tres obxectivos específicos: (1) caracterizar a ocorrencia natural e artificial da especie en distintos ecosistemas montanos; (2) analizar o seu comportamento fenolóxico en función de gradientes edáficos e orográficos; (3) avaliar a súa variabilidade fenotípica en viveiro e campo.

O primeiro artigo caracteriza a estrutura poboacional, distribución espacial e abundancia de *J. neotropica* en seis localidades das provincias de Loja e Zamora Chinchipe, mediante inventarios forestais, análises dasométricas e índices de agregación. Os resultados revelan unha distribución agrupada, con densidades que oscilan entre 29 e 399 individuos por hectárea, e diferenzas significativas en diámetro, altura e volume entre sitios. Esta caracterización territorial proporciona a base ecolóxica sobre a cal se desenvolven os análises fenotípicos e fenolóxicos posteriores.

O segundo artigo analiza a variación fenolóxica de poboacións nativas e reforestadas, considerando gradientes ambientais como altitude, pendente, tipo de solo, temperatura e humidade relativa. Monitorizáronse eventos estacionais clave (brotación, floración, fructificación e senescencia) durante cinco anos, evidenciando que a expresión fenolóxica está modulada polo contexto ecolóxico e a idade dos individuos. Localidades como El Tundo e La Victoria presentan maior sincronía fenolóxica e mellor desempeño reprodutivo, mentres que La Argelia, aínda que naturalizada, exhibe patróns diferenciados. Estes achados permiten construír calendarios fenolóxicos representativos e adaptar as prácticas de manexo forestal ás condicións locais.

O terceiro artigo avalía a variabilidade fenotípica de *J. neotropica* en viveiro e campo, considerando tres procedencias locais (El Tundo, La Victoria e La Argelia) e catro tratamentos pregerminativos. Analizáronse parámetros como xerminación, supervivencia, altura, diámetro basal e número de follas en tres ambientes de plantación: bosque secundario, bosque ripario e pastizal. Os resultados demostran que a aplicación de urea mellora a supervivencia (100%) e que o tratamento de auga e sol favorece a xerminación. O maior diámetro basal rexistrouse no pastizal (13,2 mm/ano), mentres que a maior altura acadouse no bosque secundario (54,8 cm/ano), o que confirma a plasticidade adaptativa da especie e permite identificar combinacións xenotipo-ambiente con alto potencial para restauración ecolóxica e mellora xenética.

En conxunto, os tres estudos confirman a capacidade de *J. neotropica* para responder a condicións ambientais contrastantes, e achegan evidencia técnica para a súa conservación activa, propagación *ex situ* e aproveitamento sustentable. A Tese Doutoral valida un enfoque metodolóxico multietapa, contextualizado territorialmente, que integra ferramentas de xeorreferenciación, monitorización fenolóxica, análise estatística bifactorial e avaliación estrutural. Este enfoque pode ser replicado noutras rexións andinas con especies forestais de interese ecolóxico e económico.

Os achados contribúen ao fortalecemento de políticas públicas, viveiros comunitarios e estratexias de restauración ecolóxica en zonas de alta fraxilidade ambiental. Así mesmo, promoven a valorización científica e territorial de *J. neotropica* como especie clave para a resiliencia ecosistémica, o desenvolvemento local e a conservación da biodiversidade andina.

Palabras clave: Nogueira, ecosistema forestal, especies nativas, plasticidade fenotípica, bosques montanos andinos, silvicultura tropical, mellora forestal

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Nota editorial: Las tablas y figuras insertadas como imágenes o páginas PDF en esta Tesis Doctoral corresponden a materiales originales publicados en revistas científicas indexadas o documentos técnicos complementarios. Debido a su formato de incorporación, no están vinculadas al índice automático del cuerpo de la Tesis Doctoral. No obstante, se han ubicado de manera lógica dentro de cada artículo o sección metodológica, respetando su numeración y leyenda original. Esta decisión garantiza la integridad editorial, la trazabilidad científica y el cumplimiento de los estándares de publicación

1. INTRODUCCIÓN GENERAL

Los ecosistemas andinos del sur de Ecuador presentan una alta complejidad ecológica, caracterizada por gradientes altitudinales, microclimas, coberturas vegetales y prácticas culturales que configuran una matriz ambiental diversa y frágil. Esta región alberga una riqueza biológica excepcional, donde destacan especies forestales nativas de gran valor ecológico, económico y cultural. Entre ellas, *Juglans neotropica* Diels —conocida localmente como "Nogal" o "Tocte"— cumple un papel clave en la regulación hídrica, conservación de suelos y provisión de servicios ecosistémicos, además de su potencial para restauración ecológica, conservación genética y manejo forestal sostenible (Toro Vanegas & Roldán Rojas, 2018; IUCN, 2022).

La especie, endémica de los Andes tropicales, se distribuye entre los 400 y 3000 m s.n.m., ocupando ecosistemas como el Bosque Siempreverde Montano Oriental y el Bosque Semideciduo de Pie de Montaña Catamayo-Alamor. Su presencia se ha documentado en provincias como Loja, Bolívar, Azuay y Pichincha, así como en localidades específicas como La Argelia, El Zañe, El Tibio y La Merced, lo que evidencia una notable plasticidad ecológica y capacidad de adaptación a condiciones contrastantes (Nieto & Rodríguez, 2002; Palacios-Herrera et al., 2023). Incluso se ha reportado su cultivo en zonas urbanas de Nueva Zelanda, lo que refuerza su resiliencia frente a escenarios climáticos diversos (Bachman et al., 2011).

Desde una perspectiva filogenética, el género *Juglans* se originó en Asia hace aproximadamente 50 millones de años, diversificándose en especies como *J. regia*, *J. olanchana* y *J. neotropica*, esta última presente en Ecuador desde el siglo XV (Fjellstrom & Parfitt, 1995; Aradhya et al., 2004). Esta historia evolutiva y su dispersión geográfica configuran una estructura poblacional compleja que requiere enfoques multiescalares y territorialmente contextualizados.

La presión antrópica, la expansión agrícola, la fragmentación de hábitats y el cambio climático han comprometido la resiliencia de los ecosistemas montanos, situando a *J. neotropica* en peligro de extinción y dificultando su regeneración natural (Vaca Llivigañay & Palacios-Herrera, 2023). La escasa información sobre su estado de conservación y distribución limita la formulación de políticas y estrategias de manejo sostenible (Ramírez & Kallarackal, 2021).

La presente Tesis Doctoral se estructura como un compendio de tres artículos científicos publicados en revistas indexadas de acceso abierto, que abordan de forma complementaria la ecología funcional, la variabilidad fenotípica y la dinámica fenológica de *J. neotropica* en ecosistemas montanos del sur de Ecuador. Esta unidad temática se justifica por la coherencia en los objetivos, el enfoque territorial compartido y la integración metodológica basada en indicadores dendrométricos, reproductivos y sanitarios (Jiménez Cueva & Palacios-Herrera, 2023; Hansen & Pélabon, 2021). Los tres estudios emplean criterios de selección multiescalar, análisis estadísticos robustos, herramientas geoespaciales y revisión bibliográfica especializada, lo que permite construir una narrativa científica sólida, transversal y editorialmente defendible.

En el marco de esta investigación se diferencian tres niveles de análisis: la fenología, entendida como el estudio de los eventos periódicos del ciclo de vida de la especie; el fenotipo, como el conjunto de características observables resultantes de la interacción genotipo-ambiente; y los rasgos fenotípicos, que corresponden a atributos específicos medibles (altura, diámetro, número de hojas, etc.). Esta distinción se mantiene a lo largo de la tesis para garantizar consistencia conceptual.

1.1 Caracterización Ecológica y Estructural de las Poblaciones de *J. neotropica*, Tanto en Ambientes Naturales como en Plantaciones

Comprender la distribución de una especie es fundamental, ya que representa el área geográfica donde esta ocurre e interactúa con el ecosistema a lo largo del tiempo, ya sea en el corto, mediano o largo plazo. Mientras algunas especies tienen una amplia distribución natural, otras presentan un rango limitado. Una distribución más amplia incrementa la probabilidad de encontrar variación genética, dado que diferentes poblaciones se adaptan a diversos ambientes locales (Zunino & Palestrini, 1991; Futuyma & Moreno, 1988).

El género *Juglans* pertenece a la familia Juglandaceae, originaria del continente asiático hace aproximadamente 56 millones de años. Este género incluye especies como *J. ailantifolia*, *J. mandshurica* y *J. regia*, siendo esta última la más cultivada y distribuida tanto en el Viejo como en el Nuevo Mundo, principalmente por sus frutos altamente nutritivos y su madera valiosa (Fjellstrom & Parfitt, 1995; Guo et al., 2020). Hace unos 23 millones de años surgieron otras especies americanas de nogal, que conservaron características físicas heredadas de sus antecesores asiáticos. Estas especies migraron desde América del Norte hacia América Central, específicamente México, donde *J. olanchana* se convirtió en el epicentro de especiación para otras especies centro y sudamericanas. Entre ellas se encuentran *J. boliviana* en Bolivia, *J. australis* en Argentina y *J. neotropica* en Colombia, extendiéndose también a Perú y siendo descubierta en Ecuador alrededor del siglo XV (Manning, 1960).

Comprender los patrones históricos de distribución y los eventos de especiación de las especies de *Juglans* es esencial por varias razones. Primero, permite entender los procesos evolutivos que han moldeado la diversidad genética y las adaptaciones observadas en distintas poblaciones. Segundo, contribuye a los esfuerzos de conservación al identificar regiones con alta riqueza de especies y potenciales reservorios genéticos. Finalmente, posibilita el desarrollo de estrategias informadas para el manejo y uso sostenible de estos valiosos recursos (Frei, 2021).

Mediante el análisis de la distribución de las especies de *Juglans* en el tiempo y el espacio, los investigadores pueden desentrañar las complejas relaciones entre los organismos y su entorno. Este conocimiento puede contribuir a la conservación y uso sostenible de estas especies, asegurando su supervivencia frente a los cambios ambientales y las actividades humanas. Además, ofrece oportunidades para futuras investigaciones sobre interacciones ecológicas, historia evolutiva y aplicaciones potenciales de estos notables árboles (Leal Carretero, 2017).

En este estudio, se busca ampliar el conocimiento sobre los patrones de distribución y la dinámica evolutiva de la especie *J. neotropica*. A través del análisis de registros históricos, datos genéticos y factores ecológicos, se pretende esclarecer los elementos que influyen en la distribución y diversificación de *J. neotropica*, contribuyendo así al conocimiento general sobre evolución, conservación y prácticas de manejo sostenible (Aradhya, Potter & Simon, 2004).

1.2 Dinámica Fenológica de *J. neotropica* en Poblaciones Nativas y Reforestadas, Considerando Gradientes Edáficos, Orográficos y Climáticos que Modulan el Crecimiento, la Reproducción y la Salud de los Árboles.

Los ecosistemas andinos en Ecuador, caracterizados por un delicado equilibrio entre fragilidad ecológica y vitalidad biológica, desempeñan un papel crucial en la regulación climática regional, la conservación de la biodiversidad y la producción sostenible de recursos valiosos. Actuando como barrera climática, los Andes modulan la temperatura, la precipitación y los patrones de viento, generando un mosaico de zonas altitudinales y microclimas que sustentan una gama única y diversa de especies adaptadas a condiciones térmicas y de humedad específicas (Allen et al., 2010; Lindner et al., 2010; Reichstein et al., 2013). Estos ecosistemas proveen servicios esenciales como la regulación hídrica, la fertilidad del suelo, el control de la erosión y el almacenamiento de carbono, beneficiando tanto a las comunidades locales como al equilibrio ambiental global. Además de ofrecer plantas medicinales y alimentos nativos, los bosques andinos albergan especies arbóreas multipropósito como *Juglans neotropica*, *Cedrela odorata*, *Ocotea quixos* y *Polylepis spp.*, que proporcionan madera de alta calidad y beneficios medicinales, nutricionales y ecológicos, convirtiéndose en aliados clave para la conservación y el desarrollo sostenible (Toro Vanegas & Roldán Rojas, 2018; IPCC, 2021).

J. neotropica es un árbol de rápido crecimiento que prospera en suelos fértiles y húmedos, alcanzando alturas de hasta 30 metros en bosques naturales. Se caracteriza por sus ramas gruesas y tronco recto, con una apariencia similar al cedro, lo que facilita su identificación. Con un manejo silvicultural adecuado —incluyendo prácticas de mejoramiento genético, técnicas de regeneración, manejo del suelo y control de plagas— esta especie puede alcanzar un crecimiento óptimo y, después de 30 a 40 años, ofrecer una producción sostenible de madera de alta calidad (Suk-In et al., 2005; Toro Vanegas & Roldán Rojas, 2018). La germinación sexual de *J. neotropica*, considerada por la Unión Internacional para la Conservación de la Naturaleza (UICN) como especie en peligro de extinción, es un proceso esencial no solo para fines comerciales, sino también para la conservación y restauración de la biodiversidad global. Este método de propagación mejora la variabilidad genética, crucial para la adaptabilidad y resistencia a enfermedades, plagas y cambios ambientales (Buzatti et al., 2019; Nicotra et al., 2010). Además, facilita la restauración de ecosistemas degradados al garantizar que las plantas reintroducidas puedan adaptarse y prosperar, promoviendo la estabilidad y salud ecológica. A nivel *ex situ*, los bancos de semillas y viveros desempeñan un papel clave en la preservación de estas especies, permitiendo su conservación y futura reintroducción (Toro Vanegas & Roldán Rojas, 2018). La implementación de plantaciones forestales con especies nativas de distintas localidades puede contribuir al mejoramiento genético y a la conservación de la biodiversidad, siempre que se realice con criterios ecológicos adecuados y programas de selección genética (Cornejo Oviedo et al., 2009). Las plantaciones de *J. neotropica* son esenciales para la adaptación climática y la restauración ecológica, ya que mejoran suelos degradados, mantienen la calidad del aire y del agua en sistemas agroforestales, y proveen hábitat y alimento para la fauna silvestre. Esta estrategia no solo promueve la variabilidad genética, sino que también permite identificar y seleccionar individuos con rasgos deseables para futuros programas de conservación y producción forestal (Martínez & Hernández, 2004; Jara, 1995).

En el área de estudio se identifican tres estratos vegetales asociados a *J. neotropica*: (i) bosque secundario, caracterizado por regeneración natural tras disturbios; (ii) bosque ribereño, ubicado a lo largo de la quebrada de la microcuenca Zañe; y (iii) estrato de pastizal, compuesto por gramíneas utilizadas para actividades ganaderas. Cada estrato presenta características únicas en términos de biodiversidad, dinámica sucesional y uso del suelo, siendo esenciales para comprender los procesos ecosistémicos y orientar estrategias de manejo sostenible (Palacios-Herrera et al., 2025b).

El propósito de esta investigación fue optimizar la propagación y el establecimiento de *J. neotropica* en contextos de restauración ecológica y producción forestal, evaluando la calidad de la semilla, la variabilidad fenotípica y el establecimiento temprano en condiciones de vivero y campo. Esta aproximación permite evaluar la plasticidad fenotípica de la especie en un ambiente común, facilitando la selección de genotipos superiores capaces de prosperar bajo condiciones ambientales adversas. Además, contribuye a la conservación *ex situ*, proporcionando una reserva genética para futuras reintroducciones y estudios científicos (Niinemets, 2010; Kramer et al., 2000).

1.3 La Variabilidad Fenotípica de *J. neotropica* Durante las Etapas de Vivero y Plantación, Evaluando el Desempeño de Individuos Provenientes de Distintas Procedencias Bajo Condiciones Controladas y de Campo.

El estudio de los rasgos fenotípicos de los árboles es esencial para comprender cómo las variables ambientales influyen en su desarrollo, comportamiento y capacidad de adaptación. Diversas investigaciones han demostrado que el clima, las propiedades del suelo y la competencia biológica afectan significativamente el crecimiento, la morfología y la salud de los árboles (Raurau, 2012; Geilfus & Bailon, 1994). Entre estos factores, el clima, las características edáficas y la pendiente del terreno destacan como determinantes críticos de la expresión fenotípica. Este enfoque multidimensional ofrece una visión integral de la interacción entre la biología forestal y las condiciones ambientales, proporcionando información valiosa para el manejo sostenible de los recursos forestales. El cambio climático, por ejemplo, ha desencadenado respuestas fenotípicas notables en los árboles, alterando su fisiología, distribución espacial y sincronización de eventos estacionales (Roldán & Garde, 2018; Boeri & Dalzotto, 2018). Las variaciones en la temperatura, los patrones de lluvia y la frecuencia de eventos extremos intensifican el estrés térmico y afectan negativamente los ciclos de crecimiento, floración y fructificación (López Alfonsin & Bucetto, 2019).

Como organismos sésiles, los árboles son altamente sensibles a las condiciones ambientales cambiantes. Factores como la radiación solar, la humedad relativa y la temperatura ambiente están estrechamente vinculados a la productividad arbórea. En este contexto, comprender los factores que moldean la diversidad genética y fenotípica intraespecífica es clave para descifrar los mecanismos que impulsan la divergencia en biomas altamente diversos como los Andes ecuatorianos. Estudios recientes destacan la importancia de seleccionar árboles en función de rasgos fenotípicos vinculados a las propiedades del suelo, subrayando cómo la disponibilidad de nutrientes, la textura y la capacidad de retención de agua influyen directamente en el desarrollo de raíces, troncos y follaje (Geilfus & Bailon, 1994; Raurau, 2012). *J. neotropica* se desarrolla mejor en suelos fértiles y bien drenados, especialmente aquellos con texturas franco-arcillosas o franco-limosas y un pH ligeramente ácido a neutro. Estas condiciones son ideales para su crecimiento óptimo y son cruciales para el establecimiento y mantenimiento exitoso de plantaciones de esta especie. Los árboles adaptados ecológicamente a condiciones edáficas específicas exhiben un crecimiento mejorado, además de contribuir significativamente a la conservación de la biodiversidad y a la resiliencia frente al estrés ambiental. Esta contribución se manifiesta en la capacidad de los árboles para regular procesos ecológicos clave, como la redistribución de agua y nutrientes, lo que mejora la calidad del suelo y la eficiencia productiva, especialmente en contextos de cambio climático (Dharmawan, Haryono, & Suryadiputra, 2024; Priyadarshini et al., 2025).

Más allá de los factores edáficos, la morfología y estructura de los árboles están estrechamente relacionadas con las condiciones geográficas, particularmente la pendiente del terreno. La variación topográfica regula la distribución del agua, la dinámica de la erosión y la disponibilidad de nutrientes esenciales para el crecimiento arbóreo. Investigaciones recientes sugieren que la pendiente del terreno puede influir significativamente en la arquitectura y el desarrollo funcional de los árboles, especialmente en regiones montañosas. En estos ambientes, los árboles tienden a desarrollar sistemas radiculares más robustos y cohesionantes como respuesta adaptativa a la inclinación del terreno, lo que mejora su estabilidad y resistencia frente a disturbios ambientales (Wang et al., 2020). Asimismo, la posición en la pendiente y su orientación afectan la disponibilidad de agua y nutrientes, modulando indirectamente la estructura de la copa y la distribución espacial de las especies (Tyagi et al., 2023).

Antes de detallar los atributos específicos de la especie, se realizó una exhaustiva revisión bibliográfica para caracterizar los patrones fenológicos de *J. neotropica* en hábitats de bosque nativo. Estos hallazgos orientaron la selección de sitios de estudio y la interpretación de indicadores de desempeño estacional. En estudios de fenología arbórea, se suele prestar atención a factores como el clima, el suelo y la topografía, pero un aspecto crucial a menudo se pasa por alto: la edad del árbol. En especies como *J. neotropica*, la edad no es solo una medida temporal, sino un determinante clave del comportamiento fenológico.

Los árboles jóvenes, por ejemplo, no florecen ni fructifican de la misma manera que los individuos maduros. Sus respuestas a los cambios estacionales pueden ser más variables o incluso ausentes. Brunner et al. (2017) explican que los árboles presentan una larga fase juvenil durante la cual no son competentes para la reproducción, y que los cambios fenológicos están estrechamente ligados a las transiciones de fase vegetativa y reproductiva, las cuales dependen de la edad y madurez del individuo. Asimismo, Silvestro et al. (2025) destacan que la variabilidad fenológica entre órganos (raíces, hojas, madera) está influenciada por factores ecofisiológicos, entre ellos la edad, que determina la sincronización y duración de los eventos estacionales. Comprender cómo la edad interactúa con los factores edafoclimáticos y orográficos puede ofrecer una visión más completa de los patrones fenológicos en ecosistemas complejos como los del sur de Ecuador.

2. HIPÓTESIS Y OBJETIVOS

La presente Tesis Doctoral se estructura como un compendio de tres artículos científicos publicados en revistas indexadas, que abordan de forma complementaria la ecología funcional, la variabilidad fenotípica y la dinámica fenológica de *Juglans neotropica* Diels en ecosistemas montanos del sur de Ecuador. Esta unidad temática se justifica por la coherencia territorial, metodológica y científica de los estudios, los cuales comparten un enfoque multiescalar, criterios de representatividad ecológica y una orientación aplicada hacia la conservación, restauración y manejo forestal sostenible.

La investigación se desarrolla en el contexto de los ecosistemas andinos de la Zona 7 del Ecuador, caracterizados por su alta biodiversidad, gradientes altitudinales pronunciados, suelos heterogéneos y presiones antrópicas crecientes. En este escenario, *J. neotropica* —especie nativa y clasificada como amenazada por la UICN— representa un recurso estratégico para la sostenibilidad territorial, tanto por su valor ecológico como por su potencial económico y cultural.

Considerando los objetivos, metodologías y resultados de los tres artículos científicos que conforman esta Tesis Doctoral por compendio de artículos, se plantearon las siguientes hipótesis de trabajo, cada una correspondiente a un estudio específico sobre *J. neotropica* en el sur de Ecuador:

2.1 HIPÓTESIS

1. La distribución espacial, estructura forestal y abundancia de *J. neotropica* en el sur de Ecuador varían significativamente entre ecosistemas naturales y artificiales, y están influenciadas por factores ecológicos como altitud, tipo de bosque y grado de intervención humana.
2. Las variaciones edáficas y orográficas, incluyendo la pendiente del terreno, el tipo de suelo y los gradientes altitudinales, influyen significativamente en los rasgos fenológicos de *J. neotropica*, tanto en poblaciones nativas como reforestadas, evidenciando una alta plasticidad fenotípica frente a condiciones ambientales contrastantes.
3. La procedencia de las semillas de *J. neotropica* influye significativamente en la calidad, germinación y desarrollo inicial de las plántulas en vivero y en campo, y su interacción con tratamientos pregerminativos y condiciones edafoclimáticas determina el éxito en el establecimiento y crecimiento de la especie en programas de restauración ecológica.

2.2 OBJETIVO GENERAL

- Analizar la distribución ecológica, la variabilidad fenotípica y el comportamiento fenológico de *Juglans neotropica* Diels en poblaciones nativas y reforestadas del sur de Ecuador, con el fin de generar indicadores técnicos que contribuyan a su conservación adaptativa, restauración ecológica y planificación forestal sostenible en territorios de alta vulnerabilidad ambiental.

2.3 OBJETIVOS ESPECÍFICOS

- ✓ Caracterizar la ocurrencia natural y artificial, la estructura poblacional y la abundancia de *J. neotropica* en ecosistemas montanos de Loja y Zamora Chinchipe, mediante inventarios forestales, análisis espaciales y evaluación de parámetros dasométricos.

- ✓ Analizar la influencia de gradientes climáticos, edáficos y topográficos sobre los rasgos fenotípicos y el comportamiento fenológico de *J. neotropica*, estableciendo correlaciones entre atributos ambientales y respuestas adaptativas en campo.

- ✓ Evaluar la calidad de semillas, la variabilidad fenotípica y el desempeño inicial de plántulas de *J. neotropica* en vivero y plantación, considerando procedencias locales, tratamientos pregerminativos y estratos ecológicos diferenciados.

2.4 DISTRIBUCIÓN DE LOS CAPÍTULOS

La Tesis Doctoral se organiza como un compendio de tres artículos científicos publicados en revistas indexadas de acceso abierto. Cada capítulo aborda aspectos complementarios sobre la ecología funcional, la variabilidad fenotípica y la dinámica fenológica de *J. neotropica* en ecosistemas montanos del sur de Ecuador. Esta estructura responde a una lógica metodológica y territorial coherente, orientada a la conservación adaptativa, la restauración ecológica y el manejo forestal sostenible.

Figura 1. Distribución espacial, estructura forestal y abundancia.

Fuente: Elaboración propia basada en Palacios-Herrera et al. (2023, 2025a, 2025b), artículos publicados en *Agronomy*, *Diversity y Forests* (MDPI). La figura resume gráficamente los tres objetivos específicos de la tesis, vinculando hipótesis, territorios y enfoques metodológicos.

- El **capítulo 1** desarrolla el Objetivo específico 1 y la Hipótesis 1, mediante la caracterización de la ocurrencia natural y artificial, la estructura poblacional y la abundancia de *J. neotropica* en seis localidades de las provincias de Loja y Zamora Chinchipe. A través de inventarios forestales, análisis espaciales y evaluación de parámetros dasométricos, se identifican patrones de distribución y estructura poblacional en función de variables ecológicas como altitud, tipo de bosque y grado de intervención antrópica, según lo reportado en el artículo publicado en Agronomy por Palacios-Herrera et al., (2023).

- El **capítulo 2** desarrolla el Objetivo específico 2 y la Hipótesis 2, mediante el análisis de la influencia de gradientes climáticos, edáficos y topográficos sobre los rasgos fenotípicos y el comportamiento fenológico de *J. neotropica*, tanto en poblaciones nativas como reforestadas. Se establecen correlaciones entre atributos ambientales y respuestas adaptativas en campo, evidenciando una alta plasticidad fenotípica frente a condiciones ambientales contrastantes, según lo reportado en el artículo publicado en Diversity por Palacios-Herrera et al., (2025a).
- El **capítulo 3** desarrolla el Objetivo específico 3 y la Hipótesis 3, enfocado en la evaluación de la calidad de semillas, la variabilidad fenotípica y el desempeño inicial de plántulas de *J. neotropica* en vivero y plantación. Se analizan los efectos de la procedencia de las semillas, los tratamientos pregerminativos y las condiciones edafoclimáticas sobre el establecimiento y crecimiento de la especie en contextos de restauración ecológica, según lo reportado en el artículo publicado en Forests por Palacios-Herrera et al., (2025b).

3. METODOLOGÍA GENERAL

La articulación metodológica de la Tesis Doctoral se fundamenta en criterios de representatividad territorial, diseño multiescalar, integración de variables ambientales y aplicación de herramientas estadísticas y geoespaciales. Este enfoque permite construir una unidad científica sólida, contextualizada y coherente.

3.1 Área de Estudio

Los estudios se desarrollaron en localidades de las provincias de Loja y Zamora Chinchipe, dentro de la Zona 7 del Ecuador (3°30′–5°00′ S; 78°20′–80°30′ O). Esta región presenta heterogeneidad ecológica, con gradientes altitudinales entre 1000 y 3000 m s.n.m., pendientes superiores al 30 %, suelos de textura franco-arenosa a franco-limosa y ecosistemas como el Bosque Siempreverde Montano Oriental y el Bosque Semideciduo de Pie de Montaña Catamayo-Alamor (Palacios-Herrera et al., 2023).

Las localidades seleccionadas —Tibio, Merced, Tundo, Victoria, Zañe y Argelia— fueron escogidas por su representatividad ecológica, presencia confirmada de *J. neotropica* y diversidad de condiciones edafoclimáticas. Se garantizó una superficie mínima de 0,5 ha por sitio, siguiendo criterios del MAATE (2023).

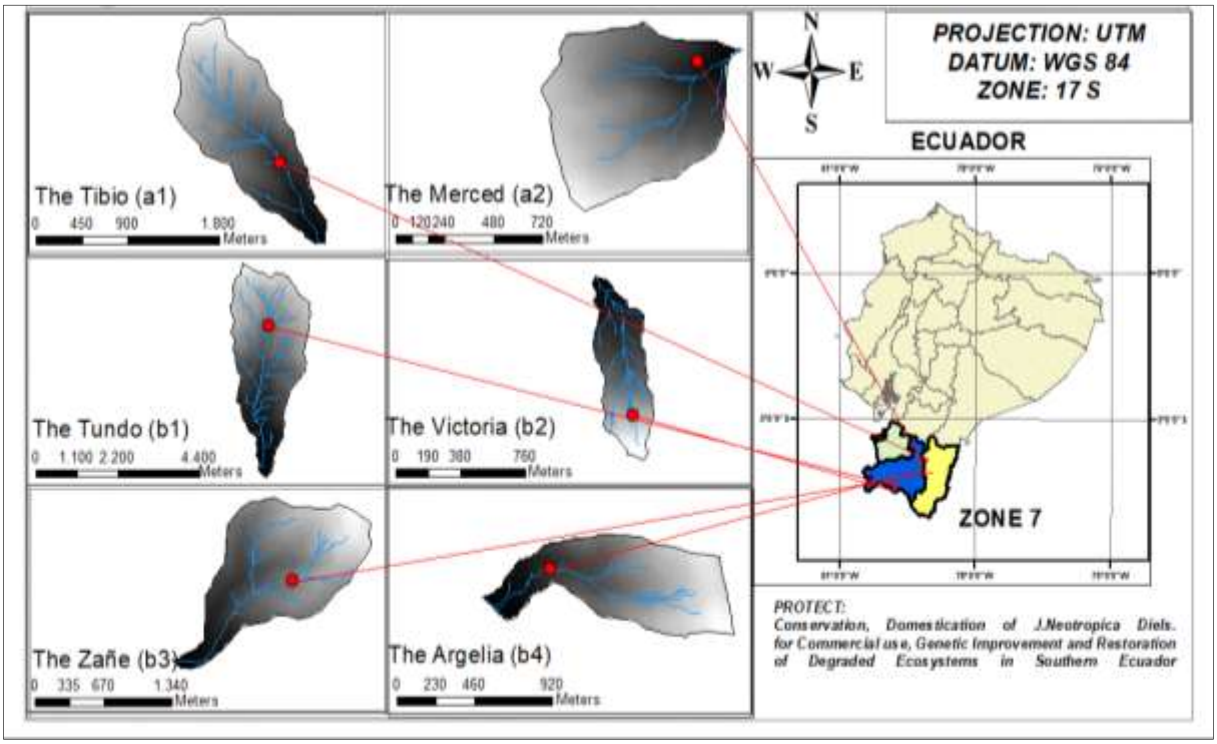

Figura 2. Ubicación geográfica de las localidades de estudio con presencia de *J. neotropica* en áreas ≥0,5 ha.

Fuente: Tomado íntegramente de Palacios-Herrera et al. (2023), Agronomy, 13(10), 2531. https://doi.org/10.3390/agronomy13102531

3.2 DISEÑO METODOLÓGICO POR ENFOQUE

3.2.1 Ecología funcional y estructura poblacional

El primer estudio aplicó un diseño de muestreo sistemático y por conglomerados en seis sitios distribuidos entre las provincias de Loja y Zamora Chinchipe. Se realizaron inventarios forestales utilizando dos métodos: censo total en áreas ≤1 ha y muestreo aleatorio simple en áreas mayores. Se evaluaron parámetros dasométricos como diámetro a la altura del pecho (DAP), altura total (HT), altura comercial (HC), área basal (G) y volumen (V), organizados en clases diamétricas de 10 cm (Palacios-Herrera et al., 2023).

Para determinar el patrón de distribución espacial se aplicó el índice de Morisita, que permite identificar distribuciones regulares, aleatorias o agregadas (Amaral et al., 2015). La abundancia se estimó según criterios del Acuerdo Ministerial 125, considerando densidades inferiores a 0,33 árboles/ha como baja abundancia (MAE, 2015). La información fue georreferenciada mediante GPS Garmin Montana 650 y procesada en ArcGIS 10.8.

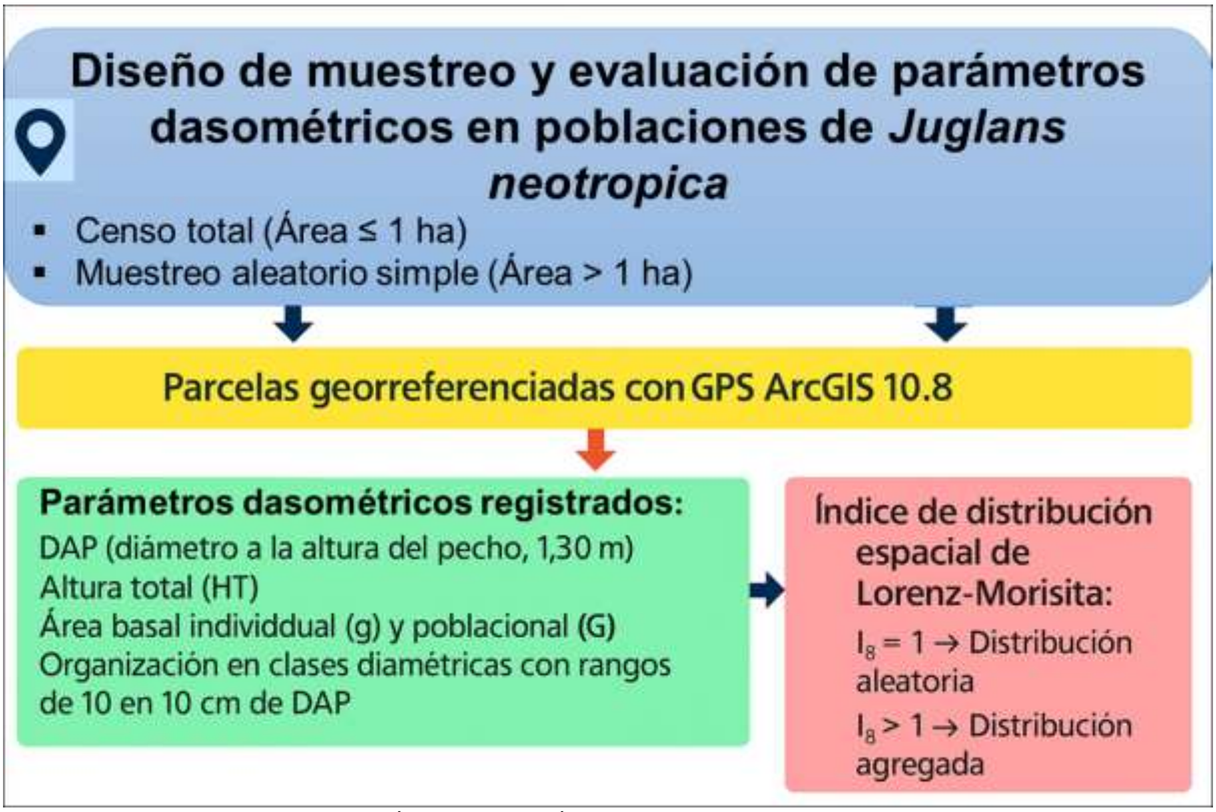

Figura 3. Diseño de muestreo y parámetros dasométricos evaluados.
Fuente: Elaboración propia basada en Palacios-Herrera et al. (2023), Agronomy, 13(10), 2531. https://doi.org/10.3390/agronomy13102531

3.2.2 Dinámica fenológica y gradientes ambientales

El segundo estudio implementó un monitoreo fenológico continuo entre 2019 y 2023, registrando eventos como brotación, floración, fructificación y caída foliar en individuos de diferentes edades y procedencias. Se correlacionaron estos eventos con variables ambientales como temperatura, precipitación, humedad relativa, pH, textura del suelo y pendiente del terreno (Palacios-Herrera et al., 2025a).

La caracterización edafológica se realizó mediante muestreo estratificado en tres profundidades (0–10 cm, 10–20 cm, 20–30 cm), en parcelas mayores a 0,5 ha, utilizando herramientas como barrenos cilíndricos y palas. Se aplicó el protocolo SIGTIERRAS 2022, integrando cartografía geopedológica a escala 1:25.000 y criterios de capacidad de uso de suelo. Las muestras fueron compuestas por tres submuestras por profundidad, etiquetadas con metadatos geoespaciales y almacenadas bajo normas de bioseguridad. Se analizaron variables físicoquímicas como pH, capacidad de intercambio catiónico (CIC), textura, materia orgánica, salinidad, humedad, temperatura, drenaje, profundidad efectiva, pedregosidad y fertilidad, siguiendo procedimientos establecidos por el Geoportal del Agro Ecuatoriano.

La pendiente se calculó mediante modelos digitales de elevación (DEM) y se clasificó según índices de riesgo ecológico. Los datos climáticos fueron obtenidos de la plataforma POWER Data Access Viewer y validados con registros locales.

Figura 4. Perfil de muestreo estratificado del suelo en bosques con *J. neotropica*

Fuente: Tomado íntegramente de Palacios-Herrera et al. (2025a), Diversity, 17(9), 627. https://doi.org/10.3390/d17090627

Tabla 1. Variables ambientales consideradas en el monitoreo fenológico.

Localidades	Altitud (m s.n.m.)	Temperatura media (°C)	Humedad Relativa (%)	Contexto Ecologico
El Tibio	2100–2600	~18	90	Bosque siempreverde montano del sur de la Cordillera Oriental de los Andes
El Merced	2000–2500	~20	90	Bosque siempreverde montano del sur de la Cordillera Oriental de los Andes
El Tundo	1200–2400	~14	77	Bosque montano de pie semideciduo Catamayo-Alamor y bosque montano estacional siempreverde

La Victoria	1000-1600	~23	75	Bosque montano de pie semideciduo Catamayo-Alamor
El Zañe	2200-3000	~11	80	Bosque siempreverde montano del sur de la Cordillera Oriental de los Andes
La Argelia	2130-2200	~15	78	Bosque siempreverde montano del sur de la Cordillera Oriental de los Andes

Fuente: Tomado íntegramente de Palacios-Herrera et al. (2025a), Diversity, 17(9), 627. https://doi.org/10.3390/d17090627

Antes de describir la variabilidad fenotípica evaluada en vivero y plantación, es necesario precisar la clasificación conceptual utilizada en esta investigación. Se distinguen tres niveles complementarios de análisis:

- **Fenología**: estudio de los eventos periódicos del ciclo de vida de los individuos (brotación, floración, fructificación, senescencia), registrados mediante monitoreo estacional en campo.
- **Fenotipo**: conjunto de características observables de los individuos, resultado de la interacción entre su genotipo y el ambiente.
- **Rasgos fenotípicos**: atributos específicos del fenotipo que pueden ser medidos y comparados, tales como altura, diámetro basal, número de hojas, tasa de germinación y supervivencia.

Esta distinción se mantiene a lo largo de la tesis con el fin de garantizar consistencia terminológica, claridad metodológica y coherencia interpretativa en el análisis de resultados.

3.2.3 Variabilidad fenotípica en vivero y plantación

El tercer estudio se desarrolló en dos fases complementarias: vivero y campo. En la fase de vivero, se aplicó un diseño completamente aleatorizado en bloques (CRBD) con arreglo bifactorial y tres repeticiones, evaluando semillas de tres procedencias (Tundo, Victoria y Argelia) bajo cuatro tratamientos pregerminativos: control, escarificación mecánica, inmersión en agua caliente y exposición agua-sol (Palacios-Herrera et al., 2025b). Estos procedimientos han sido utilizados en especies forestales nativas como estrategias para mejorar la viabilidad de semillas y la emergencia de plántulas, favoreciendo la ruptura de la latencia y el aporte nutricional inicial (Bonner & Karrfalt, 2008; Hartmann, Kester, Davies & Geneve, 2011). En particular, la aplicación de urea y la hidratación controlada se han documentado como métodos eficaces para incrementar la disponibilidad de nutrientes y activar procesos fisiológicos asociados a la germinación (Willan, 1991; ISTA, 2020).

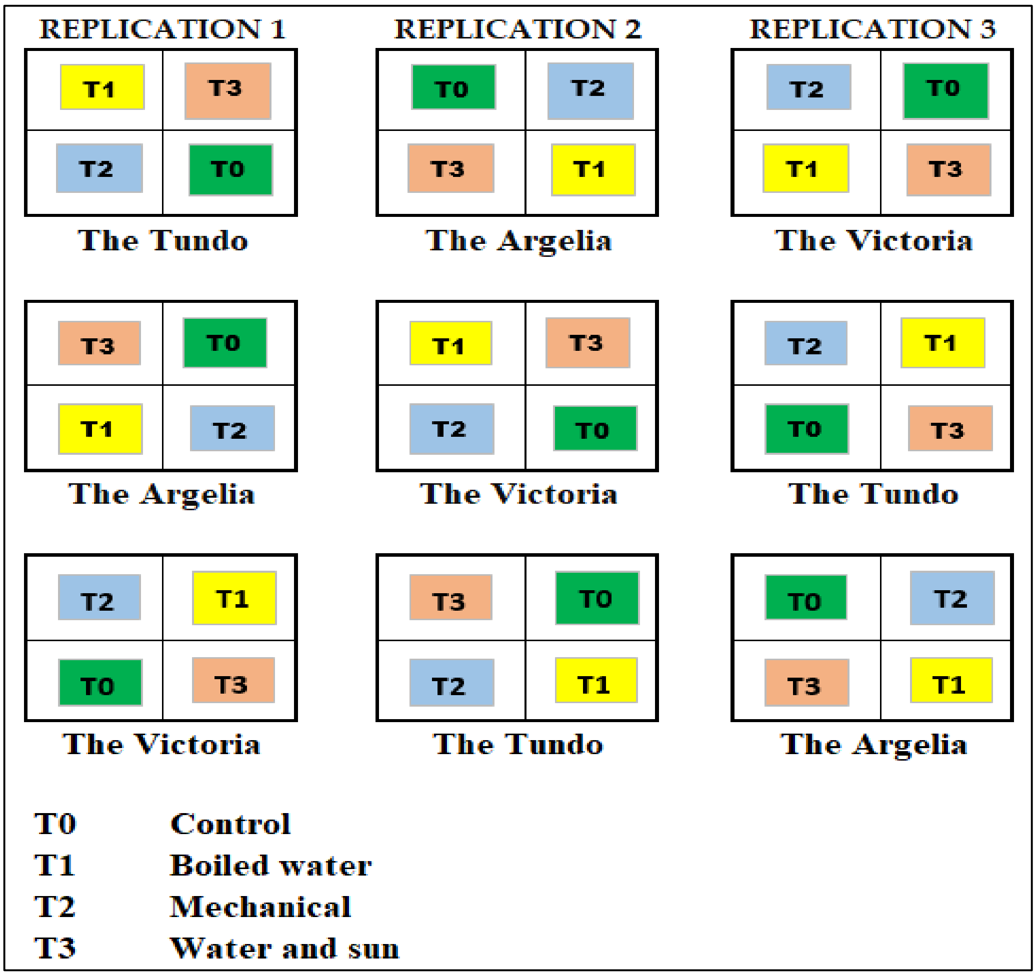

Figura 5. Diseño experimental bifactorial aplicado en vivero y distribución de tratamientos.
Fuente: Tomado íntegramente de Palacios-Herrera et al. (2025b), Forests, 16(7), 1141. https://doi.org/10.3390/f16071141

Se midieron variables como peso, tamaño, humedad, viabilidad, porcentaje de germinación, altura, diámetro basal y número de hojas. La calidad de semillas se evaluó siguiendo los protocolos de la International Seed Testing Association (ISTA, 2021), y la humedad se determinó mediante pérdida de peso en almacenamiento a temperatura ambiente durante seis meses. El análisis estadístico se realizó mediante ANOVA y prueba de Tukey ($p \leq 0,05$), utilizando InfoStat y RStudio.

En la fase de campo, se establecieron plantaciones en tres estratos ecológicos: bosque secundario, bosque ripario y pastizal. Se aplicaron criterios de selección territorial basados en condiciones edafoclimáticas, accesibilidad, cobertura vegetal y antecedentes de uso del suelo.

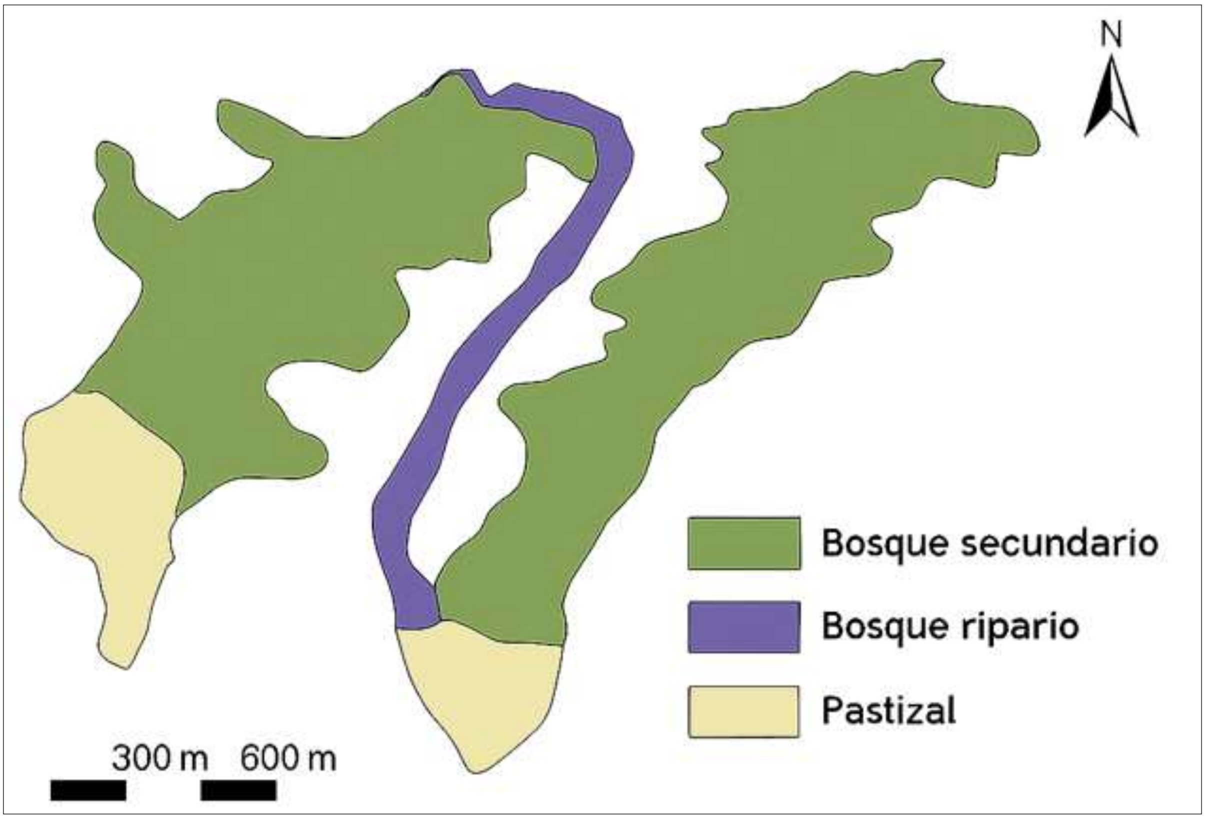

Figura 6. Estratos ecológicos seleccionados para la fase de plantación.
Fuente: Elaboración propia basada en Palacios-Herrera et al. (2025b), Forests, 16(7), 1141. https://doi.org/10.3390/f16071141

4. RESULTADOS

4.1 Artículo I. Natural and Artificial Occurrence, Structure, and Abundance of *Juglans neotropica* Diels In Southern Ecuador

Nota editorial:

Este primer artículo desarrolla el Objetivo específico 1 de la Tesis Doctoral, centrado en la caracterización ecológica y estructural de *J. neotropica* en ecosistemas montanos del sur de Ecuador. Mediante inventarios forestales, análisis dasométricos e índices de distribución espacial, se analiza la ocurrencia natural y artificial, la estructura poblacional y la abundancia de la especie en seis localidades de las provincias de Loja y Zamora Chinchipe. Este estudio proporciona la base territorial y ecológica sobre la cual se articulan los análisis fenotípicos y fenológicos desarrollados en los capítulos posteriores.

Referencia completa:

Palacios-Herrera, B.; Pereira-Lorenzo, S.; Pucha-Cofrep, D. (2023). Natural and Artificial Occurrence, Structure, and Abundance of *Juglans neotropica* Diels in Southern Ecuador. *Agronomy*, 13(10), 2531. MDPI. ISSN: 2073-4395.

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Indicios de calidad:

- JCR (Web of Science) 2024: Factor de impacto 3.4; Q1 en Agronomy (21/129); Q1 en Plant Sciences (68/273).
- SJR (Scopus): Clasificación Q1 en Agronomy and Crop Science.
- CiteScore 2024: 6.7.
- ResearchGate: 1,583 lecturas (Reads), 7 citas (Citations), 1 recomendación (Recommendation), y un Research Interest Score de 8.6.

Contribución del doctorando:

El doctorando Byron Palacios-Herrera participó como autor principal, siendo responsable del diseño metodológico, levantamiento de datos en campo, análisis estadístico, redacción científica y elaboración de figuras. Esta contribución fue clave para cumplir el objetivo específico uno.

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Article

Natural and Artificial Occurrence, Structure, and Abundance of *Juglans neotropica* Diels in Southern Ecuador

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Abstract: This study investigated the presence and characteristics of *Juglans neotropica* in three ecosystems in Southern Ecuador: Montane Evergreen Forest, Evergreen Seasonal Lower Montane Forest, and Semideciduous Foot Montane Forest. The main focus was the species' multipurpose nature as both a fruit and timber source. Six study sites, totaling at least 0.5 hectares each, were established, with four in Loja province and two in Zamora Chinchipe province. The results showed significant differences in dendrometric variables across the sites, with the most favorable growth recorded in The Tundo, where trees exhibited an average diameter at breast height (DBH) of 45.16 cm, basal area (G) of 1.41 m^2, total height (TH) of 19.22 m, canopy height (CH) of 13 m, cubic volume (CV) of 3.55 m^3, and total volume (TV) of 5.22 m^3. The species displayed a clumped distribution pattern, as indicated by a Morisita index greater than 1. Regarding abundance, the highest density of 297 trees per hectare was found in Argelia, while Victoria had the lowest density of 46 trees per hectare. The research provides a better insight into the occurrence, forest structure characteristics, and distribution of *Juglans neotropica*, an important multipurpose species, in Southern Ecuador.

Keywords: fruit; forest; ecosystem; wood; native; Ecuador

Citation: Palacios-Herrera, B.; Pereira-Lorenzo, S.; Pucha-Cofrep, D. Natural and Artificial Occurrence, Structure, and Abundance of *Juglans neotropica* Diels in Southern Ecuador. *Agronomy* **2023**, *13*, 2531. https://doi.org/10.3390/agronomy13102531

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1. Introduction

Understanding the distribution of a species is of utmost importance as it represents the geographic area where the species occurs and interacts with the ecosystem over time, be it short, medium, or long term [1]. While some species have a wide natural distribution, others have a limited range. A broader distribution increases the likelihood of encountering genetic variation, as different populations adapt to diverse local environments [2].

The *J.* genus belongs to the Juglandaceae family, which originated on the Asian continent approximately 56 million years ago. This genus includes species such as *J. ailantifolia*, *J. mandshurica*, and *J. regia*, with the latter being the most extensively cultivated and widely distributed across both the old and the New World. This is primarily due to its highly nutritious fruits and valuable wood [3,4].

Around 23 million years ago, other American walnut species emerged, retaining physical characteristics inherited from their Asian counterparts. These species migrated from North America to Central America, specifically Mexico, with *J. olanchana* as the epicenter of speciation for other Central and South American species. Among these species, *J. boliviana* is found in Bolivia, *J. australis* in Argentina, and *J. neotropica* in Colombia. The latter species also extends its presence to Peru and was discovered in Ecuador around the 15th century [5].

Understanding the historical distribution patterns and speciation events of *Juglans* species is essential for various reasons. First, it provides insight into the evolutionary processes that have shaped the genetic diversity and adaptations observed in different populations. Second, it aids in conservation efforts by identifying regions of high species richness and potential genetic reservoirs. Last, it enables the development of informed strategies for the management and sustainable use of these valuable resources [6].

By examining the distribution of *Juglans* species across time and space, researchers can unravel the intricate relationships between the organisms and their environment [7]. This knowledge can contribute to the conservation and sustainable utilization of these species, ensuring their survival in the face of environmental changes and human activities. Moreover, it offers opportunities for further research of the ecological interactions, evolutionary history, and potential applications of these remarkable trees.

In this study, we aim to expand our understanding of the distribution patterns and evolutionary dynamics within the *J. neotropica* species. By examining historical records, genetic data, and ecological factors, we seek to shed light on the factors influencing the distribution and diversification of *J. neotropica*. Through this research, we hope to contribute to the broader knowledge of evolution, conservation, and sustainable management practices [8].

Juglans neotropica, commonly known as "Nogal" or "Tocte," is a woody plant native to the South American Andes, specifically Ecuador, Colombia, Peru, and Bolivia. This species is of particular interest due to its wide distribution and cultural significance in Ecuador. It has been reported in various provinces of Ecuador, including Bolívar, Loja, Azuay, Tungurahua, Chimborazo, Pichincha, Napo, and Galapagos [9].

In Ecuador, *J. neotropica* is predominantly found in the inter-Andean region, encompassing the valleys and foothills of the Andes mountain range. The species thrives in diverse ecosystems characterized by different altitudinal ranges. Within the Southern Montane Evergreen Forest of the Eastern Cordillera of the Andes, *J. neotropica* is distributed between 2200 and 3000 m above sea level (masl). Specifically, it can be found in towns such as The Argelia, The Zañe, The Tibio, and The Merced. Furthermore, in the Catamayo-Alamor Semideciduous Foot Montane Forest ecosystem, which ranges from 400 to 1600 masl, *J. neotropica* is present in the provenances of The Tundo and The Victoria. Notably, in The Tundo provenance, walnut trees were also observed in the Evergreen Seasonal Montane Forest ecosystem, situated under Catamayo-Alamor, at altitudes ranging from 1600 to 2000 masl [10].

The distribution of *J. neotropica* extends beyond South America, with a surprising occurrence in New Zealand, specifically in the city of Auckland. However, its presence in South America, particularly in Ecuador, holds historical and cultural significance. There is evidence of its cultivation in the Equatorial Andes since pre-Columbian times, highlighting its long-standing importance to local communities [11].

The factors involved in the spatial distribution of plant species propose three approaches. First, the methods that discretize the space occupied by trees. These involve dividing the study area into predefined units and counting the trees in each, which reflects the population density. The variance of this intensity is linked to the spatial distribution of each tree. Second, methods based on distance calculation focus on the relationship between a randomly selected tree and its nearest neighboring tree. The tree-tree distance is compared with the point-tree distance, with values of less than 1, indicating regular distributions and greater than 1, indicating aggregate distributions. [12]

J. neotropica is currently classified as an endangered species, facing severe threats that have greatly hindered its regeneration in the early stages of growth [13]. Anthropogenic activities, such as the recruitment of natural regeneration and expansion of agricultural land into forested areas, have played a significant role in this decline [14]. Regarding the regulatory and protection entities responsible for endangered species in Ecuador, particularly *J. neotropica*, there is currently a lack of comprehensive information regarding its occurrence, distribution, abundance, and overall conservation status. As a result, the conservation efforts for this species have been hindered.

In terms of its ecological guild, *J. neotropica* exhibits a semi-heliophytic nature, requiring shade during its initial stages of growth but becoming heliophytic as an adult, dominating the upper canopy of the forest. Additionally, as a deciduous species, the leaf litter of *J. neotropica* plays a vital role in maintaining ecosystem balance by providing a source of energy, contributing nutrients, and forming humic substances in the soil. The most significant impact of this species is observed in South America's dry and montane forests, which serve as its natural habitat [15,16].

Understanding the distribution patterns and ecological preferences of *J. neotropica* is crucial for its conservation and sustainable management. Moreover, investigating the factors that contribute to its successful adaptation to different altitudes and ecosystems can provide valuable insight into the species' ecological resilience and potential for the future cultural significance of *J. neotropica* in Ecuador, shedding light on its ecological role and potential conservation strategies. By analyzing existing literature and conducting field surveys, we aim to contribute to the broader understanding of this valuable species and promote its sustainable use and preservation in Ecuador and beyond.

2. Materials and Methods

2.1. Study Area

The study area of this research is situated in Southern Ecuador or Zone 7, encompassing the geographic coordinates 3°30′ and 5°0′ south latitude, and 78°20′ and 80°30′ west longitude. It shares borders with zones 5 and 6 to the north, Peru to the south and east, and Peru and the Pacific Ocean to the west [17] This region holds great ecological significance due to its distinct topographic, altitudinal, climatic, and soil characteristics.

To conduct the present study, we conducted fieldwork in the three provinces within Zone 7 that had documented occurrences of the species *J. neotropica*. These provinces are Loja (11,065.6 km^2), El Oro (5866.6 km^2), and Zamora Chinchipe (10,559.7 km^2), collectively covering an area of 27,491.9 km^2, which represents approximately 11% of the total land area of Ecuador [17]

In order to provide a comprehensive analysis of *J. neotropica* and its associated factors, we selected these provinces as they exhibit diverse characteristics that are vital to understanding the species' distribution and ecology. By focusing on these specific regions, we aim to contribute valuable insight into the habitat preferences, population dynamics, and conservation implications of *J. neotropica* within Zone 7.

Through our investigation, we seek to shed light on the ecological importance of this area and provide valuable information that can guide future conservation efforts. The findings of this study will help to improve our understanding of *J. neotropica's* habitat requirements, enabling more effective conservation strategies to protect this species and its associated ecosystems in Southern Ecuador.

2.2. Occurrence

To determine the occurrence of the species in Southern Ecuador, we consulted databases from nationally and internationally recognized entities such as Geo-Cat, Tropics Database, and the Ecuadorian Biodiversity System (BNDB). These platforms contain a comprehensive collection of regional and international botanical data sourced from various institutions, collectors, and research projects, both public and private.

Additionally, we gathered information from the decentralized Autonomous Governments (GAD's), public institutions such as MAATE, and private landowners. We also accessed data from the National University of Loja's Reinaldo Espinosa Herbarium and the Private Technical University of Loja, which house collections of books containing valuable information on the flora of the Andean forest.

To validate the occurrence of the species, we carefully verified the geographic details of all the collected information. Furthermore, we utilized internet resources to obtain reports on the species' occurrence. Notably, the most reliable and accurate information came from residents and owners of private land where the species was suspected to exist.

All the collected information was meticulously entered into the ARCGIS 10.8 geographic information system to generate precise geographic locations for the occurrence of the species.

By following this comprehensive methodology, we ensured that our research on the occurrence of the species in Southern Ecuador was based on reliable data from reputable sources and validated through geographic verification and resident reports. The utilization of the ARCGIS 10.8 system further enhanced the accuracy of our findings.

2.3. Structure

Following the identification of species occurrence, a series of field trips were conducted to select suitable sites where *J. neotropica* was found. These field trips spanned a duration of 12 months. Each site was visited a minimum of three and a maximum of five times, depending on the forest size.

To assess the parameters and structural indices, a comprehensive forest inventory was conducted, employing two distinct methods:

1. Statistical Method: A 100% inventory was performed for areas ≤one hectare. For areas larger than one hectare, a simple random sampling approach was implemented.
2. Objective-based Method: An inventory was carried out for the management of natural forests, with the intensity ranging from 1% to 5% of the total area [18].

To determine the reliability and representativeness of the sampled area, the sampling intensity formula (I) was applied.

$$I = \frac{Sample\ surface}{Population\ area} \times 100 \quad (1)$$

where:

I = Sampling intensity
Ss = *Surface* of the *sample*
Pa = *Population area*
100 = Constant

By applying these methods, we ensured a rigorous and comprehensive assessment of the forest structure, allowing for accurate data collection and analysis. The statistical method provided a systematic approach, while the objective-based method facilitated the management of natural forests. The combination of these approaches ensured a robust evaluation of the species' habitat and supported the reliability of our findings.

Making multiple visits to each site and the implementation of various inventory methods enabled us to capture a comprehensive picture of the forest's structure and characteristics. This approach contributes to the overall validity and reliability of our study, ensuring that our conclusions are well-founded and representative of the larger population of interest.

2.3.1. Structural Parameters

To assess the structural characteristics of the study area, individuals with a diameter at breast height ($DBA_{1.30m}$) of $\geq$ 10 cm were georeferenced. These individuals, commonly referred to as stems in forestry, were located using a Garmin Montana 650 GPS device.

Once the inventory and georeferencing of *J. neotropica* individuals were completed, various dasometric parameters were calculated, including DBH, TH, CH, G(m^2), and V(m^3). The DBH data of the inventoried individuals were then organized into diameter classes of 10 cm widths, following the established protocol [19] (Table 1).

Table 1. Dasometric parameters.

Denomination	Formula	
Diameter at breast height, above ground level	$DBH_{1.30\ m}$	
Total height	TH (m)	
Commercial height	CH (m)	
Basal area of an individual	$\hat{g} = \frac{\pi}{4} \times DBH^2$	(2)
Basal area of the population	$\hat{G}m^2 = \frac{\pi}{4} \times DBH^2$	(3)
Volume of the stem in cubic meters	$Vm^3 = \hat{G}m^2 \times CH \times F$	(4)

2.3.2. Structural Indices

Subsequently, a structural valuation index was calculated:
Morisita index:

$$I_\delta = q \sum_{i=1}^{q} ní \frac{ní - 1}{N(N-1)} \quad (5)$$

where:

Iδ = Spatial distribution index
q = number of frames
ní = Number of individuals in í-th square
N = Total number of individuals in all *q* squares

Values of less than 1 indicate a regular or uniform distribution, while a value equal to 1 suggests a random distribution, and values greater than 1 indicate an aggregated distribution (Morisita 1959). Uniform distribution implies that the population is equally spaced, random indicates that it is spaced at random, and clustered distribution means that the population is distributed in groups (Figure 1).

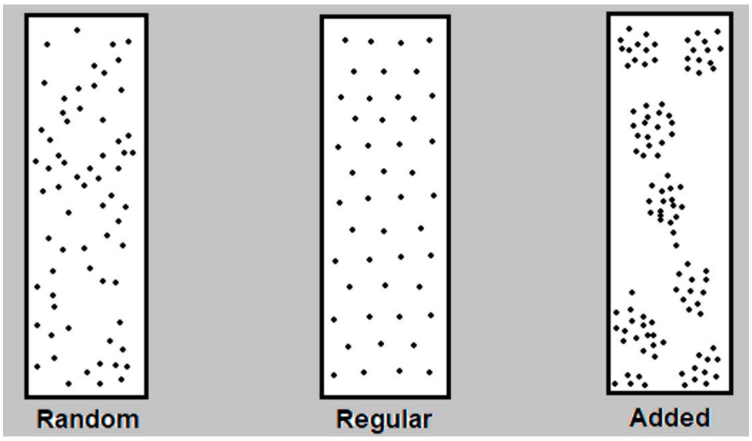

Figure 1. Spatial distribution models. Amaral et al., 2015 [20].

2.4. Abundance

To assess the abundance of *J. neotropica*, we followed the guidelines set forth in [21], as outlined in ministerial agreement 125, article 11. According to these guidelines, a species is considered to have low abundance when the density is less than one tree per three hectares (0.33 trees/ha^{-1}). Hence, we determined the abundance of *J. neotropica* by identifying the reference tree in each site and applying the specified criteria. This approach allows for an accurate evaluation of the species' abundance and facilitates comparisons across different sites.

Finally, the following formula was applied:

$$Ai = \sum n \quad (6)$$

where:

Ai = Absolute abundance
$\sum n$ = Number of individuals of a species present in an area

3. Results

3.1. Ocurrence the J. neotropica

The natural and artificial occurrence of *J. neotropica* species was observed in six locations within southern Ecuador, encompassing the provinces of Loja, El Oro, and Zamora Chinchipe. These occurrences were identified in forested areas measuring ≥0.5 hectares. Specifically, four instances were recorded in the province of Loja, while the remaining two were documented in the province of Zamora Chinchipe (Table 2).

Table 2. Occurrence of *J. neotropica* Diels growth sites in Southern Ecuador.

PROVINCE	CANTON	FOREST SITE	AREA (ha)
Zamora C hinchipe	Zamora	"Tibio" (a1)	0.8
		"Merced" (a2)	3
Loja	Sozoranga	"Tundo" (b1)	120
	Macará	"Victoria" (b2)	0.9
	Loja	"Zañe" (b3)	92
		"Argelia" (b4)	0.7
El Oro	No records	No records	0

In this study, the provenances were located in terms of political and geographical location, as can be seen in Figure 2.

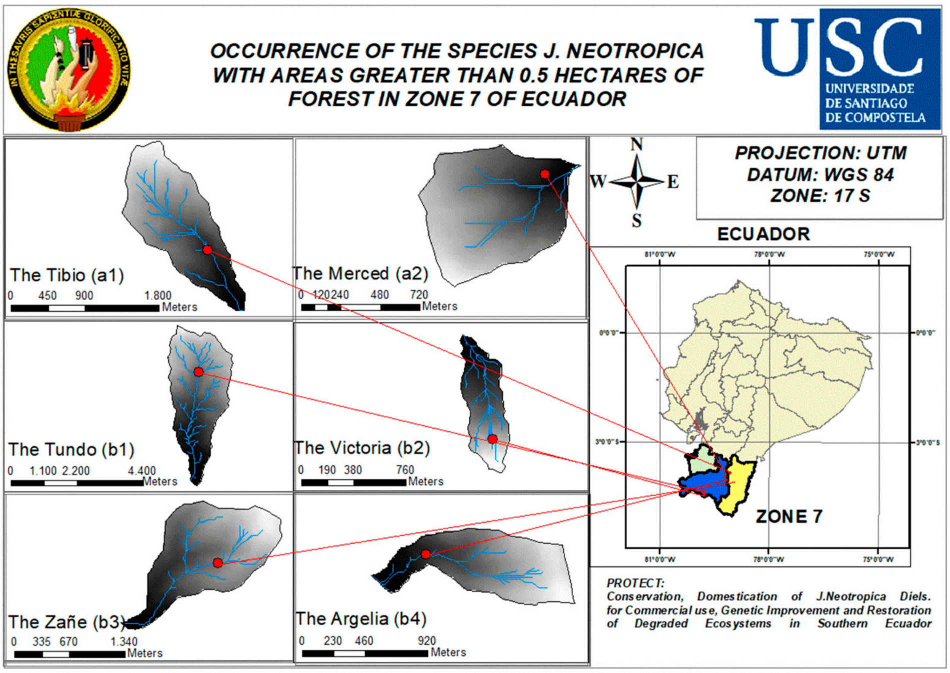

Figure 2. Geographic location of occurrences of the specie *J. neotropica* in areas greater than 0.5 hectares of forest in southern Ecuador.

3.2. Structural Parameters

In terms of structural parameters, we successfully determined the dasometric variables for all the locations with areas exceeding 0.5 hectares. The data obtained represent the number of individuals recorded within the sampled areas, appropriately adjusted to hectares to facilitate interpretation (Figure 3).

Figure 3. Measurement of structural parameters in the different locations of southern Ecuador, Tibio (**a1**), Merced (**a2**); Tundo (**b1**) Victoria (**b2**), Zañe (**b3**), Argelia (**b4**).

3.2.1. Horizontal Structure

The analysis of the horizontal structure across all provenances revealed significant variations in diameter classes and the number of individuals within each class. The Tundo Protected Forest exhibited the highest diversity, with 12 distinct diameter classes. Additionally, this provenance recorded the largest individuals in terms of diameter ($DBH_{1.30}$), with an impressive measurement of 134 cm (Figure 4). These findings emphasize the importance of considering provenance when assessing the horizontal structure of forest stands, as it can significantly influence the distribution and size of trees within a given area. These results contribute to our understanding of forest dynamics and have implications for sustainable forest management practices.

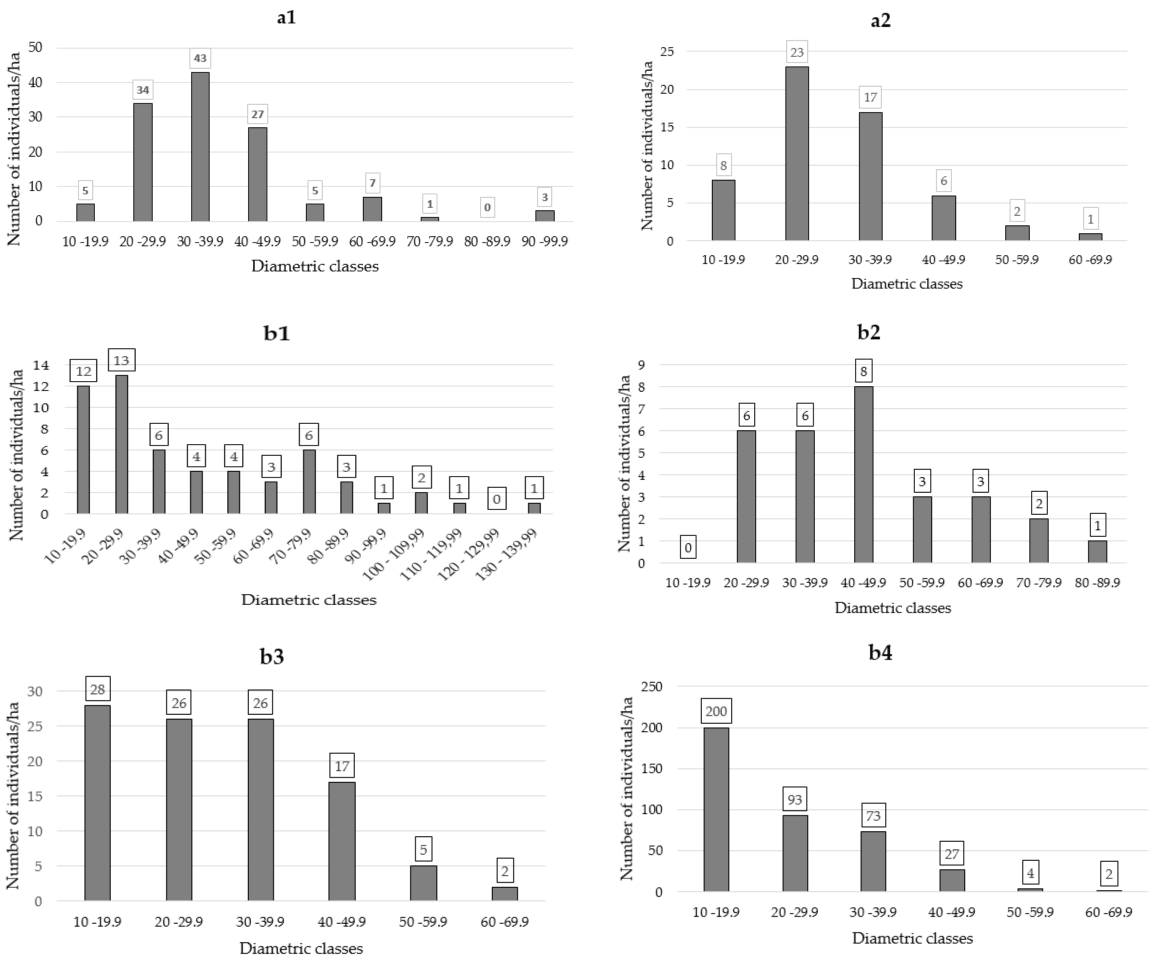

Figure 4. Number of individuals per class diameter classes in different locations of the study area at **DBH$_{\mathbf{(1.30cm)}}$**. Tibio (**a1**), Merced (**a2**), Tundo (**b1**), Victoria (**b2**), Zañe (**b3**), Argelia (**b4**).

Among the different provenances studied, The Argelia naturalized forest displayed the highest density of individuals per hectare, with a remarkable count of 399 ind/ha. This finding highlights the exceptional abundance and richness of this particular forest ecosystem.

The analysis of the Morisita Index (Iδ) revealed a distribution pattern greater than 1 in all the studied sampling units of the various provenances. This finding indicates an aggregated distribution pattern. (Table 3).

Table 3. Morisita index by locations.

ECUADOR			
ZONE 7			
OCCURRENCES			
PROVINCES	CANTONS	FORESTS	MORISITA INDEX
ZAMORA CHINCHIPE	ZAMORA	Tibio (a1)	1.18
		Merced (a2)	1.22
LOJA	SOZORANGA	Tundo (b1)	120
	MACARA	La Victoria (b2)	1.30
	LOJA	El Zañe (b3)	1.26
		Argelia (b4)	1.02
EL ORO	No register	No register	0

3.2.2. Vertical Structure

In relation to the vertical structure observed in all the identified provenances, our findings demonstrate that the arboreal component of *J. neotropica* attains impressive heights, ranging from 24 to 36 m, depending on the provenance. Notably, the tallest individuals were found within the Tibio Protected Forest and the Tundo provenances. (Figure 5).

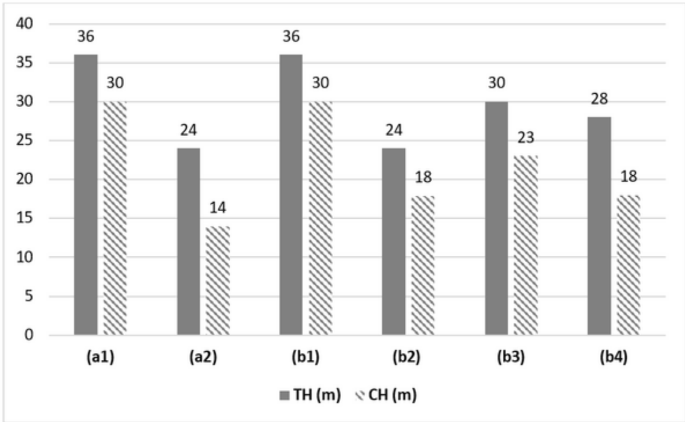

Figure 5. Vertical structure in the different locations of the study area The Tibio (**a1**), The Merced (**a2**), The Tundo (**b1**), The Victoria (**b2**), The Zañe (**b3**), The Argelia (**b4**).

3.2.3. Growth Variability

Regarding the growth behavior of dasometric variables among provenances in southern Ecuador, our study successfully demonstrated significant differences between the *J. neotropica* forests' dasometric variables using ANOVA. These findings highlight the variability in growth patterns across different provenances. The results contribute valuable insight into the understanding of tree growth in this region and have important implications for forest management and conservation strategies. Our study underlines the need for considering provenance-specific factors when developing sustainable forestry practices. These findings provide a solid foundation for future research and decision-making in the context of forest ecosystems in Southern Ecuador (Figure 6).

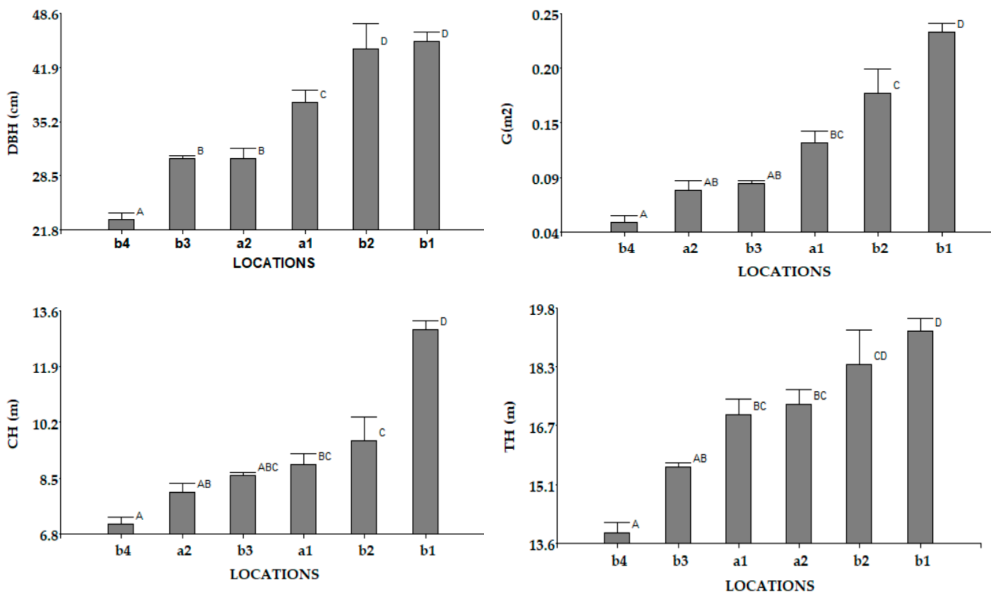

Figure 6. *Cont.*

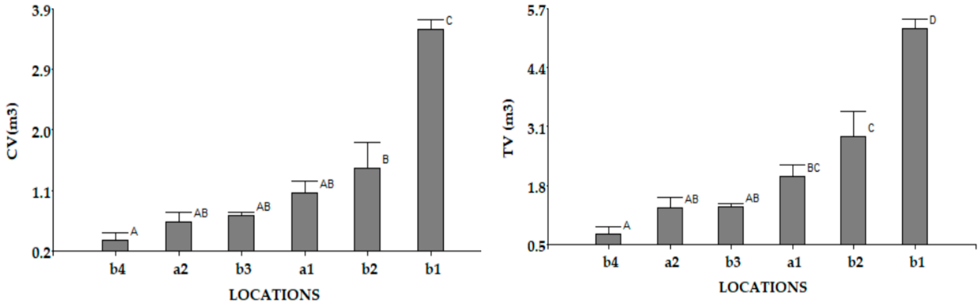

Figure 6. Analysis of variance of dasometric variables in the different locations of the study area Tibio (**a1**), Merced (**a2**), Tundo (**b1**), Victoria (**b2**), Zañe (**b3**), Argelia (**b4**). Means with a common letter are not significantly different ($p > 0.05$).

3.3. Abundance

The number of registered individuals of the *J. neotropica* species varied across different localities per hectare (Figure 7), with a minimum of 29 in Victoria and a maximum of 399 in Argelia.

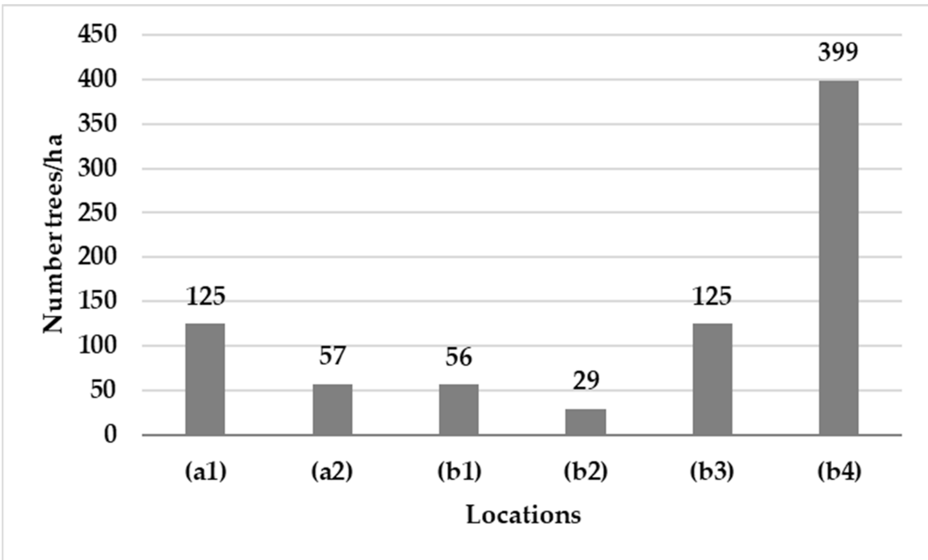

Figure 7. Number of individuals of the species recorded per hectare in the different locations of the study area Tibio (**a1**), Merced (**a2**), Tundo (**b1**), Victoria (**b2**), Zañe (**b3**), Argelia (**b4**).

4. Discussion

4.1. Occurrence

The occurrence of the *J. neotropica* species was investigated in southern Ecuador, specifically in the provinces of Loja and Zamora Chinchipe, excluding the province of El Oro. Six localities with areas greater than 5000 m^2 were identified as potential habitats for the species. Previous studies support the findings of this research regarding the occurrence of the species in the identified localities.

One study conducted by [22] reported the presence of the Tundo walnut forest in the canton of Sozoranga in the province of Loja. This forest comprises 96 hectares of native forest, located at altitudes ranging from 800 to 2645 m above sea level (masl). The area has a strongly inclined relief, which aligns with the findings of our study regarding the occurrence of the *J. neotropica* species.

Additionally, [23] documented the occurrence of the species in the canton of Loja in the Loja province, specifically in the Argelia sector. In this location, a planted forest approximately 70 years old has provided a suitable habitat where the *J. neotropica* species has naturalized effectively. The forest covers an area of 0.7 hectares and spans an altitudinal range of 2170 to 2250 masl, corroborating the findings of our study.

However, our research has revealed new occurrences of the *J. neotropica* species in previously unreported locations. The first location is Cerro el Zañe in the canton of Loja, characterized by an altitudinal range of 2100 to 2800 masl and a strongly inclined relief. The second location, the Victoria, corresponds to the canton of Macará in Loja and spans an altitudinal range of 1400 to 1600 masl. Furthermore, the species has been observed in the Merced, with an altitudinal range of 200 to 2200 masl, as well as in The Tibio, with an altitudinal range of 2400 to 2600 masl, in the canton of Zamora in Zamora Chinchipe. The precise locations of these occurrences have been reported for the first time in this study.

According to [14], the *Juglans* species exhibits a relative gregariousness in mature forest conditions, resulting in its scarcity within natural ecosystems. This pattern aligns with the findings of our research, further supporting the similarity between our study and previous observations of *Juglans* species.

4.2. Structure

Regarding the structural parameters of the forest in the discovered provenances of the *J. neotropica* species, all the dendrometric variables were correctly identified. However, the limited availability of research related to this species makes it challenging to compare our findings with other studies. Nevertheless, a study by [24] notes that the planted forest of *J. neotropica* in the Argelia exhibits very similar dendrometric variables to those observed in our study. The results underline the significance of the Argelia as a biodiverse habitat, showcasing its potential for conservation efforts and sustainable management. The high density of individuals within this forest emphasizes its ecological value and warrants further investigation into the factors contributing to its remarkable success. These findings provide valuable insight for forest management strategies and conservation initiatives in similar ecosystems.

Additionally, [25] mentions that young walnut trees have well-formed stems, reaching heights of 25 to 30 m with a diameter at breast height (DBH) of 90 cm. Our observations align with these findings at the study sites. This study sheds light on the remarkable vertical growth potential of *J. neotropica* and highlights the significant role played by specific provenances, such as The Tibio Protected Forest and the Tundo, in nurturing exceptionally tall individuals of this species.

In terms of Morisita's structural index, the species demonstrates an aggregated distribution behavior ($I\delta > 1.0$), indicating a preference for dominating specific sectors within the ecosystem. As described by [26], this type of distribution is not random but rather irregular, occurring in response to local habitat differences (microhabitats). The authors also highlight that added distribution is the most frequent pattern observed in nature and is a result of the inherent tendency of individuals to aggregate. Therefore, plants tend to disperse their seeds in close proximity to or in the same location where they reside.

Furthermore, the distribution of the species indicates a decreasing number of individuals over time, suggesting a gradual decline. However, it can still be found, albeit with difficulty, between 2200–3000 m above sea level (masl) in natural forest ecosystems covering areas greater than 5000 m^2.

4.3. Abundance

The abundance data obtained reveal notable differences in the number of individuals per hectare for the species *J. neotropica* across different provenances. The highest abundance was observed in the Argelia, followed by Zañe and Tibio. According to a previous study [23], the forest Argelia, being a forest plantation, exhibited the highest number of individuals per unit area in this investigation. This particular provenance, with an approximate age of 70 years, has adapted remarkably well to the prevailing climatic conditions at the site.

The Tundo Protected Forest and the Tibio provenance, which are native forests, also reported a relatively higher number of individuals per unit area according to another study [27]. Despite being located in different provinces, these forests share similar climate characteristics, which contribute to their higher abundance.

However, when considering the area extension, it is worth noting that the Tundo provenance boasts the largest forest area, covering approximately 130 hectares, whereas Argelia has the smallest extent, with only 0.7 hectares.

In terms of *J. neotropica* abundance, variations were observed in the number of individuals per hectare across the different provenances. These differences can be attributed to the severe threat posed to these ecosystems by various anthropic activities, such as livestock rearing and agriculture [28]. As a consequence, the species has been categorized as endangered by [16].

To better understand the abundance patterns and conservation status of *J. neotropica*, it is crucial to consider the interplay between provenance, climate conditions, and anthropic activities. The Algerian provenance, originating from a forest plantation, exhibited the highest abundance due to its successful adaptation to the local climatic conditions over several decades. Meanwhile, the Tundo Protected Forest and the Tibio provenance, being native forests, demonstrated a relatively higher abundance due to their favorable climate characteristics despite their geographical separation. However, the overall abundance of *J. neotropica* is alarmingly affected by human activities, with livestock rearing and agriculture exerting significant pressure on the species' survival.

5. Conclusions

In southern Ecuador, there are not many relicts or fragments of native forests of *J. neotropica*, the few fragments that exist presented a vertical structure in the form of an inverted j, which means that there is good growth dynamics, insofar as to the vertical structure, the individuals presented a dominance of the site with regard to other individuals that share their habitat. However, the number of individuals per hectare is not abundant in all locations.

The data obtained from the analysis of variance between the dasometric variables in relation to the different provenances of *J. neotropica* indicate that there are significant statistical differences, finding better growth in the fragments of forests with ecosystems of Semideciduous Forest Foot Montane of Catamayo-Alamor, which has a altitudinal variation of 400–1600 masl, as well as ecosystems of the Lower Montane Seasonal Evergreen Forest of Catamayo-Alamor, which has an altitudinal variation of 1600–2000 masl.

The number of trees found in the Argelia forest provenance is greater in relation to the other provenances because this is a naturalized plantation with more than 70 years of age. However, its forest area is very small with 0.7 hectares and with lower dasometric growth than the rest of the provenances studied.

Wild fruit trees, especially the *J. neotropica* species, play a crucial role in preserving biodiversity and providing natural resources in various ecosystems. It is essential to recognize the significance of these species in conserving flora and fauna, particularly in places like the Tundo walnut forest in the canton of Sozoranga, where favorable conditions exist for their development. The protection and promotion of these wild trees are fundamental in maintaining environmental harmony and balance, ensuring a sustainable future for later generations.

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4.2 Artículo II. Phenological Variation of Native and Reforested *Juglans neotropica* Diels in Response to Edaphic and Orographic Gradients in Southern Ecuador

Nota editorial:

Este segundo artículo desarrolla el Objetivo específico 2 de la Tesis Doctoral, enfocado en el análisis de la variación fenológica de *J. neotropica* en poblaciones nativas y reforestadas del sur de Ecuador. El estudio evalúa cómo gradientes edáficos, orográficos y climáticos (altitud, pendiente, tipo de suelo, temperatura y humedad relativa) influyen en eventos fenológicos clave como brotación, floración, fructificación y senescencia. Mediante un monitoreo multianual (2019–2023), se construyen calendarios fenológicos representativos por localidad, lo que permite comprender la plasticidad adaptativa de la especie frente a condiciones ecológicas contrastantes. Estos hallazgos aportan criterios técnicos para la planificación de reforestaciones, la conservación *ex situ* y el diseño de estrategias de restauración ecológica en territorios de alta fragilidad ambiental.

Cabe señalar que este análisis se centra exclusivamente en la expresión fenológica de la especie, diferenciándose de los rasgos fenotípicos evaluados en vivero y plantación en el tercer artículo.

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- JCR (Web of Science) 2024: Factor de impacto 2.1; Q2 en Biodiversity Conservation.
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Contribución del doctorando:

El doctorando Byron Palacios-Herrera participó como autor principal, siendo responsable del diseño metodológico, monitoreo fenológico en campo, análisis estadístico multivariado, redacción científica y elaboración de figuras. Esta contribución fue clave para cumplir el objetivo específico tres.

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Phenological Variation of Native and Reforested *Juglans neotropica* Diels in Response to Edaphic and Orographic Gradients in Southern Ecuador

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Abstract

Juglans neotropica Diels, classified as endangered on the IUCN Red List, plays a crucial role in the resilience of Andean montane forests in southern Ecuador—a megadiverse region encompassing coastal, Andean, and Amazonian ecosystems. This study examines how climatic, edaphic, and topographic gradients influence the species' phenotypic traits across six source localities—Tibio, Merced, Tundo, Victoria, Zañe, and Argelia—all of which are localities situated in the provinces of Loja and Zamora Chinchipe. By integrating long-term climate records, slope mapping, and soil characterization, we assessed the effects of temperature, precipitation, humidity, soil moisture, and terrain steepness on leaf presence, fruit maturation, and tree architecture. Over the past 20 years, temperature increased by 1.5 °C ($p < 0.01$), while precipitation decreased by 22%, disrupting local edaphoclimatic balances. More than 2000 individuals were measured in forest stands, with estimated ages ranging from 11 to 355 years. ANOVA results revealed that Tundo and Victoria exhibited significantly greater DBH, height, and volume ($p \leq 0.05$), with Victoria showing a 30% larger DBH than Argelia, the lowest-performing provenance. Soils ranged from loam to sandy loam, with slopes exceeding 45% and pH levels from slightly acidic to neutral. These findings confirm the species' pronounced phenotypic plasticity and ecological adaptability, directly informing site-specific conservation strategies and long-term forest management under shifting climatic conditions.

Keywords: phenotypic plasticity; diameter-class modeling; Andean montane forests; dendrochronology; soil fertility; altitudinal variation; forest provenance; climate–soil interaction

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1. Introduction

The study of tree phenotypic traits is fundamental to understanding how environmental variables influence their development and behavior [1]. Multiple studies by prominent researchers [2–6] have demonstrated that climate, soil properties, and biological competition significantly influence tree growth, morphology, and health. Among these factors, climate, soil properties, and terrain slope stand out as critical determinants of phenotypic expression [7,8]. This multidimensional perspective offers a comprehensive view of the interaction between forest biology and environmental conditions, providing valuable insights for the sustainable management of forest resources [9].

Climate change has become a major global concern due to its direct impacts on biodiversity and ecosystem functioning [10]. Trees, in particular, face considerable challenges from climate fluctuations. Variations in temperature, rainfall patterns, and the increasing frequency of extreme weather events have triggered notable phenotypic responses [11]. Recent research has documented how climate change alters tree physiology and behavior, influencing spatial distribution and the timing of seasonal events [12–14]. Moreover, rising incidents of drought and wildfires have further exacerbated forest vulnerability and adaptive capacity [10]. According to a report by the NGO Manos Unidas, elevated temperatures, stronger storms, and more frequent droughts are among the key climate change impacts affecting tree health and development [15,16].

The global rise in temperature poses a significant threat to the survival and development of the planet's flora, especially trees, which are vital components of terrestrial ecosystems. As sessile organisms, trees are highly sensitive to changing environmental conditions that directly affect their growth and reproductive success. Factors such as solar radiation, relative humidity, and ambient temperature are closely tied to tree productivity [17,18]. Thermal stress, intensified by climate change, and shifts in precipitation regimes—as discussed in a recent study [19]—present considerable challenges to tree vitality. These environmental stressors disrupt natural cycles of growth, flowering, and fruiting, thereby negatively impacting phenotypic expression [20,21].

Understanding the environmental factors that shape both genetic and phenotypic intraspecific diversity is essential for decoding the mechanisms that drive divergence in highly diverse biomes such as the Neotropical savannas [22].

Building on this relationship, recent studies underscore the importance of selecting trees based on phenotypic traits linked to soil properties, highlighting how nutrient availability, texture, and water retention capacity directly influence root development, trunk growth, and foliage production. This reinforces the close relationship between soil characteristics and tree physiology, supporting the need to study this interaction as a basis for sustainable forest management [8–23].

Juglans neotropica Diels performs best in fertile, well-drained soils—particularly those with loam-clay or loam-silt textures and a pH ranging from slightly acidic to neutral. According to [24], these conditions are ideal for its optimal development. In fact, these soil attributes are crucial for the successful establishment and maintenance of plantations of this species [25].

Therefore, understanding and accurately selecting the appropriate soil type is essential to enhance productivity and ensure long-term viability.

Trees that are ecologically adapted to specific soil conditions not only exhibit enhanced growth but also contribute significantly to biodiversity conservation and resilience to environmental stress. The intrinsic relationship between soil properties and tree development has been demonstrated in studies emphasizing the importance of selecting trees based on phenotypic responses to edaphic factors [23].

Key attributes such as nutrient availability, soil texture, and moisture retention are central to the development of roots, trunks, leaves, and fruits [26,27].

Beyond soil-related factors, tree morphology and structure are intricately linked to geographical conditions, particularly terrain slope. Topographic variation, defined by the inclination of the terrain, plays a critical role in regulating water distribution, erosion dynamics, and the availability of essential nutrients for tree growth [23,26]. Research further suggests that terrain slope can modulate genetic expression and tree architecture, especially in mountainous regions [23]. On steep slopes, trees often develop stronger root systems and aerodynamic crown structures that enhance resilience to wind exposure and other environmental challenges.

Prior to detailing species-specific attributes, an exhaustive literature review was conducted to characterize the phenological patterns of *J. neotropica* in native forest habitats. These findings informed the selection of study sites and the interpretation of seasonal performance indicators.

In studies of tree phenology, much attention is typically given to environmental factors such as climate, soil, and topography. However, one crucial aspect is often overlooked: tree age. In species like *J. neotropica* Diels, age is not merely a measure of time but a key determinant of phenological behavior. Young trees, for instance, do not flower or fruit in the same way as mature individuals. Their responses to seasonal changes can be more variable or even absent altogether. This variation in the timing and intensity of phenological events has been documented in several studies [28–30], supporting the inclusion of age as a meaningful explanatory variable. Understanding how age interacts with edaphoclimatic and orographic factors can provide a more comprehensive view of phenological patterns in complex ecosystems such as those found in southern Ecuador.

J. neotropica, commonly referred to as Andean walnut, is endemic to the montane forests of South America and plays a pivotal role in ecosystem stability. Its presence on steep slopes contributes to soil conservation and water retention through a complex root system [25]. In addition to its ecological function, this robust tree—distinguished by its bark and edible fruits—enhances biodiversity and offers important resources to mountain communities reliant on high-altitude ecosystems.

Classified as Endangered by the IUCN, *J. neotropica* provides multiple ecological and societal benefits, including edible seeds, natural dyes, and medicinal properties. It is also valued in urban landscaping due to its environmental adaptability.

To prevent its extinction, conservation strategies that incorporate genetic, ecological, and evolutionary approaches are essential. In this context, the study of biological diversity allows for the evaluation and preservation of species, the understanding of ecological interactions and adaptations, and the advancement of genetic improvement initiatives. Altogether, such efforts help safeguard biodiversity and support the sustainability of forest ecosystems.

This study explores the ecological significance of *J. neotropica* in montane forest conservation and its interactions with local communities, emphasizing its relevance to both environmental sustainability and human well-being. Therefore, the objective of this research was to analyze the influence of climate, soil type, and terrain topography on the phenotypic traits of parent trees in natural and planted populations of *J. neotropica* ($\geq$0.5 ha). A comprehensive assessment was undertaken to evaluate how these environmental variables affect dendrometric growth, health status, and reproductive performance.

The selected phenotypic traits—including dendrometric parameters, reproductive indicators, and overall health—were chosen for their relevance as adaptive responses to climatic, edaphic, and topographic variation. Their assessment provides technical insight into the species' ecological performance and informs targeted conservation strategies.

The main objectives of the study were:

- To deepen the understanding of the ecophysiology of *J. neotropica*, providing a solid foundation for its scientific analysis and application through slope-adaptation assessment and soil–phenotype correlations.
- To generate technical evidence that contributes to the sustainable management and long-term conservation of both natural and cultivated populations, adapting to diverse environmental conditions.

2. Materials and Methods

2.1. Study Area

The research focuses on Zone 7 in southern Ecuador, located between latitudes 3°30′ and 5°0′ south, and longitudes 78°20′ and 80°30′ west. It borders Zones 5 and 6 to the north, Peru to the south and east, and Peru and the Pacific Ocean to the west [31]. This area, recognized for its biological diversity, is distinguished by steep slopes often exceeding 45%, altitudinal gradients ranging from 400 to 3000 m a.s.l., transitional climates with temperature fluctuations above 25 °C and relative humidity below 70%, and soils of loam-clay to sandy-loam texture with neutral to slightly acidic pH. These physical and environmental traits confer significant ecological importance, shaping both species distribution and phenotypic variation across forest localities [32,33].

The study focused on the provinces of Loja and Zamora Chinchipe, with a combined area of 21,625.3 km^2, which constitutes approximately 8.65% of the Ecuadorian territory [31]. Six localities were selected: The Tundo, The Victoria, The Tibio, The Merced, The Zañe, and The Argelia. Notably, The Argelia is a forest plantation that has naturalized over time, meaning it exhibits ecological characteristics typical of a self-sustaining native forest—such as spontaneous regeneration, stable canopy cover, and functional integration into the surrounding ecosystem. This naturalization process has been observed over a period of approximately 25 to 30 years, during which the planted stand developed traits consistent with locally adapted populations. These areas host populations of *J. neotropica* Diels within homogeneous disetaneous forests, primarily belonging to Evergreen Montane Forest and transitional ecosystems of Zone 7, southern Ecuador [32].

To complement the regional description and support ecological interpretation, we compiled a comparative summary of environmental attributes across the six sampling localities. Table 1 presents elevation ranges, mean temperatures, relative humidity, and ecological classifications for each site. Precise coordinates were intentionally omitted due to the IUCN Red List status of *J. neotropica* as an endangered species; instead, these descriptors serve to spatially anchor the study while preserving location sensitivity.

Table 1. Environmental Context of *Juglans neotropica* Diels Localities in Southern Ecuador.

Localities	Elevation (m a.s.l.)	Mean Temperature (°C)	Relative Humidity (%)	Ecological Context
The Tibio	2100–2600	~18	90	Southern Montane Evergreen Forest of the Eastern Cordillera of the Andes
The Merced	2000–2500	~20	90	Southern Montane Evergreen Forest of the Eastern Cordillera of the Andes
The Tundo	1200–2400	~14	77	Catamayo-Alamor Semideciduous Foot Montane Forest and Evergreen Seasonal Montane Forest
The Victoria	1000–1600	~23	75	Catamayo-Alamor Semideciduous Foot Montane Forest
The Zañe	2200–3000	~11	80	Southern Montane Evergreen Forest of the Eastern Cordillera of the Andes
The Argelia	2130–2200	~15	78	Southern Montane Evergreen Forest of the Eastern Cordillera of the Andes

Note: The six sampling localities—The Tibio, The Merced, The Tundo, The Victoria, The Zañe, and The Argelia—were selected based on the presence of *J. neotropica* populations and ecological representativeness. This table provides a general overview of site-level environmental conditions to support territorial characterization and conservation relevance.

Fieldwork was carried out in these localities due to their ecological representativeness and concentration of mature individuals of different age classes. The combination of steep slopes, altitudinal gradients, and heterogeneous soils makes this region a suitable setting for evaluating the influence of environmental factors on phenotypic traits, providing key data for medium- and long-term conservation planning [31].

2.2. Climate

To assess the influence of climatic and edaphic factors—including precipitation, temperature, relative humidity, and soil moisture at one-meter depth—data collection was carried out following standardized field protocols in areas where *J. neotropica* is present in southern Ecuador. To obtain reliable data, globally recognized sources such as POWER—Data Access were consulted, providing daily climatological records from 1981 to the present [34].

These data were verified by cross-referencing climatological information from databases maintained by municipal governments, provincial councils, and parish administrations, as well as reports from both public and private research entities. These complementary sources significantly contributed to illuminating relevant climatic aspects of the study areas [35].

The resulting records originate from within natural populations of *J. neotropica* monitored over four decades (1981–2023). Climatic data were retrieved using the POWER Data Access Viewer platform on a daily basis over a 12-month period, totaling 365 days per year. Across the 42-year span, this approach yielded 15,330 individual data points per variable, yielding annual mean values that provide a robust and longitudinal characterization of the climatic conditions experienced by *J. neotropica* across decades.

2.3. Soil

To obtain detailed information on soil properties in the study area, a technical-administrative approach was implemented using SIGTIERRAS 2022 and the geopedological unit. In the first stage, geopedological mapping at a scale of 1:25,000 from SIGTIERRAS was used to analyze soil fertility, as well as physical, chemical, and microbiological aspects of the soil. The methodology incorporated the mass valuation of rural lands, following specific guidelines published in the Geoportal del Agro Ecuatoriano in 2017. Additionally, soil and geomorphology data were integrated to conduct a land use capacity analysis, with the active participation of SIGTIERRAS-MAG-IEE. This comprehensive approach provided a complete understanding of soil characteristics, facilitating more effective planning and sustainable management for *J. neotropica*.

Data collection was carried out using the SIGTIERRAS platform, selecting relevant variables that helped interpret how they affected the phenotypic characteristics of *J. neotropica* populations in the study area in southern Ecuador; these variables included hydrogen potential (pH), cation exchange capacity (CEC), fertility, morphology, slope, taxonomic order, texture, drainage, depth, stoniness, salinity, temperature, humidity, and organic matter (OM).

To ensure comprehensive information in the selected locations with the presence of the native forest species *J. neotropica*, a rigorous and scientific methodology proposed by [33] was implemented. This comprehensive methodology supports the acquisition of precise data on the composition and properties of the forest soil, thus establishing a solid scientific basis for subsequent analysis and conclusions. The process is detailed below:

2.3.1. Identification of Representative Areas

Representative areas larger than 0.5 ha of forest were selected, classified into homogeneous zones based on the predominant vegetation specifically *J. neotropica* and topography, allowing for precise environmental mapping. Specialized tools, such as shovels and cylindrical corers, were employed to extract composite soil samples at three distinct depths: 0–10 cm, 10–20 cm, and 20–30 cm. For each forest plot larger than 0.5 ha, three subsamples were collected per depth and combined into a single composite sample, ensuring exhaustive and representative collection. All samples were labeled with geospatial and environmental metadata and stored in airtight containers under biosafety protocols.

As shown in (Figure 1), the sampling pit reached a depth of 30 cm, enabling stratified collection across three soil layers.

Figure 1. Soil Sampling Profile in a *Juglans neotropica* Diels Forest.

Representative excavation site illustrating vertical depth measurement during composite soil sampling in a disetaneous forest dominated by *J. neotropica* in southern Ecuador. The measuring tape marks a depth of approximately 30 cm. This procedure was applied to forest plots exceeding 0.5 ha, with samples collected at three defined strata (0–10 cm, 10–20 cm, 20–30 cm), enabling stratified analysis of soil characteristics across ecological layers.

Furthermore, multiple samples were taken from each locality of origin to capture soil heterogeneity, with each sample labeled with detailed information regarding location, vegetation type, altitude, and orientation, facilitating subsequent analysis and study replication. The samples were stored in airtight containers following biosafety practices, and meteorological conditions, such as temperature and humidity, were documented during the collection process to enrich the environmental context of the analyses.

2.3.2. Sample Conservation and Laboratory Shipment

The soil samples collected were preserved following the methodology proposed by [36]. It was ensured that the samples were precisely labeled and recorded, stored under conditions that prevented contamination, and documented with relevant climatic data. These practices not only ensured the acquisition of accurate data regarding the composition and properties of the soil but also provided a solid scientific basis for future analyses.

2.4. Slope

Topographic Digitization of Localities

To determine the spatial distribution of *J. neotropica* habitats, a detailed methodological strategy was implemented. A slope map was first generated using control points obtained via GPS. Field information was subsequently processed with ARCGIS 10.8 software to ensure accuracy and robustness of the results. This strategy combined technical precision with local expertise, resulting in a comprehensive assessment of the target areas (Table 1). Terrain slope was calculated as a percentage using a Digital Elevation Model (DEM), establishing a quantitative basis for spatial analysis. A reclassification was then applied using previously defined indices, following the methodology proposed by [37,38] (Table 2). While Table 2 presents the classification indices, Table 1 was designed to identify and digitally map areas with slopes exceeding 30% inclination. Experts and local landowners indicated that surpassing this threshold poses a significant ecological risk, particularly to *J. neotropica* habitats when forested areas are cleared for anthropogenic activities. In addition, criteria provided by local professionals and producers from the study areas were incorporated—such as site accessibility, slope operability for manual sampling, dominance of *J. neotropica*, and recent ecological disturbances reported by local actors. These practical, context-specific inputs enriched the methodology by ensuring ecological representativeness and logistical feasibility across selected sampling localities.

Table 2. Indices for classifying slopes in micro-watersheds of different localities.

Slope (%)	Classification Indices
0–15	1
15–30	2
30–45	3
>45	4

The purpose of Table 1 was to identify and digitally map areas with slopes exceeding 30% inclination. Experts and local landowners indicated that surpassing this threshold poses a significant ecological risk, particularly to *J. neotropica* habitats when forested areas are cleared for anthropogenic activities.

2.5. Phenology

To study the phenology of *J. neotropica* in ecologically representative contexts, including both native forests and naturalized forest plantations such as The Argelia, a comprehensive methodology was implemented, encompassing various stages [39]. Information was gathered on seasonal patterns, life cycles, and environmental factors influencing the phenology of the selected species. Subsequently, the key species was identified through systematic sampling techniques, using study plots strategically distributed in the native forest.

The geographic layout of the studied localities—including native forests and The Argelia plantation—is illustrated in Figure 2, providing contextual reference for phenological monitoring.

Once the individuals of the species *J. neotropica* were identified, continuous monitoring protocols were established to record phenological events such as flowering, fruiting, and leaf fall. These records were maintained over a representative period of one calendar year to capture monthly variability. This temporal design follows current environmental sensitivity criteria that emphasize organ-specific phenological responses to climatic variation, as reported by [29]. To complement direct observation, advanced technologies such as state-of-the-art binoculars or prismatic devices were employed to obtain more detailed and precise data on the phenology of the forest species. In addition, visual inspection methods grounded in [40] were applied to assess desirable phenotypic attributes of *J. neotropica*, including vigor, dominance, structural conformation, apparent health, and foliar expression. This inclusive characterization covered approximately 30% of the individuals recorded in each provenance locality, without applying exclusion criteria, thereby contributing to a representative ecological description aligned with sustainable forest monitoring practices.

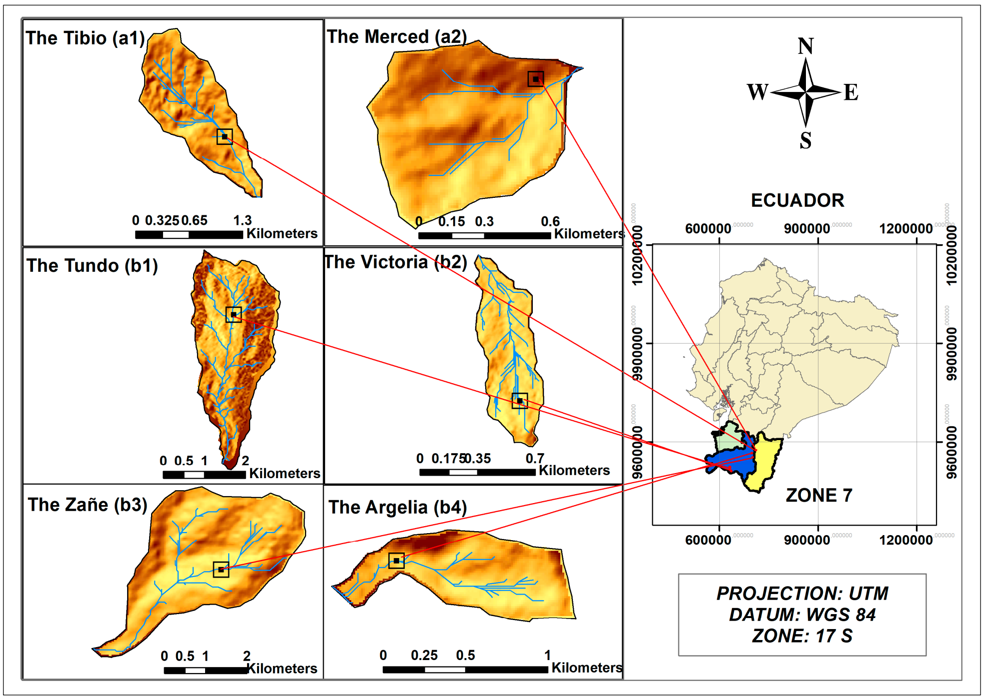

Figure 2. Spatial distribution of the six provenance localities with *J. neotropica* forest patches over 0.5 ha in southern Ecuador. Native forests and the naturalized plantation The Argelia are highlighted. (a1) The Tibio; (a2) The Merced; (b1) The Tundo; (b2) The Victoria; (b3) The Zañe; (b4) The Argelia. Adapted from [32].

Phenological monitoring has been conducted continuously since 2019. In 2023, a partial analytical cutoff was made, linked to the completion of the associated doctoral studies. Nevertheless, monitoring efforts continue to the present day. Given the recurrent patterns observed between 2019 and 2023, representative phenological calendars were developed for each locality.

Data collection was complemented with environmental measurements, including climatic variables, soil properties, and topographic characteristics of the study area. This approach allowed for the analysis of the relationship between phenological events and environmental factors, providing a more comprehensive understanding of the processes governing the phenology in the *J. neotropica* forest. Finally, advanced statistical analyses were applied to identify significant patterns and establish correlations between the different variables collected.

Phenological monitoring has been conducted continuously since 2019 across ecologically distinct localities. In 2023, a partial analytical cutoff was applied, coinciding with the completion of the associated doctoral research. Despite this cutoff, monitoring efforts remain ongoing. Based on recurrent patterns observed between 2019 and 2023, representative phenological calendars were constructed for each locality. These calendars integrate key developmental events—flowering duration, fruiting onset, and leaf abscission timing—alongside environmental variables such as altitude, slope, temperature, and relative humidity, enabling correlation analyses and supporting the interpretation of phenophase variability.

The proposed methodology aimed not only to document the phenology of *J. neotropica* within native forest environments, but also to characterize its interactions with surrounding environmental factors across both natural and planted contexts, recognizing the ecological relevance of semi-natural stands in the study region.

This integrative methodology generated foundational insights for the conservation, sustainable management, and ecological restoration of *J. neotropica*, particularly by encompassing phenological patterns across both native and naturalized forest stands, in alignment with restoration-oriented forest monitoring practices recommended by the [41]. Its rigorous and systematic implementation ensured the acquisition of robust and contextually relevant data, thereby advancing scientific understanding of species dynamics and resilience in response to environmental fluctuations

2.6. Determination of the Age of Trees

2.6.1. The Calculation of Transit Time

In accordance with the mixed-method framework established for the ecological characterization of *J. neotropica*, transit time estimation was incorporated as a technically justified, non-invasive strategy to approximate tree age across the study area. This approach offered a means to harmonize indirect estimation techniques with empirical field observations, particularly in contexts where legally constrained sampling limited the availability of conventional dendrochronological data. The model's application draws on regionally validated growth increments (CAI-A), ensuring methodological continuity while enabling diameter-class-based temporal reconstruction.

As part of the mixed-method approach applied to the ecological characterization of *J. neotropica*, the age of individual trees was estimated through indirect methods, grounded in field-based dendrometric data, archival validation, and ethically sourced plant material.

Given that *J. neotropica* is classified as "Endangered" by the International Union for Conservation of Nature (IUCN), and in accordance with current regulations from Ecuador's Ministry of the Environment, Water and Ecological Transition (MAATE), destructive sampling techniques on live specimens are prohibited. This restriction limited the application of conventional dendrochronological methods across much of the study area, thereby necessitating indirect strategies for growth estimation.

Nevertheless, in locations characterized by steep slopes, high wind exposure, and geodynamic landslides, naturally fallen individuals were encountered. In such areas—including sites such as The Tundo, The Victoria, and montane sectors of the Loja Highlands such as The Zañe—material was ethically collected without compromising the integrity of remnant forest populations or violating environmental regulations. For these cases, the method proposed by Gonzaga (1997), cited in [42], was applied. This technique involves the extraction of cross-sections near ground level (Figure 3A), followed by the calculation of the Annual Current Increment (CAI-A) (Figure 3B).

Figure 3. Cross-section of *J. neotropica* trunk at 60 cm above ground level (**A**); schematic depiction of CAI-A calculation methodology (**B**).

While this study prioritized indirect approaches, it is acknowledged that ring-counting in cross-sections constitutes the most direct method for age determination, as highlighted by [43] in their evaluation of tropical species in India's Western Ghats. However, in the case of *J. neotropica*, factors such as indistinct ring formation and legal limitations preclude the systematic use of such techniques.

A total of 2176 individuals were recorded across all surveyed forest localities. The technical procedure was carried out in five stages:

1. **Diameter-Based Classification**
   Trees were grouped into diameter classes using diameter at breast height (DBH) measurements, taken at 1.30 m above ground level. The class intervals were set at 10 cm, following the methodological criteria proposed by [44] in Silviculture in the Tropics: Tropical Forest Ecosystems and Their Tree Species—Possibilities and Methods for Their Long-Term Management. This segmentation is widely recognized as a practical silvicultural tool for characterizing forest structure and analyzing population dynamics in tropical ecosystems. It enabled the modeling of growth variability and facilitated the construction of class-specific adjustment curves for transit time estimation.
2. **Calculation of Annual Current Increment (CAI-A)**
   CAI-A was estimated for each diameter class by correlating observed growth with the approximate age of representative individuals.
3. **Adjustment of CAI-A vs. Diameter Class Curve**
   Values were corrected by class and fitted with a trend curve to model growth variability.
4. **Calculation of Transit Time by Class**
   Obtained by dividing the range of each diameter class by its corresponding CAI-A, representing the time required for an average tree to transition through the class.
5. **Estimation of Total Growth Duration**
   The cumulative transit times were summed to estimate age from seedling stage to the upper limit evaluated.

The transit time model served as a complementary adjustment mechanism, grounded in validated CAI-A references, without altering the underlying indirect estimation framework applied throughout the study.

Prior to consulting tropical growth models developed in Asia and South America, region-specific research conducted in Loja province was reviewed. The studies by [45,46] applied dendrochronological methods to Andean forest ecosystems, providing technically relevant parameters for age estimation and biological rotation periods of *J. neotropica*. These locally derived findings were considered as empirical reference points to support the growth ranges used in the present study.

In sites where direct sampling was not feasible, growth models developed for ecologically similar tropical species—such as *Ocotea radiaei*, *Baikiaea plurijuga*, and *Mora excelsa*—from Malaysia, Guyana, India, and Thailand [42] were consulted. This approach enabled reliable estimates within acceptable error margins, ensuring scientific robustness, legal compliance, and respect for forest conservation principles. It is worth noting that the age estimation model employed was developed with an empirically established margin of error of ±5%, operating at a 95% confidence level, as a methodological basis prior to inferential statistical analysis.

2.6.2. Dendrochronological Validation and Error Estimation

To validate transit-time estimates, a dendrochronological protocol was applied to 12 naturally fallen trees (one section per tree) in The Tundo, The Victoria, and The Zañe:

1. **Sample preparation**
   Twelve cross-sections were collected at 60 cm above the root collar. Sections were air-dried for 14 days and sanded sequentially with 180, 320, to 4000-µm grit sandpapers.
2. **Ring-width measurement**
   Under a 20× binocular microscope and using a digital caliper (0.01 mm precision), ring widths were measured and recorded in a structured datasheet.
3. **Visual crossdating**
   Width patterns (narrow vs. wide rings) across the 12 series were compared to assign each ring to its calendar year. Samples with highly eroded or indistinct rings were excluded.
4. **Correlation between CAI-A and dendrochronological age**
   Pearson's correlation coefficient (r) was calculated between ages estimated by the transit-time method (CAI-A) and those obtained by ring counts, yielding r = 0.91 ($p < 0.001$; $n = 12$).
5. **Error estimation and confidence intervals**

The standard error (SE) of the CAI-A age estimates was computed as:

$$SE = \frac{SD}{\sqrt{n}}$$

Here SD is the standard deviation of age differences and n = 12.
The 95 % confidence interval was determined by:

$$IC_{95\%} = t_{0,95,n-1} * SE$$

The average margin of error across all diameter classes was ±5%.

These validations confirm the reliability of CAI-A curves and transit-time estimates are supported by reliable dendrochronological ages, strengthening the indirect approach for estimating the age of *J. neotropica*.

To complement this validation, locality-specific margins of estimation error were calculated using the CAI-A approach across six sampling sites. These site-level averages ranged from ±1.21 years in The Argelia to ±3.08 years in The Tundo, with maximum deviations reaching ±19.23 years in large-diameter individuals (Table 3). This variability reflects local structural heterogeneity and supports a spatially contextualized application of the model. By explicitly reporting error margins, we address calibration concerns raised by reviewers and reinforce the reliability of age estimates within the current ecological framework.

Table 3. Estimated Margins of Error by Locality Based on CAI-A Transit-Time Methodology.

Locality	Mean ± SD (Years)	Min–Max (Years)
The Tibio	2.20 ± 1.50	0.53–9.61
The Merced	1.64 ± 0.72	0.55–4.06
The Tundo	3.08 ± 3.49	0.43–19.23
The Victoria	2.81 ± 1.76	0.85–8.52
The Zañe	2.07 ± 1.30	0.42–14.82
The Argelia	1.21 ± 0.66	0.42–3.84

Estimated margins of error by forest locality derived from CAI-A transit-time estimates. Dispersion reflects site-specific diameter distributions and ecological heterogeneity.

2.7. Data Analysis

For data analysis, climatic variables were examined and graphs were generated using information collected over a 42-year period from the POWER-Data Access platform, covering precipitation, temperature, relative humidity, and Soil moisture at root level exceeded 60% in 1983, 1989, and 1998 in the localities of The Zañe, The Merced, The Tibio, and The Argelia. Time series analysis techniques were employed to identify trends and patterns over time. The data were preprocessed to eliminate outliers, and descriptive statistical methods were applied, visualizing the results using graphs created in Excel. For the soil variable, detailed information was collected using the SIGTIERRAS platform, including physical and chemical properties such as pH, cation exchange capacity (CEC), fertility, morphology, slope, taxonomic order, texture, drainage, depth, stoniness, salinity, temperature, moisture, and organic matter (O.M.) content. These properties were subjected to principal component analysis (PCA) to identify the main factors influencing soil characteristics, with the PCA results contrasted with physical and chemical laboratory analyses conducted for each study locality. Regarding the slope variable of the terrain, georeferenced information was collected and slope maps of the soil were constructed using ArcGIS 10.8, with a DATUM WGS84 projection and UTM coordinates, zone 17 South. The phenological records were analyzed to identify temporal trends in leaf production, flowering, and fruiting intensity across localities and months. Finally, for the age variable, descriptive statistical analysis was conducted, including mean, standard deviation, minimum, and maximum values. Regarding the dasometric variable (DBH), exploratory data analysis was performed to assess distributional assumptions. Given the non-normal distribution of DBH across localities, as evidenced by its skewed structure and high variability, the Kruskal–Wallis test was applied instead of ANOVA. This non-parametric test allowed for the comparison of median DBH values among localities without assuming normality. Post hoc comparisons were conducted to identify statistically homogeneous groups. This approach ensured methodological robustness in evaluating structural differences across provenances. All statistical analyses were conducted using InfoStat/Professional 2020 software.

3. Results

3.1. Climate

Long-term climate monitoring revealed consistent and statistically significant shifts in key ecological variables across natural populations of *Juglans neotropica* Diels. In The Zañe, The Tibio, and The Argelia, precipitation and soil moisture declined over time ($\tau = -0.263$ and -0.414, respectively; $p < 0.05$), while temperature increased steadily ($\tau = +0.427$, $p < 0.001$). These trends, confirmed by the Mann–Kendall test, align with broader regional warming scenarios and suggest a progressive reduction in water availability across mid-elevation zones. These patterns are visually summarized in Figure 4, which illustrates site-specific climatic variation from 1981 to 2023. Relative humidity also decreased significantly ($\tau = -0.345$, $p = 0.005$), with notable drops in 2005 (68.7%) and 2010 (69.5%), disrupting previously stable microclimatic conditions in montane forests. In contrast, The Victoria and The Tundo exhibited more abrupt climatic shifts. Precipitation declined more steeply ($\tau = -0.379$, $p = 0.002$), and temperature increases were more pronounced ($\tau = +0.590$, $p < 0.001$), with values exceeding 30 °C across multiple periods from 1981 to 2023. Relative humidity in these sites fluctuated more sharply, falling below 60% in years such as 1985, 2005–2007, and 2022. Soil moisture remained relatively stable between 50–60%, yet by 2023, a decline to 55% was observed, suggesting a gradual depletion of subsurface reserves. Interannual records show that The Zañe, The Merced, The Tibio, and The Argelia received over 800 mm/year of precipitation during periods such as 1981–1984, 1986, 1989–1990, 1992–1994, 1997–2002, 2008, 2011–2012, 2021, and 2023. In these same sites, temperatures surpassed 25 °C in 2005 and 2010. Meanwhile, The Tundo and The Victoria recorded precipitation above 300 mm/year during 1981–1984, 1986–2004, 2008, 2011–2013, 2015–2017, and 2019–2023, while temperatures exceeded 30 °C consistently from 1981 to 2023. Relative humidity patterns further illustrate site-specific contrasts. In The Zañe, The Merced, The Tibio, and The Argelia, humidity remained above 70% during 1981–2004, 2006–2009, and 2011–2023. In The Tundo and The Victoria, values exceeded 60% during selected years but dropped below that threshold in periods such as 2005–2007, 2009–2011, and 2022. Soil moisture at root level also varied across sites. In The Zañe, The Merced, The Tibio, and The Argelia, values exceeded 60% in 1983, 1989, and 1998. In The Tundo and The Victoria, moisture levels remained between 50–60% throughout the study period, with peaks in 1983 (66%), 1989 (62%), and 1998 (70%), but declined to 55% by 2023. These climatic shifts, interpreted collectively, may compromise seedling recruitment, growth rates, and root-soil interactions essential to the resilience of *J. neotropica* in fragmented Andean forests.

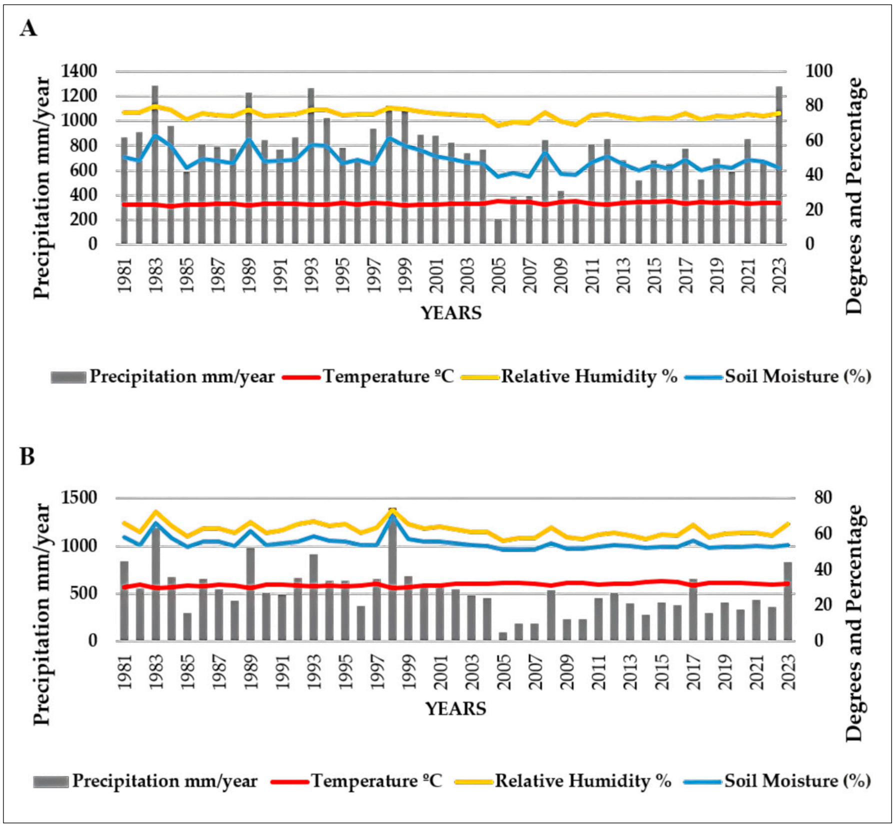

Figure 4. Climatic variation (1981–2023) in *J. neotropica* sites: The Zañe, The Merced, The Tibio, The Argelia (**A**); The Tundo and The Victoria (**B**). Mann–Kendall tests revealed significant site-specific trends in precipitation, temperature, humidity, and soil moisture, with implications for forest resilience (Section 3.1).

3.2. Soil

The results present the physical and chemical properties of the soil recorded in natural and planted populations of *J. neotropica* (Table 4).

In The Tundo, The Victoria, The Zañe, and The Argelia, the soil presented a neutral pH of 7.0 (Table 4), while in The Merced and The Tibio, it was slightly acidic, with pH values of 6.7 and 6.8, respectively, averaging 6.75 (Table 3). The Victoria and The Zañe had a high Cation Exchange Capacity (CEC), with recorded values of 22 and 25 meq/100 g, respectively (Table 3), For The Tundo, the Cation Exchange Capacity (CEC) was medium, with a recorded value of 14 meq/100 g (Table 3); For The Tibio and The Argelia, the Cation

Exchange Capacity (CEC) was low, with recorded values of 8 meq/100 g for both sites (Table 3); and for The Merced, the Cation Exchange Capacity (CEC) was very low, with a recorded value of 4 meq/100 g (Table 3). The Victoria, The Zañe had medium fertility; for The Tundo and The Argelia, it was low; and for The Merced and The Tibio, it was very low. The Tundo, The Victoria, and The Zañe presented a mountainous relief morphology; The Merced had a rectilinear slope; The Tibio had a heterogeneous slope; and The Argelia had a medium hilly relief. The Tundo, The Victoria, and The Zañe had a very steep slope > 70%; The Merced, The Tibio, and The Argelia had a steep slope of 40–70%. The Tundo and The Victoria had a taxonomic order of Alfisols; The Merced and The Tibio had Inceptisols; and The Argelia and The Zañe had Entisols. The Tundo, The Victoria, and The Tibio had a clay loam texture; The Merced had a silty clay texture; The Argelia had a sandy loam texture; and The Zañe had a loam texture. The Tundo had moderate drainage; The Victoria, The Merced, The Tibio, and The Zañe had good drainage, and The Argelia had excessive drainage. The Tundo, The Victoria, The Merced, and The Tibio had shallow depth; while The Argelia and The Zañe had very shallow depth. The Argelia and The Zañe had abundant stoniness; The Tundo and The Merced had frequent stoniness; The Victoria had few stones, and The Tibio had none. Regarding salinity, all locations shared non-saline soil. Regarding temperature, all locations shared isothermal soil. The Tundo, The Victoria, and The Argelia had ustic moisture; The Merced, The Tibio, and The Zañe had udic moisture. The Tibio had high Organic Matter (OM); The Victoria and The Zañe had medium OM; The Tundo, The Merced, and The Argelia had low OM.

Table 4. Physical, chemical, and morphological soil properties of *J. neotropica* sampling localities in zone 7 of Ecuador.

Localities	**The Tibio**	**The Merced**	**The Tundo**	**The Victoria**	**The Zañe**	**The Argelia**
pH	6.8	6.7	7.0	7.0	7.0	7.0
CEC meq/100 g	8.0	4.0	14	22	25	8.0
Fertility	Very low	Very low	Low	Medium	Medium	Low
Morphology	Heterogeneous slope	Rectilinear slope	Mountainous relief	Mountainous relief	Mountainous relief	Medium hilly relief
Slope	Steep > 40–70%	Steep > 40–70%	Very steep > 70%	Very steep > 70%	Very steep > 70%	Steep > 40–70%
Taxonomic Order	Inceptisols	Inceptisols	Alfisols	Alfisols	Entisols	Entisols
Texture	Clay loam	Silty clay loam	Clay loam	Clay loam	Loam	Sandy loam
Drainage	Good	Good	Moderate	Good	Good	Excessive
Depth	Shallow	Shallow	Shallow	Shallow	Superficial	Superficial
Stoniness	None	Frequent	Frequent	Few	Abundant	Abundant
Salinity	Non-saline	Non-saline	Non-saline	Non-saline	Non-saline	Non-saline
Temperature	Isothermal	Isothermal	Isothermal	Isothermal	Isothermal	Isothermal
Moisture	Udic	Udic	Ustic	Ustic	Udic	Ustic
O.M	High	Low	Low	Medium	Medium	Low

CODE: Site code; pH: Potential of Hydrogen; CEC: Cation Exchange Capacity; meq/100 g: milliequivalents per 100 gram; Fertility: Soil fertility level; Morphology: Relief morphology; Slope: Gradient as percentage; Taxonomic Order: Soil classification (USDA); Texture: Soil particle composition; Drainage: Water infiltration capacity; Depth: Effective soil depth; Stoniness: Presence of stones; Salinity: Salt content; Temperature: Thermal regime; Moisture: Soil moisture regime; O.M.: Organic Matter.

3.3. Slope

Topographic slope emerged as a defining environmental variable across all *J. neotropica* localities, shaping hydrological dynamics, erosion susceptibility, and land-use constraints. All sampled populations were located on terrains with slopes exceeding 45%, a threshold that influences both root anchorage and water retention capacity.

Marked differences in steepness were observed among micro-watersheds, with certain fragments exhibiting abrupt elevation gradients that may affect phenotypic expression and regeneration success. These spatial patterns are visualized in the slope maps presented in Figure 5, which highlight the geomorphological context of each locality and its implications for forest structure and management.

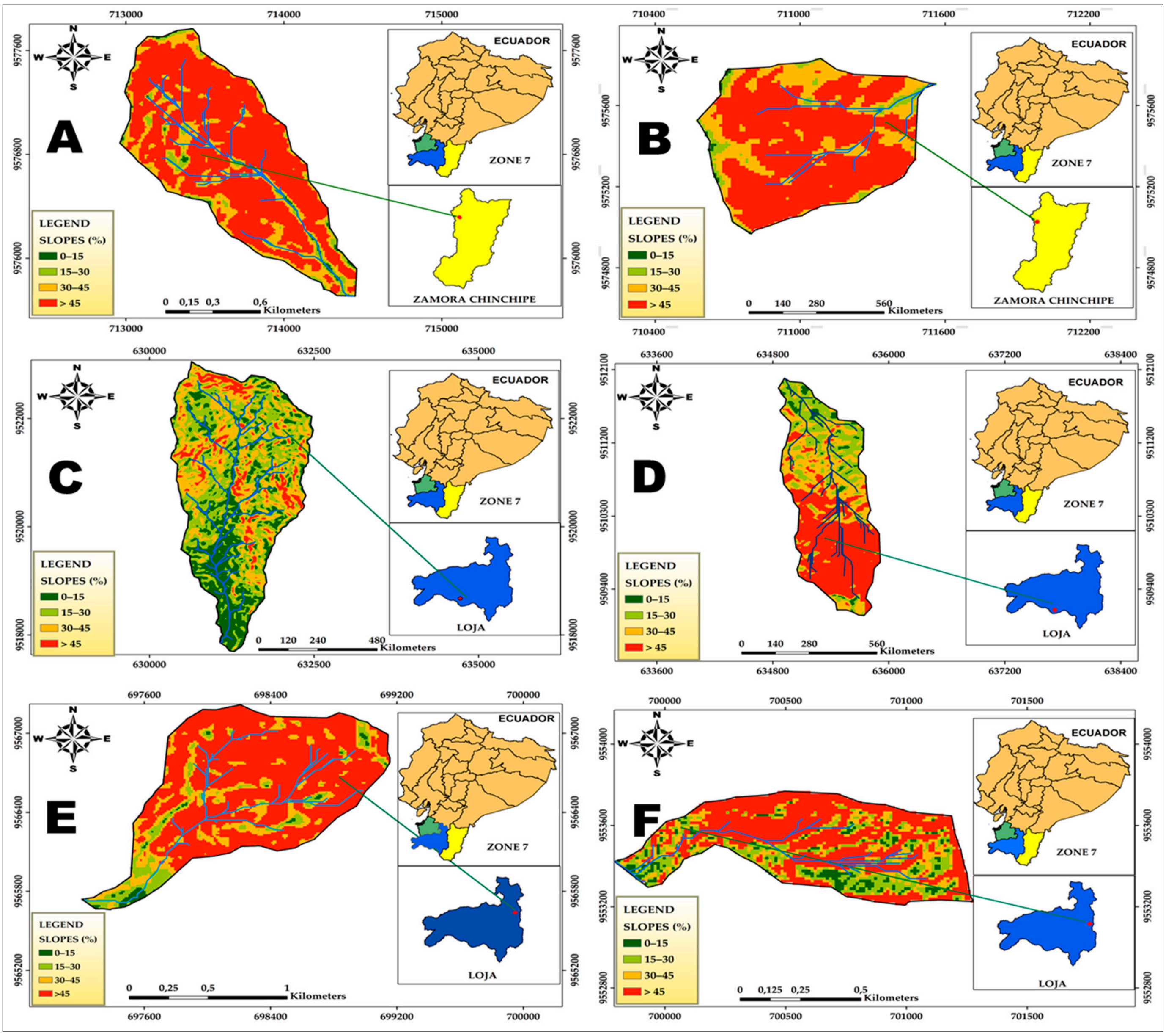

Figure 5. Topographic slope maps of six micro-watersheds (**A**–**F**) in southern Ecuador, depicting elevation-derived steepness relevant to the ecological variation of *J. neotropica*. The sites include: The Tibio (**A**), The Merced (**B**), The Tundo (**C**), The Victoria (**D**), The Zañe (**E**), and The Argelia (**F**).

3.4. Phenology

Phenological monitoring of *J. neotropica* between 2019 and 2023 revealed consistent seasonal rhythms and marked ecological differentiation across localities. Organ-specific responses to climatic variation were documented through continuous sampling protocols, complemented by visual inspection and precision instrumentation. This multifactorial approach—grounded in descriptive statistics and correlation analyses—enabled the identification of intra- and inter-provenance trends in flowering intensity, fruiting onset, and leaf abscission. Rather than offering a simple comparative overview, the analysis captured underlying ecological interactions and adaptive responses, highlighting how phenological rhythms are modulated by altitude, temperature, humidity, and slope. These findings reinforce the importance of geographic and environmental differentiation when designing conservation strategies tailored to the ecological profiles of *J. neotropica* populations. The high interannual consistency observed across the study period allowed for the construction of phenological calendars for each locality, summarizing the timing and duration of key developmental events. These calendars continue to be refined as monitoring progresses, ensuring that seasonal patterns remain validated and up to date. To deepen the understanding of seasonal dynamics, a multi-year analysis was conducted across four core localities—The Tundo, The Zañe, The Argelia, and The Victoria—coinciding with the completion of associated doctoral research in 2023. Flowering duration ranged from 4 to 9 weeks, with longer cycles in The Tundo and shorter ones in The Victoria. Fruiting onset occurred between weeks 28 and 36, with complete synchrony between The Argelia and The Zañe ($r = 1.00$), and pronounced asynchrony between The Victoria and The Tundo ($r = -0.90$). Pearson correlation analysis, based on 84 pairwise comparisons, revealed strong ecological affinities between high-altitude sites and divergent phenological rhythms in lower-elevation fragments. The Victoria consistently exhibited negative correlations across multiple traits, suggesting a distinct ecological profile shaped by thermal and hydric gradients. In contrast, The Argelia and The Zañe showed high synchrony, reinforcing their phenological alignment. These patterns are synthesized in Table 5, which presents a comparative summary of environmental and phenological parameters across the four core localities. The table highlights how altitude, slope, temperature, and humidity interact to influence developmental timing and synchrony, offering a robust framework for site-specific conservation planning.

Table 5. Environmental and Phenological Parameters of Core Localities (2019–2023).

Locality	Altitude (m)	Slope (%)	Flowering Duration (Weeks)	Fruiting Onset (Week of Year)	Leaf Abscission Peak (Week of Year)	Mean Temperature (°C)	Relative Humidity (%)
The Tundo	1850	>55	12	26	17	~14	77
The Victoria	1500	>45	8	21	21	~23	75
The Zañe	2250	>60	8	30	22	~11	80
The Argelia	2150	>45	8	30	22	~15	78

Note: This table integrates environmental and phenological metrics from four core localities—The Tundo, The Victoria, The Zañe, and The Argelia—used for correlation analysis and seasonal development assessment. It complements the general environmental overview presented in Table 1 by linking site conditions to phenological synchrony and contrast.

Building upon the environmental and phenological parameters previously discussed, a correlation matrix was developed to examine pairwise relationships among the four core localities. This analysis encompassed 84 comparisons across seven variables, applying Pearson's r coefficient to quantify degrees of ecological synchrony and contrast. The results revealed strong affinities between The Argelia and The Zañe, particularly in fruiting onset and leaf abscission (r = 1.00), while The Victoria consistently diverged, especially in thermal and phenological traits (e.g., r = −0.90 in fruiting onset; r = −0.87 in mean temperature). These patterns reinforce the ecological differentiation outlined earlier, underscoring the influence of altitudinal, thermal, and hydric gradients on seasonal development. The full correlation matrix, including technical interpretations for each locality pair, is provided in Supplementary Table S1. This resource offers a granular view of how environmental variables shape phenological rhythms and supports the broader ecological framework established in Table 5.

Seasonal calendars were constructed for four of the six monitored localities, revealing consistent developmental patterns with approximately one-month variations in key events. These patterns are visually summarized in Figure 6, which presents the phenological calendars for The Tundo, The Victoria, The Zañe, and The Argelia, based on continuous monitoring conducted between 2019 and 2023. These calendars synthesize long-term observations and reflect the species' adaptive responses to site-specific conditions. The Tibio and The Merced were excluded from this synthesis due to insufficient or non-reproducible data—likely resulting from adverse environmental conditions or inconsistencies that compromised scientific validity. Despite these limitations, the selected localities provide robust and representative insights into the phenological dynamics of *J. neotropica*, highlighting the interplay of climatic, edaphic, and geographic factors in shaping seasonal development.

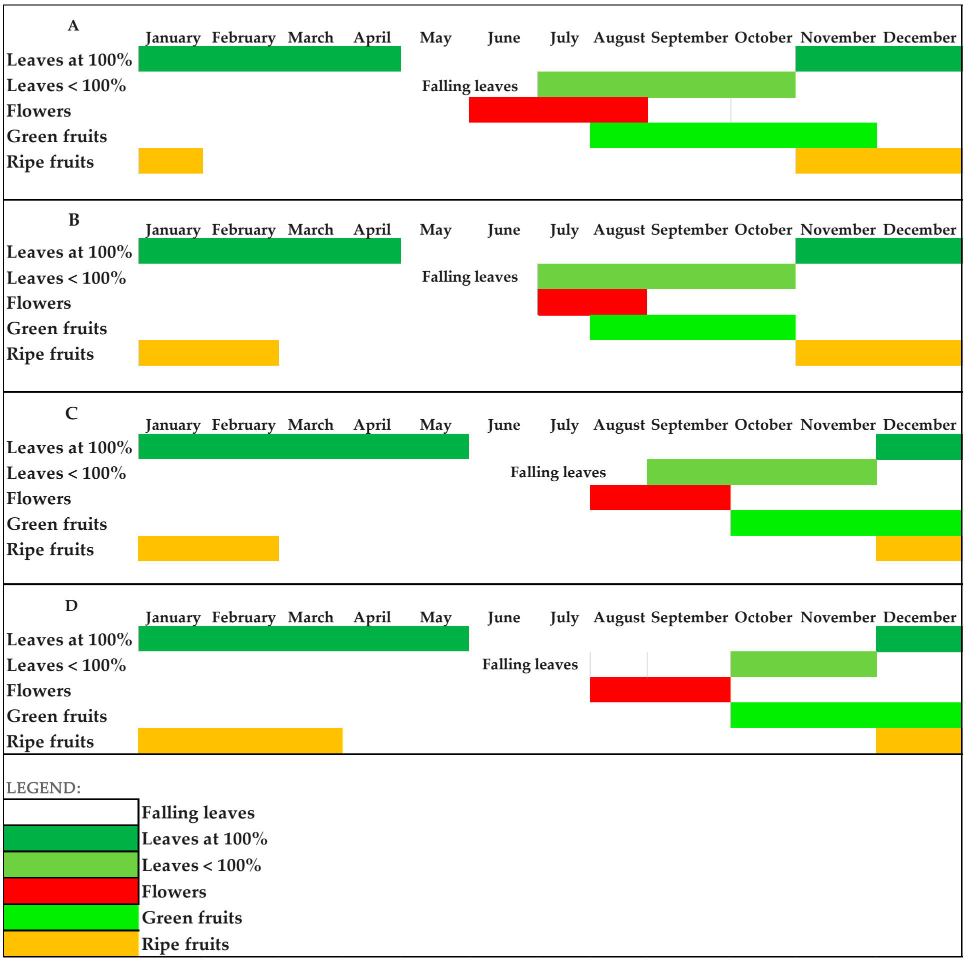

Figure 6. Phenological calendars of *J. neotropica* from four localities in southern Ecuador—The Tundo (**A**), The Victoria (**B**), The Zañe (**C**), and The Argelia (**D**)—based on continuous monitoring conducted between 2019 and 2023. Calendars summarize seasonal patterns in flowering, fruiting, and leaf abscission. The Tibio and The Merced were excluded due to insufficient and non-reproducible data.

Taken together, these findings establish a robust foundation for site-specific conservation planning and adaptive management. In ecologically distinct localities such as The Victoria, the observed phenological asynchrony likely reflects unique adaptive pressures and habitat requirements. Recognizing these divergences is essential for tailoring interventions that align with local ecological dynamics, ensuring that conservation strategies remain responsive to both species-level traits and territorial gradients.

3.5. Age Structure

Age estimations of *J. neotropica* populations across six localities were derived from field-measured diameters and calibrated using previously established growth correlations. These estimations, represented in Figure 7, reveal distinct demographic profiles shaped by site-specific ecological histories.

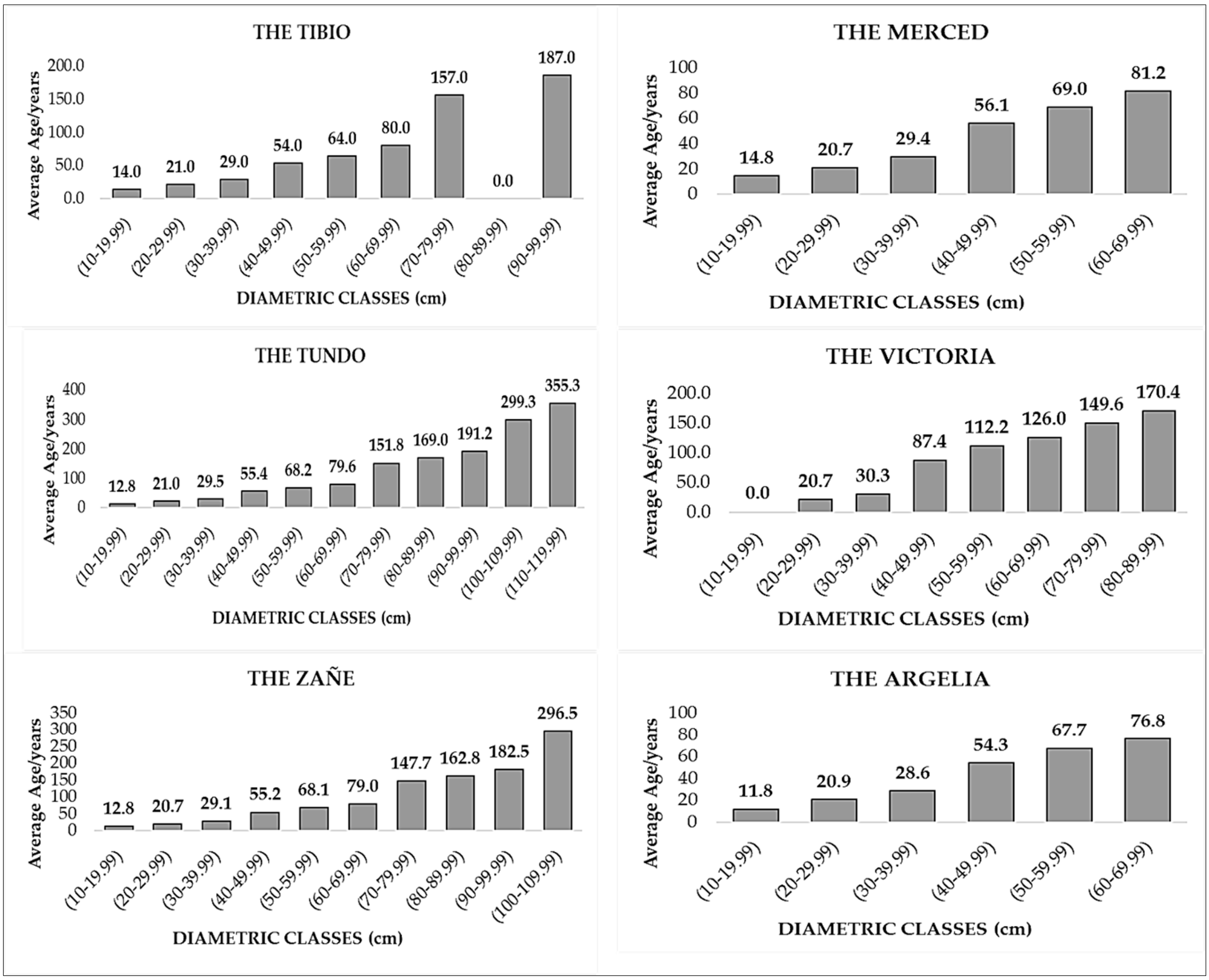

Figure 7. Estimated mean age by diameter class in six locations with the presence of *J. neotropica* in southern Ecuador.

In The Tibio, tree ages ranged from 14 to 187 years, distributed across nine diameter classes. The Merced exhibited a narrower age span, from 14.8 to 81.2 years, across six classes. The Tundo showed the broadest age distribution, with individuals ranging from 12.8 to 355 years, represented in eleven classes. In The Victoria, ages ranged from 20.7 to 170.4 years across eight classes, with the first diameter class unrecorded due to the absence of specimens. The Zañe presented ages from 12.8 to 296.5 years in ten classes, while The Argelia ranged from 11.8 to 76.8 years across six classes.

These age distributions reveal contrasting forest dynamics. Sites such as The Tundo and The Zañe exhibit wide age ranges, suggesting heterogeneous regeneration processes and possible historical disturbances or selective extraction. In contrast, The Argelia and The Merced display narrower age spans, potentially indicative of more recent establishment or uniform recruitment episodes. The absence of individuals in the smallest diameter class at The Victoria may reflect limited regeneration, sampling gaps, or site-specific constraints.

Such demographic contrasts underscore differentiated successional stages and reinforce the need for localized forest management strategies. Tailoring interventions to each site's age structure is essential for promoting sustainable regeneration, conserving mature individuals, and maintaining long-term ecological resilience.

3.6. Statistical Data Analysis and Its Influence on the Phenotypic Traits of J. neotropica in Southern Ecuador

3.6.1. ANOVA Climate

Statistical analysis using ANOVA revealed significant differences ($p < 0.05$) in climatic variables across the studied localities, confirming spatial heterogeneity in the environmental conditions that influence *J. neotropica* populations. These differences are illustrated in Figure 8, which compares temperature and precipitation patterns among the six monitored sites and highlights statistically significant contrasts. Mean annual temperature varied notably between mid-elevation and lowland sites, with potential implications for phenological timing, growth rates, and DBH–age correlations. Precipitation patterns also differed significantly, with southern localities exhibiting lower rainfall levels—conditions that may be linked to narrower age distributions and reduced recruitment potential.

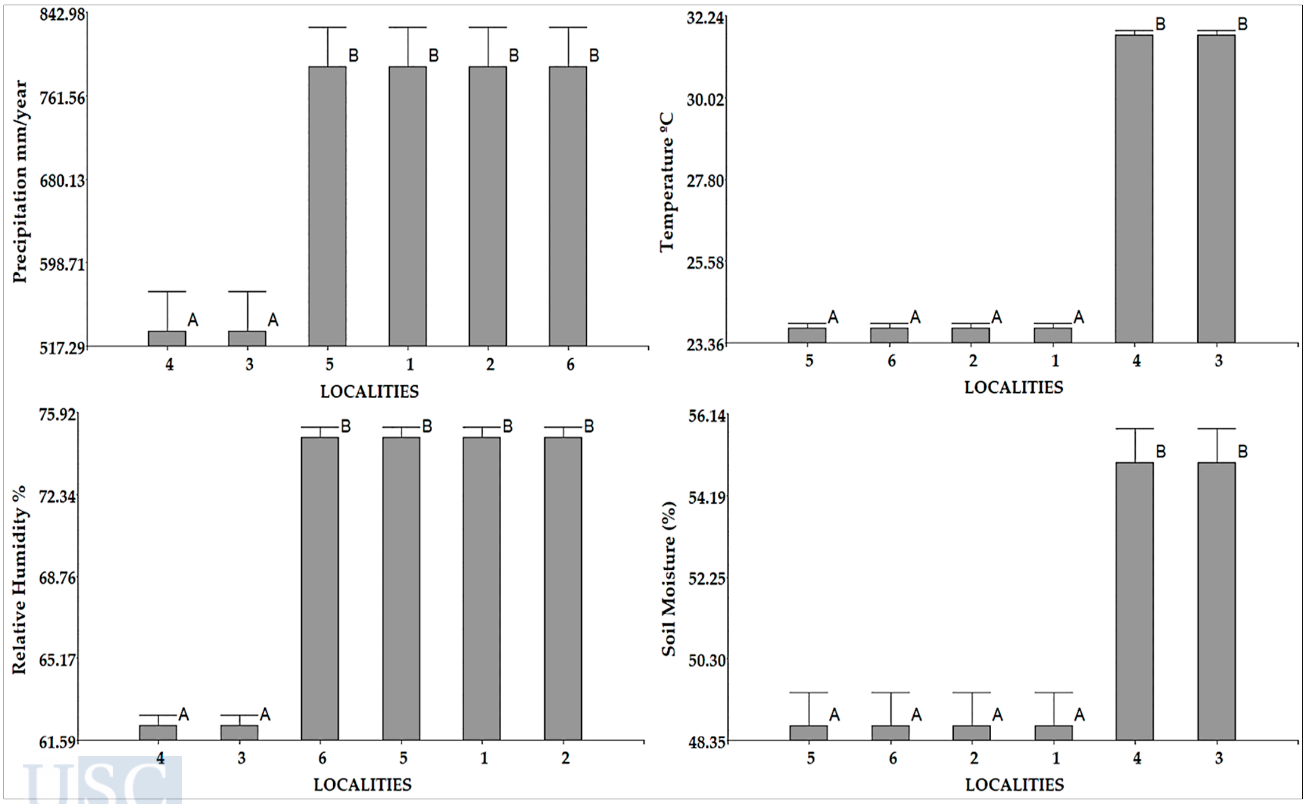

Figure 8. Comparison of environmental variables among different localities. The Tibio (1), The Merced (2), The Zañe (3), The Argelia (4), The Tundo (5), The Victoria (6). Different letters indicate significant differences ($p \leq 0.05$).

These climatic gradients offer a coherent explanatory framework for the ecological contrasts described in Sections 3.5 and 3.6. They underscore the role of abiotic factors in shaping demographic structure, regeneration dynamics, and phenotypic expression across populations. Understanding these spatial patterns is essential for interpreting site-specific responses and for guiding adaptive management strategies that align with local environmental realities.

3.6.2. Biplot Analysis of the Physical and Chemical Properties of Soil

The biplot analysis revealed distinct interactions between soil properties and localities, allowing for the identification of key ecological patterns. These relationships are visualized in Figure 9, which displays the distribution of physical and chemical soil variables across the six monitored sites. Component 2 (CP2) distinguished The Tibio and The Merced based on variables such as taxonomic order, depth, cation exchange capacity (CEC), moisture, fertility, and drainage. In contrast, The Tundo, The Victoria, The Argelia, and The Zañe grouped around the remaining properties, indicating shared edaphic profiles.

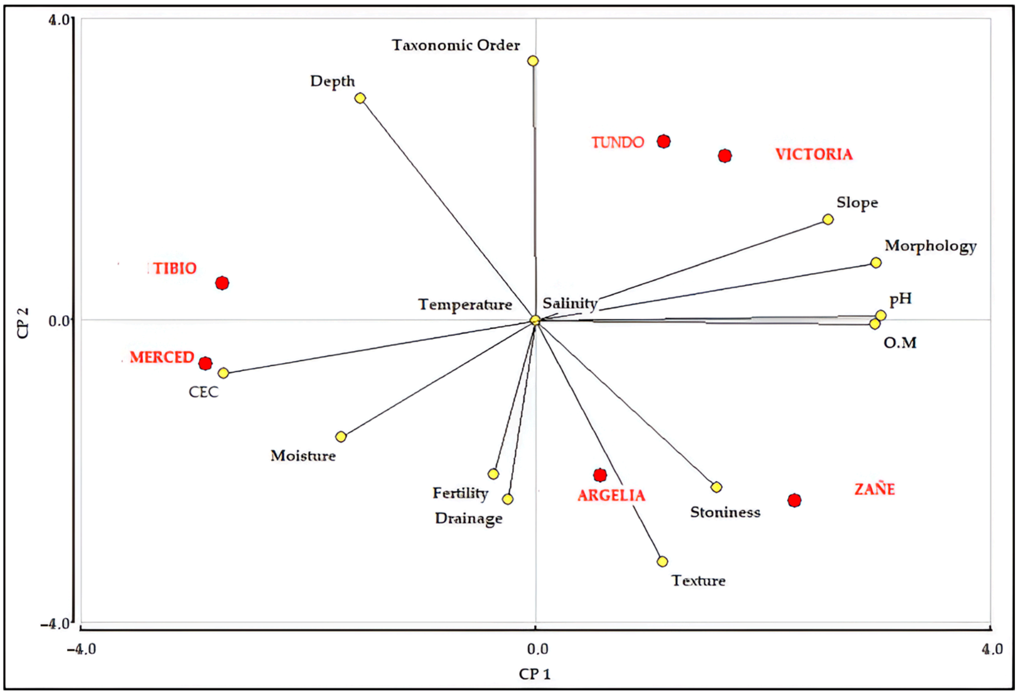

Figure 9. Biplot. Archive of physical and chemical soil properties from different localities.

When physical and chemical properties were examined independently, specific affinities emerged: The Tibio and The Merced closely aligned in terms of CEC; The Argelia and The Zañe shared similarities in texture and stoniness; and The Tundo and The Victoria exhibited convergence in slope characteristics. Soil temperature and salinity showed minimal variation across all sites, suggesting the influence of uniform climatic conditions on these parameters.

The construction of CP1 was primarily weighted by organic matter (OM), pH, morphology, slope, and CEC, while CP2 was shaped by taxonomic order, depth, texture, drainage, and fertility. These components provide a robust framework for interpreting edaphic differentiation and its potential influence on phenotypic expression and site-specific adaptation.

3.6.3. Statistical Comparison of Phenotypic Traits

Phenotypic variation across *J. neotropica* populations was assessed using both parametric and non-parametric approaches, depending on the distributional properties of the data. These results are summarized in Figure 10, which compares DBH, height, volume, and phenological traits across the six monitored localities. Due to the lack of normality and homogeneity of variances in DBH measurements, a Kruskal–Wallis test was applied, revealing significant differences among the six localities (H = 157.69; $p < 0.0001$). The Victoria and The Tundo exhibited the highest median DBH values, while The Argelia recorded the lowest, suggesting structural heterogeneity shaped by ecological gradients and regeneration dynamics.

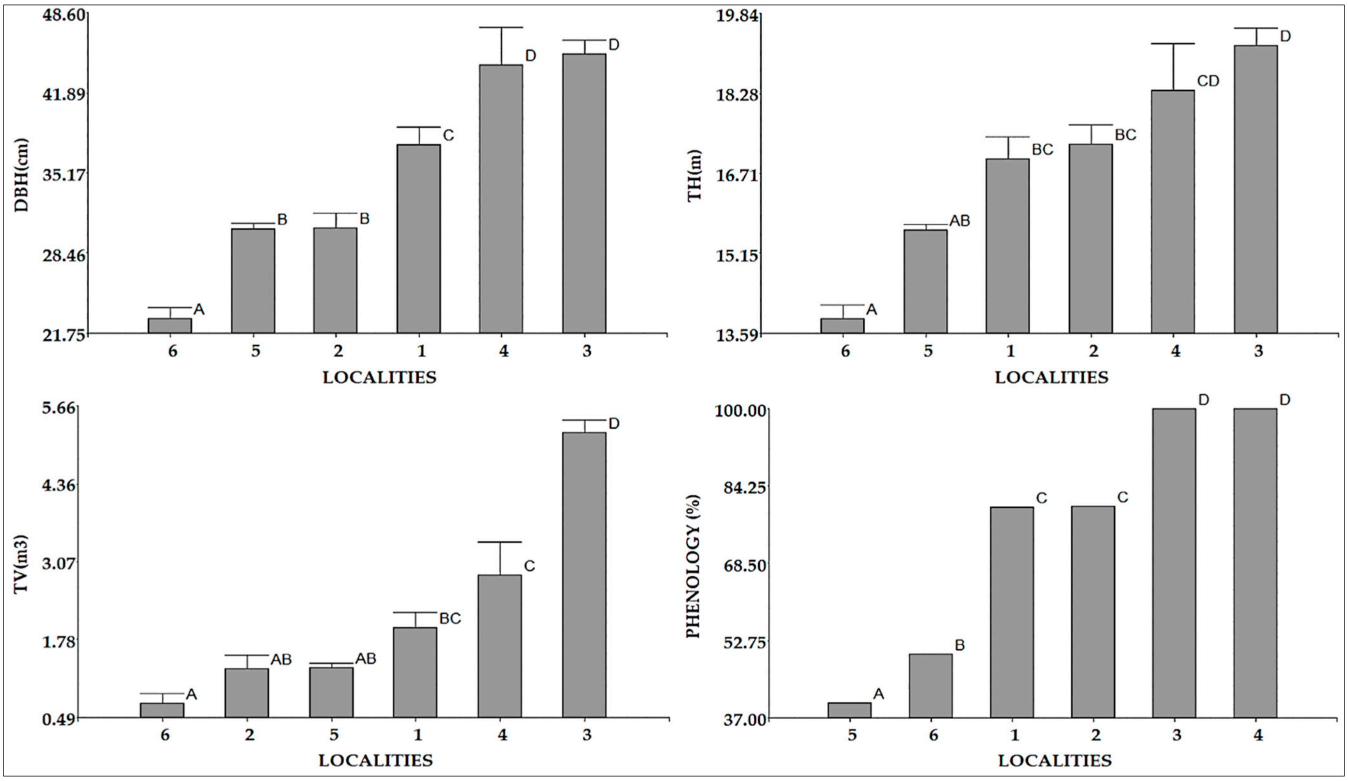

Figure 10. Comparison of phenotypic traits among different localities. The Tibio (1), The Merced (2), The Tundo (3), The Victoria (4), The Zañe (5), The Argelia (6). Different letters indicate statistically significant differences ($p \leq 0.05$).

For traits such as Total Height (TH), Total Volume (TV), and Phenology (%), ANOVA was employed, as assumptions of normality and homoscedasticity were met. The Tundo and The Victoria consistently showed superior values across these traits, indicating favorable growth conditions and enhanced phenological performance. In contrast, The Argelia and The Zañe recorded the lowest values, reinforcing the ecological contrasts discussed in previous sections and highlighting the influence of site-specific environmental factors on phenotypic expression.

4. Discussion

4.1. Precipitation and Temperature

The results of this study confirm a sustained increase in temperature across the Loja–Zamora region, matching the trends reported by [47], who analyzed data from 40 meteorological stations from 1970 to 2000. While average temperatures remained below 18 °C in previous decades, recent records indicate a significant rise. Although no formal trend modeling was performed, temperature and precipitation trajectories were evaluated by contrasting historical records (1970–2000) with recent data (2001–2024) from study localities. Temporal shifts were interpreted using standardized annual means, consistent with regional methodologies [47,48]. This warming trend correlates with phenological changes observed in *Juglans neotropica* Diels, especially in earlier flowering and faster seed maturation, consistent with the responses described by [11,22,48].

Precipitation patterns display altitudinal divergence: higher zones show reduced rainfall, while lower elevations reveal an increasing trend, also supported by [47]. These dynamics affect phenological events such as reproductive synchrony, leaf expansion, and fruit drop timing. Data collected in different study localities reflect these hydrological sensitivities, particularly during extended drought periods.

Importantly, regional climate variability is heavily influenced by global phenomena—most notably the El Niño Southern Oscillation (ENSO)—which intensify temperature and rainfall anomalies in this transboundary region [25,49]. These interactions underscore the need to integrate global climatic variables into localized phenological models and adaptive forest management frameworks.

Study limitations include the use of interpolated climate data instead of in situ sensor readings, which may obscure microclimatic nuances. Additionally, phenological monitoring was partially limited in steep zones due to access constraints.

Practical applications of these findings include the need to adjust seed collection schedules, nursery cycles, and restoration interventions based on changing precipitation and temperature regimes. Further research should extend multi-year monitoring and incorporate genetic markers to assess the adaptive capacity of *J. neotropica* under evolving climatic scenarios.

4.2. Relative Humidity

The relative humidity patterns observed across the Loja–Zamora region reveal a complex interplay between altitude, seasonality, and long-term climatic shifts. Our data confirm that, while national averages remain above 70%, localized deviations—particularly in Sozoranga and parts of Loja and Zamora—suggest emerging microclimatic stressors. Notably, humidity values below 60% were recorded in multiple years (e.g., 1985, 2005, 2010, 2018), indicating episodic intensification of dry conditions that may reflect broader climatic transitions.

These findings align partially with the national trends reported by [50], yet diverge in their temporal and spatial granularity. For instance, while [50] describes stable humidity in the Oriente region (e.g., M008 Puyo station), our data show that inter-Andean zones such as Sozoranga exhibit greater variability and susceptibility to sub-threshold humidity events. This divergence underscores the need to disaggregate national datasets when modeling phenological responses at the landscape scale.

From a phenological standpoint, the observed declines in relative humidity coincide with shifts in reproductive synchrony and leaf phenophases in *J. neotropica*, particularly in sites with prolonged dry spells. Although our study did not isolate humidity as a sole driver, the correlation between low humidity years and delayed leaf expansion or fruit drop suggests a modulatory role, consistent with findings from [51,52]. These authors demonstrated that reduced atmospheric moisture can exacerbate water stress and disrupt phenological timing in broadleaf species, a dynamic we also observed in montane populations.

However, our study is limited by the use of interpolated humidity data and the absence of continuous in situ sensor readings, which may obscure short-term fluctuations and microclimatic effects. Microclimatic variability, modulated by factors such as slope orientation, canopy cover, and shading, can significantly influence the phenological expression of montane species like *J. neotropica*. Although this study relied on interpolated data, it is acknowledged that local microclimatic conditions may alter the synchrony of reproductive events, particularly in steep and ecologically fragmented zones. Ref. [53] demonstrated that forest canopy structure and terrain regulate microclimate through processes such as heat dispersion via evapotranspiration and solar radiation attenuation, directly affecting forest phenology. Moreover, the interaction between temperature, precipitation, and slope generates nonlinear effects on the onset and end of the growing season, with phenological divergences observed between shaded and sun-exposed slopes. Therefore, it is recommended to incorporate temperature and humidity sensors at both soil and canopy levels in future monitoring phases, and to evaluate slope orientation effects on phenological dynamics. This approach would better capture short-term fluctuations and strengthen predictive models of phenological response under climate change scenarios. Additionally, the lack of concurrent soil moisture measurements restricts our ability to disentangle atmospheric versus edaphic influences on phenology.

Despite these constraints, the practical implications are clear: restoration planning and nursery scheduling must account for humidity variability, especially in zones prone to episodic dryness. Incorporating humidity thresholds into phenological models could improve predictions of flowering and fruiting windows, thereby enhancing seed collection strategies and adaptive forest management.

Future research should prioritize multi-year monitoring with integrated humidity and soil moisture sensors, ideally coupled with genetic profiling to assess the adaptive capacity of *J. neotropica* under increasingly variable hydroclimatic regimes.

4.3. Soil Moisture at a Depth of One Meter (%)

The soil moisture data collected across the localities of Zañe, Merced, Tibio, and Argelia reveal consistently high root-zone water availability, with values exceeding 60% in the years 1983, 1989, and 1998. In contrast, the sites of Tundo and Victoria display a stable hydric profile ranging between 50–60%, with notable peaks in 1983 (66%), 1989 (62%), and 1998 (70%), followed by a slight decrease to 55% in 2023. These findings indicate prolonged subsurface hydric stability, punctuated by episodic moisture surges that may correspond to ecological thresholds relevant to the reproductive behavior of *J. neotropica.*

As demonstrated by [54], soil moisture plays a critical role in vegetation phenology, particularly in low-altitude ecosystems affected by water limitations. Although the sites analyzed in this study belong to montane zones, the years with elevated root-zone moisture coincide with enhanced phenological synchrony in fruiting and leaf expansion across monitored populations. This correlation—though not examined through direct physiological tracking—suggests a modulatory role of stable subsoil water availability in phenological timing, reinforcing the arguments put forth by [55,56] regarding subsurface hydrodynamics and root system architecture.

The soil moisture values observed in this study also fall within or exceed those reported by [57], who measured elevated moisture at depths of 80–100 cm; by [58], who documented fluctuations between 0.49 and 0.54 m^3/m^3 under slopes of 14–20%; and by [59], whose findings further confirm the upper bounds of soil water retention in montane environments.

Nevertheless, the use of interpolated data limits the granularity of our interpretation. The absence of in situ sensor arrays and real-time measurements at multiple depths restricts precise correlation with microclimatic and edaphic variations. Moreover, the lack of phenological monitoring specific to the root zone prevents conclusive links between subsoil moisture and reproductive timing in *J. neotropica*.

Despite these limitations, the practical implications are clear. Sites with sustained subsoil moisture—particularly Tundo and Victoria—may offer favorable conditions for nursery establishment and seedling survival. Integrating soil moisture thresholds into restoration planning and phenological modeling could enhance the accuracy of flowering and fruiting predictions, improve seed collection strategies, and guide site-specific reforestation efforts.

Future research should incorporate multi-depth soil moisture sensors and pair them with phenophase-specific observations and genetic profiling. This approach would clarify the adaptive responses of *J. neotropica* under variable hydroclimatic regimes and contribute to the design of ecophysiologically sound restoration strategies across montane forest landscapes.

4.4. Soil

The physical and chemical attributes of the soil observed across the study sites reveal consistent patterns that appear to influence the viability and phenology of *J. neotropica*. In particular, sites such as The Victoria and The Zañe, which exhibit neutral pH (7.0), high cation exchange capacity (CEC: 22–25 meq/100 g), and medium fertility, coincide with mountainous morphology, good drainage, and a very steep slope—conditions that may contribute to stable phenophase expression and fruiting success. Conversely, The Merced and The Tibio show very low fertility, acidic pH (average 6.75), and lower CEC values (4–8 meq/100 g), associated with silty clay texture and heterogeneous relief, possibly indicating more restrictive conditions for root development and water retention.

Such findings support a localized edaphic influence on *J. neotropica* populations in Loja and Zamora, aligning with broader studies of forest ecology. For instance, [60] demonstrated that altitude, soil texture, and water content modulate species diversity, while [61] highlighted the role of organic matter and nitrogen in shaping phenological patterns—traits mirrored in our dataset where The Tibio, with higher OM content, may offer conditions for prolonged foliar expansion. Furthermore, [62,63] reinforce the relevance of slope and pH in distributional models, matching well with the alfisol-based profiles of The Victoria and The Tundo.

The consistency of traits such as isothermal regimes, neutral to slightly acidic pH, and steep slopes across several localities suggests a potential edaphic envelope conducive to *J. neotropica* establishment. However, the classification of soils into Inceptisols, Entisols, and Alfisols also implies varying degrees of horizon development and nutrient retention, which may differentially affect rooting depth and physiological resilience.

Nevertheless, the absence of longitudinal in situ physiological tracking and limited granularity in soil property measurements (e.g., no real-time monitoring of salinity fluctuations or root-zone temperature gradients) represent important limitations of this study. Additionally, the reliance on static soil profiles constrains temporal interpretation and inhibits direct causality claims regarding phenological modulation.

Despite these constraints, the practical implications are compelling. Identifying sites with high CEC, medium fertility, and stable drainage—such as The Victoria and The Zañe—could enhance the success of nursery operations and improve seedling establishment in restoration programs. Integrating these soil parameters into predictive phenological models may refine the timing of fruit collection and optimize planting strategies across montane landscapes.

Future research should incorporate multi-seasonal sampling protocols, including soil nutrient dynamics, moisture fluctuations, and below-ground phenological observations. Coupling these with genetic profiling and altitude-based climate modeling would strengthen the predictive power of site selection for *J. neotropica*, ultimately contributing to resilient forest management and conservation strategies.

4.5. Slope

Research has shown that the slope of the terrain plays a significant role in the phenology of broadleaf species, differing from the more direct impact of physical and chemical soil properties, which have also been widely studied. For instance, the study by [64] investigated how topographic variations affect plant community characteristics and soil factors in alpine grasslands, finding that both the orientation and gradient of the slope significantly influence species distribution and soil attributes. Similarly, [65] analyzed the use of satellite-based observations to monitor and predict phenology at landscape scale, concluding that slope is a critical determinant in the temporal dynamics of plant communities.

Our study contributes to this understanding by identifying consistent patterns in the location of *J. neotropica* populations on slopes exceeding 40%, with all sampled micro-watersheds exceeding 45% (Figure 5). These steep gradients appear to shape habitat suitability by influencing water drainage, erosion potential, and microclimatic variation. The spatial restriction of populations to these topographic conditions supports the notion of slope-driven niche limitation, as previously suggested by [37].

Nevertheless, the ecological stability of these zones is compromised by their inherent vulnerability to landslides and erosion, particularly under conditions of reduced vegetation cover. Field observations revealed slope destabilization in areas undergoing agricultural expansion—a trend also discussed by [66] in the context of ecosystem service degradation. Such pressure may undermine the ecosystem functions that steep-slope forests provide, generating tension between land use expansion and ecological resilience.

While the study provides topographic insights, it does not incorporate slope orientation analysis (e.g., north-facing vs. south-facing aspects) nor long-term erosion modeling, which may yield deeper understanding of soil–plant interactions and forest anchorage dynamics. Additionally, no phenological traits were directly correlated with slope gradient due to accessibility constraints in rugged terrain.

Given these findings, it is plausible that steep-slope zones where *J. neotropica* persists could represent priority areas for conservation, potentially serving as genetic reservoirs. The integration of slope-aware forest management and satellite monitoring could enhance land use planning and restoration strategies. Further research could explore links between slope gradient and reproductive timing, root stabilization, and runoff dynamics, shedding light on adaptive thresholds relevant to montane forest conservation under changing climatic conditions.

4.6. Phenology

The phenological patterns observed in *J. neotropica* in the The Argelia—The Tundo area reflect a marked sensitivity to the site's topographic and edaphic conditions, consistent with previous studies highlighting intraspecific variability during nursery and plantation stages [33]. This phenotypic plasticity suggests adaptive potential that can be leveraged in restoration strategies tailored to elevation and slope gradients.

The predominance of budburst events prior to the onset of the rainy season indicates synchronization with increased soil moisture and surface nutrient availability, particularly in areas with residual vegetative cover. This trend aligns with findings by [67], who reported accelerated germination responses under optimized prehydration and mechanical scarification conditions.

Moreover, the flowering and fruiting patterns observed are consistent with the ecological fragmentation framework described by [25]. The reduction of continuous cloud forest areas generates selective pressures that shape reproductive phenology, resulting in more concentrated and less synchronized phenophases in isolated patches. This phenomenon translates into a phenological offset between localities, where differences in altitude, slope, and vegetation cover influence the timing of reproductive events. In this regard, the findings of this study underscore the urgent need to reestablish ecological corridors that facilitate genetic exchange and extend the reproductive window.

Thus, the phenological dynamics of *J. neotropica* reflect not only climatic adaptations but also functional responses to structural landscape degradation. Silvicultural management should incorporate these findings as criteria for differentiated planting, especially on exposed slopes and areas with high altitudinal variation, prioritizing provenances with greater phenological plasticity.

Although a partial cut was made in 2023 for academic purposes, phenological monitoring continues to this day. The consistency of the patterns recorded over five years supports the validity of the calendars developed, which provide a solid foundation for the ecological characterization and silvicultural planning of *J. neotropica*.

The statistical refinement applied in this study—particularly the use of Kruskal–Wallis for DBH and ANOVA for phenological traits—enhanced the resolution of inter-locality comparisons and reinforced the ecological validity of the observed patterns. The superior structural attributes recorded in The Tundo and The Victoria, such as higher DBH and total volume, coincided with more synchronized and extended phenophases, suggesting a functional linkage between growth performance and reproductive timing. In contrast, The Argelia and The Zañe exhibited both reduced structural metrics and fragmented phenological events, likely shaped by altitudinal stressors and landscape degradation. These findings validate the phenological calendars developed and support their use as tools for site-specific silvicultural planning, emphasizing the importance of selecting provenances with both structural vigor and phenological resilience.

4.7. Age

The age structure of *J. neotropica* populations across six localities in southern Ecuador reveals marked variability, with estimated ages ranging from 11.8 to 355 years, distributed across distinct diameter classes (Figure 7). The Tundo locality stands out for hosting the oldest individuals, while The Merced and The Argelia exhibit comparatively younger populations. These differences likely reflect site-specific edaphic conditions, elevation gradients, and varying disturbance and management regimes.

Such variation is not merely demographic—it directly influences forest phenology. As noted by [68], age-class structure exerts a significant indirect influence on intra-annual phenology, mediated by species composition. This interaction suggests that forests with diverse age distributions, such as Tundo and Zañe, may exhibit more resilient phenological patterns under regional climatic variability, compared to younger or more homogeneous stands.

Growth variability is also evident in the Current Annual Increment (CAI) values reported by various sources: 1.2 cm according to [69], 0.37 cm by [45], ranges between 0.648 and 0.834 cm by [46], and specific values from [32] for Tundo (0.602 cm), Shucos (0.652 cm), Saraguro (0.828 cm), and The Argelia (0.65 cm). Ref. [70] reported a lower value of 0.12 cm, underscoring the influence of local ecological conditions. The correlation between these increments and diameter-based age estimates supports the reliability of the approach used for *J. neotropica*.

Recent studies confirm the dendrochronological potential of *J. neotropica* in tropical montane environments. Ref. [71] demonstrated the presence of annual rings and the species' sensitivity to El Niño-related precipitation anomalies through isotopic and radiocarbon analyses in Piura, northern Peru. Likewise, [33] documented significant phenotypic variability among provenances during nursery and plantation stages, reinforcing the ecological influence of origin on growth and age structure.

Although systematic ring counting was not applied to all individuals in this study, direct ring counts were conducted on 12 reference trees, allowing for empirical calculation of CAI-A. These values, together with those reported by other researchers—[33,45,46,69,70,72]—formed the basis for estimating the age of all individuals across the surveyed localities. The consistency between these data and the diameter-class estimates validates the model employed and demonstrates its utility for accurately characterizing the age structure of *J. neotropica* under contrasting ecological conditions.

Furthermore, regional silvicultural guidelines and biological cutting cycles proposed by [73,74] reinforce the ecological and management relevance of age-based classifications, especially for endangered montane species such as *J. neotropica*.

Although the methodological design was robust and achieved adequate temporal and territorial coverage, two relevant limitations were identified. First, the selective harvesting of adult individuals in certain sectors of the study area may have altered the natural population structure, reducing the presence of specimens with larger diameters and advanced phenological maturity. This condition could have influenced the expression of the reproductive events observed.

Second, there was a notable lack of previous studies on the phenology of *J. neotropica* in natural forests of southern Ecuador. This gap limited the possibility of making direct comparisons and establishing regional references, which necessitated the development of interpretative criteria based on empirical observation and contextual analysis. Nevertheless, both factors were considered in the analysis, and field validation strategies were applied to ensure the reliability of the results. In this context, the few available studies—such as [39]—provided foundational insights into the species' reproductive timing and ecological responses, which we used to frame its role in Andean montane forest resilience. By integrating these references with our empirical findings, we highlight *J. neotropica* as a structurally and functionally relevant species in high-altitude forest dynamics, particularly under scenarios of climatic stress and habitat fragmentation.

Based on the results obtained and the phenological variations recorded across localities, three key aspects are identified to support the adaptive management of *J. neotropica* under conditions of high environmental variability. First, sites with high cation exchange capacity (CEC), such as The Victoria (22 meq/100 g) and The Zañe (25 meq/100 g), exhibited superior structural and phenological performance. This suggests a mechanistic link whereby soils with higher CEC retain essential macronutrients (e.g., N, P, K) more effectively, enhancing nutrient availability during critical phenophases such as flowering and fruiting. This nutrient retention likely supports reproductive synchrony and biomass accumulation, consistent with findings in tropical montane forests that associate high CEC with increased plant productivity and niche specialization [75].

Second, the diverse age-class structure observed in The Tundo (12.8–355 years) and The Zañe (12.8–296.5 years) appears to modulate phenological resilience under climatic variability. Older trees may buffer environmental fluctuations through deeper root systems, stable carbon allocation, and genetic memory, acting as ecological stabilizers and reservoirs of adaptive traits [76].

Third, to address limitations associated with interpolated climate data and to strengthen ecological modeling, it is proposed to integrate in situ microclimate sensor networks (temperature, relative humidity, soil moisture) with remote sensing tools and local meteorological stations. This approach, validated in humid montane forests using low-cost wireless systems [77], would enable high-resolution monitoring of short-term variability and microclimatic heterogeneity, facilitating the development of robust predictive models and the identification of patterns relevant to silvicultural planning. In parallel, evaluating the response of *J. neotropica* to climate change scenarios—particularly in altitudinal transition zones and highly fragmented landscapes—through eco-physiological studies, multi-scenario simulations, and long-term monitoring could help establish tolerance thresholds, project potential altitudinal shifts, and define adaptive restoration strategies.

Finally, the design of silvicultural trials with contrasting provenances is recommended, based on their structural and phenological performance. This approach would allow validation of proposed phenological calendars, identification of genotypes with greater adaptive plasticity, and optimization of plant material selection for reforestation and conservation programs in climate-vulnerable territories.

4.8. Methodological Limitations

This study faced methodological constraints due to current environmental regulations. Since *J. neotropica* is classified as “Endangered” by the IUCN and Ecuador’s Ministry of the Environment (MAATE) prohibits destructive sampling of live specimens, dendrochronological validation was limited to 12 naturally fallen trees found in areas with steep slopes and high wind exposure. This condition is acknowledged as a limitation of the study, although rigorous protocols were applied to ensure the reliability of the data obtained.

Additionally, while the calculation of the Adjusted Current Annual Increment (CAI-A) is described in detail within the methodological framework, the absence of a simplified formula may hinder understanding for some readers. For clarity, CAI-A can be expressed as:

$$\text{CAI-A} = \Delta D/\Delta t$$

where ΔD represents the observed diameter increment and Δt the estimated transit time per diameter class. This formula summarizes the principle applied in the growth modeling and may facilitate replication in future studies.

5. Conclusions

The results reveal marked climatic, edaphic, and phenological variability among the studied localities, directly influencing the population dynamics of *Juglans neotropica* Diels in fragmented Andean forests.

Significant trends of increasing temperature and decreasing relative humidity and precipitation, especially in sites such as The Argelia and The Victoria, suggest growing environmental pressure that may compromise the species’ natural regeneration. Cation exchange capacity (CEC) was highest in The Victoria and The Zañe (>20 meq/100 g), indicating greater potential for nutrient retention and vegetative development. Steep slopes (>45%) present in all localities represent a critical factor for reforestation planning, affecting erosion, drainage, and nutrient distribution.

Phenology showed intra- and inter-locality variations, with consistent patterns in four sites, while The Argelia exhibited lower phenological expression, possibly associated with less favorable edaphic and climatic conditions. Notably, The Argelia corresponds to a naturalized planted forest with over 70 years of establishment, suggesting that despite its structural maturity, factors such as low fertility, excessive drainage, and low CEC may limit its phenological performance.

Age structure revealed important contrasts among localities. Sites such as The Tundo and The Zañe exhibited wide age ranges, suggesting heterogeneous regeneration processes and possible historical disturbance or selective extraction events. In contrast, localities like The Argelia and The Merced showed narrower age distributions, potentially reflecting recent establishment or uniform recruitment. This age variability directly influences phenological expression, as younger individuals tend to exhibit less defined or incomplete patterns.

For reforestation, efforts should focus on provenances with CEC > 20 meq/100 g and slopes > 45%, while monitoring phenological changes in younger stands such as The Argelia to adjust adaptive management strategies. These findings provide a solid foundation for designing ecological restoration strategies tailored to local edaphic and climatic conditions, contributing to the effective conservation of *J. neotropica* in the Ecuadorian Andes.

Moreover, these findings align with Ecuador's national forest restoration policies, particularly those aimed at enhancing ecosystem resilience and promoting native species recovery in degraded Andean landscapes. By identifying edaphic and climatic conditions favorable for *J. neotropica*, this study provides actionable insights for site-specific reforestation planning, contributing to the strategic goals of national programs such as Plan Nacional de Restauración de Ecosistemas Forestales (National Plan for Forest Ecosystem Restoration) and Programa Nacional de Reforestación (National Reforestation Program). Integrating these results into regional restoration frameworks can improve the effectiveness of conservation efforts and support long-term forest sustainability.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/d17090627/s1. Table S1: Pairwise correlations (Pearson's r) among environmental and phenological variables across four localities of *Juglans neotropica* Diels in southern Ecuador (2019–2023). Each comparison includes the variable analyzed, correlation coefficient, and technical interpretation. This matrix supports the ecological differentiation and phenological patterns discussed in Section 3.4.

Author Contributions: Conceptualization, B.P.-H.; Investigation, B.P.-H.; Methodology, B.P.-H.; Writing—review and editing, B.P.-H.; Formal analysis, S.P.-L. and D.P.-C.; Writing—original draft preparation, S.P.-L. and D.P.-C.; Supervision, S.P.-L. and D.P.-C. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

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4.3 ARTÍCULO III. PHENOTYPIC VARIABILITY OF *JUGLANS NEOTROPICA* DIELS FROM DIFFERENT PROVENANCES DURING NURSERY AND PLANTATION STAGES IN SOUTHERN ECUADOR

Nota editorial:

Este tercer artículo desarrolla el Objetivo específico 3 de la Tesis Doctoral, centrado en la evaluación de la variabilidad fenotípica de *J. neotropica* durante las etapas de vivero y plantación en el sur de Ecuador. Se analizan rasgos fenotípicos específicos —peso y tamaño de semilla, viabilidad, germinación, supervivencia, altura, diámetro basal y número de hojas— como indicadores de plasticidad adaptativa y desempeño bajo distintos ambientes de plantación. El estudio considera tres procedencias locales (El Tundo, La Victoria y La Argelia) y cuatro tratamientos pregerminativos, evaluados tanto en ambientes controlados como en tres estratos ecológicos contrastantes: bosque secundario, bosque ripario y pastizal. Esta aproximación se diferencia del análisis fenológico realizado en el segundo artículo, centrándose aquí en atributos morfológicos y funcionales cuantificables, lo que permite identificar combinaciones genotipo–ambiente con mayor plasticidad adaptativa y aportar evidencia técnica para el mejoramiento genético, la restauración ecológica y el manejo forestal sostenible de esta especie nativa en ecosistemas montanos de alta fragilidad ambiental**.**

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Contribución del doctorando:

El doctorando Byron Palacios-Herrera participó como autor principal, siendo responsable del diseño experimental, implementación de los ensayos en vivero y campo, análisis estadístico, redacción científica y elaboración de figuras y tablas. Esta contribución fue clave para cumplir el objetivo tres.

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Article

Phenotypic Variability of *Juglans neotropica* Diels from Different Provenances During Nursery and Plantation Stages in Southern Ecuador

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Abstract

Juglans neotropica Diels, an Andean native species classified as endangered by the IUCN, holds significant potential for reforestation and sustainable forest management programs. This study evaluated seed quality, phenotypic variability, and early establishment under nursery and field conditions in southern Ecuador. Three provenance sites—The Tundo, The Victoria, and The Argelia—were evaluated during the nursery phase, and two (The Tundo and The Victoria) in plantations, applying four pre-germination treatments: control, mechanical scarification, hot water, and water-sun exposure. Parameters assessed included seed weight, size, viability, germination, survival, and growth across three planting environments: secondary forest, riparian forest, and pasture. Significant differences in seed morphometry were observed among localities, while germination was influenced by treatment but not provenance. Seed viability remained high for up to six months, decreasing with a 2% loss of moisture. Survival reached 100% with urea application, and 96% of individuals exhibited straight stems after one year. No significant differences in growth were found between localities; however, basal diameter was highest in the pasture (13.2 mm/year^{-1}), and total height was greatest in the secondary forest (54.8 cm/year^{-1}). These findings provide key technical evidence to optimize the propagation and establishment of *J. neotropica* in ecological restoration and forest production contexts.

Keywords: tropical silviculture; seed quality; phenotypic variability; forest improvement; environmental adaptation

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1. Introduction

The Andean ecosystems in Ecuador, characterized by a delicate balance between ecological fragility and biological vitality, play a crucial role in regional climate regulation, biodiversity conservation, and the sustainable production of valuable resources. Acting as a climatic barrier, the Andes modulate temperature, rainfall, and wind patterns, creating a mosaic of altitudinal zones and microclimates that support a unique and diverse range of species adapted to specific thermal and humidity conditions. These ecosystems sustain essential services such as water regulation, soil fertility, erosion control, and carbon storage, benefitting both local communities and global environmental balance. In addition to providing medicinal plants and native foods, Andean forests host multipurpose tree species such as *Juglans neotropica* Diels, *Cedrela odorata*, *Ocotea quixos*, and *Polylepis* spp., which offer high-quality timber and deliver significant medicinal, nutritional, and ecological benefits—making them key allies for conservation and sustainable development [1].

J. neotropica is a fast-growing tree that thrives in fertile and humid soils, reaching heights of up to 30 m in natural forests. It is characterized by its thick branches and straight trunk, with an appearance similar to cedar, making it easily distinguishable. With proper silvicultural management, including tree breeding practices, regeneration techniques, soil management, and pest control, this tree can achieve optimal growth and, after 30 to 40 years, provide a sustainable yield of high-quality timber. The implementation of strategies based on ecological and economic principles ensures not only productivity but also the conservation of the forest ecosystem, enhancing its resilience and functionality in the long term. It is considered the most sought-after tree species among the endemic timber flora of the Ecuadorian highlands. It is usually found in small natural groups or isolated among other native trees. Farmers value *J. neotropica* as a long-term source of income due to its fine wood and as a medium-term resource for its edible seeds [2,3].

The sexual germination of the *J. neotropica* species, considered by the International Union for Conservation of Nature (IUCN) as an endangered species, is an essential process not only for commercial purposes but also for the conservation and restoration of global biodiversity. This propagation method enhances genetic variability, which is crucial for adaptability and resistance to diseases, pests, and environmental changes [4]. Sexual reproduction facilitates the restoration of degraded ecosystems by ensuring that plants reintroduced into their natural habitat can adapt and thrive, promoting ecological stability and health [5]. Additionally, the germination of these species holds significant economic and cultural value, as many local communities depend on them for medicinal, food, and material resources [6]. At the ex situ level, seed banks and nurseries play a key role in preserving these species, allowing for their conservation and future reintroduction. Studies highlight the crucial role of these practices in preserving ecosystem health and ensuring the survival of endangered species [2,3].

The establishment of forest plantations with native species from different localities can contribute to genetic improvement and biodiversity conservation when implemented with appropriate ecological criteria and genetic selection programs. Plantations of *J. neotropica* are essential for climate adaptation and ecological restoration, as it improves degraded soils, maintains air and water quality in agroforestry systems, and provides habitat and food for wildlife. This strategy not only promotes genetic variability, which is crucial for species adaptability and resistance to adverse environmental factors such as diseases, pests, and climate changes, but also facilitates the identification and selection of individuals with desirable traits for future conservation and forestry programs [2]. The integration of various localities in a forest plantation allows for the exploration of the species' phenotypic plasticity, evaluating its performance under different edaphoclimatic conditions, which is fundamental for the success of ecological restoration programs and the recovery of degraded ecosystems [5]. Additionally, these plantations are valuable for maintaining essential ecosystem services and offer significant economic and cultural benefits to local communities, who can use these resources to obtain medicinal, food, and material products, thus contributing to their livelihood and well-being [6]. The implementation of forest plantations with native species from different localities is, therefore, a powerful tool for environmental sustainability and socioeconomic development.

In the area relevant to our study, three distinct vegetation strata associated with *J. neotropica* are identified: (i) secondary forest, characterized by natural regeneration following both anthropogenic and natural disturbances and marked by high biodiversity and active ecological succession; (ii) riparian forest, located along the ravine of the Zañe micro-watershed, shaped by specific vegetative successions linked to natural regeneration processes; and (iii) pasture stratum, composed of grassland used for livestock activities, with scattered trees and ongoing vegetative recovery. Each stratum presents unique features in terms of biodiversity, succession dynamics, and land use, making them essential for understanding ecosystem processes and informing sustainable management strategies [1–3].

The purpose of the research was to optimize the propagation and establishment of *J. neotropica* in ecological restoration and forest production by evaluating seed quality, phenotypic variability, and early establishment in nursery and field conditions—key aspects for the species' adaptability and resistance to diseases, pests, and climate changes [4]. This approach allows for the evaluation of the species' phenotypic plasticity in a common environment, facilitating the selection of superior genotypes that can thrive under adverse environmental conditions [5]. Additionally, this practice contributes to ex situ conservation, providing a genetic reserve for future reintroductions and scientific studies [6]. The integration of various localities also helps identify the best management and conservation practices, ensuring the long-term sustainability of the species and its associated ecosystems.

Despite the ecological and economic relevance of *J. neotropica* in the Andean region, there is limited knowledge regarding the influence of seed provenance, pre-germination treatments, and environmental conditions on its germination and early growth. This study aims to address this gap by evaluating seed quality, phenotypic variability, and initial seedling performance in nursery and field conditions. The objective is to optimize propagation and establishment strategies that enhance genetic diversity, promote resilience to biotic and abiotic stressors, and support both conservation and sustainable forest production efforts.

2. Materials and Methods

2.1. Study Area

The study area is located on the private estate Hacienda "The Florencia," which is situated within one of the micro-watersheds of The Zañe hill, in the Carigan parish of Loja canton and province. It has a total area of 115.8 hectares, with an altitudinal range from 2024 to 2800 m above sea level [7].

Of the 115.8 hectares of the private Hacienda "The Florencia", 93 hectares are located within the Zañe micro-basin, which comprises two distinct ecosystems. The first ecosystem is a Montane Evergreen Forest in the southern region of the Eastern Cordillera of the Andes, characterized by high fragility, medium-level threats, and high vulnerability, with moderate fragmentation and connectivity [7]. It spans an altitudinal range of 2200–3000 m above sea level, with a minimum temperature of 5.4 °C and a maximum of 17.6 °C, receiving an average annual precipitation of 2894 mm.

The second ecosystem is a Lower Montane Evergreen Forest in the southern region of the Eastern Cordillera of the Andes, situated within an altitudinal range of 1660–2200 m above sea level. It has a tropical climate, with an average temperature of 12.9 °C, a maximum of 25.4 °C, and an average annual precipitation of 2245 mm. These ecosystems are located on slopes with moderate inclines and rocky soils and are recognized for their high biodiversity, hosting a wide variety of plant species, birds, mammals, and other taxonomic groups [7].

Lastly, the micro-basin that contains the private Hacienda "The Florencia" has an approximate area of 148 hectares, within an elevation range of 2015 to 2815 m above sea level.

2.2. Study Description

The research was conducted in two phases. In the first phase, seeds from *Juglans neotropica* Diels trees were germinated, selected based on desirable phenotypic traits proposed by [8], and sourced from three specific localities: The Victoria, The Tundo, and The Argelia [7]. The second phase involved the establishment of a plantation trial with *J. neotropica* from two distinct localities, The Victoria and The Tundo, within the grounds of Hacienda The Florencia (Figure 1).

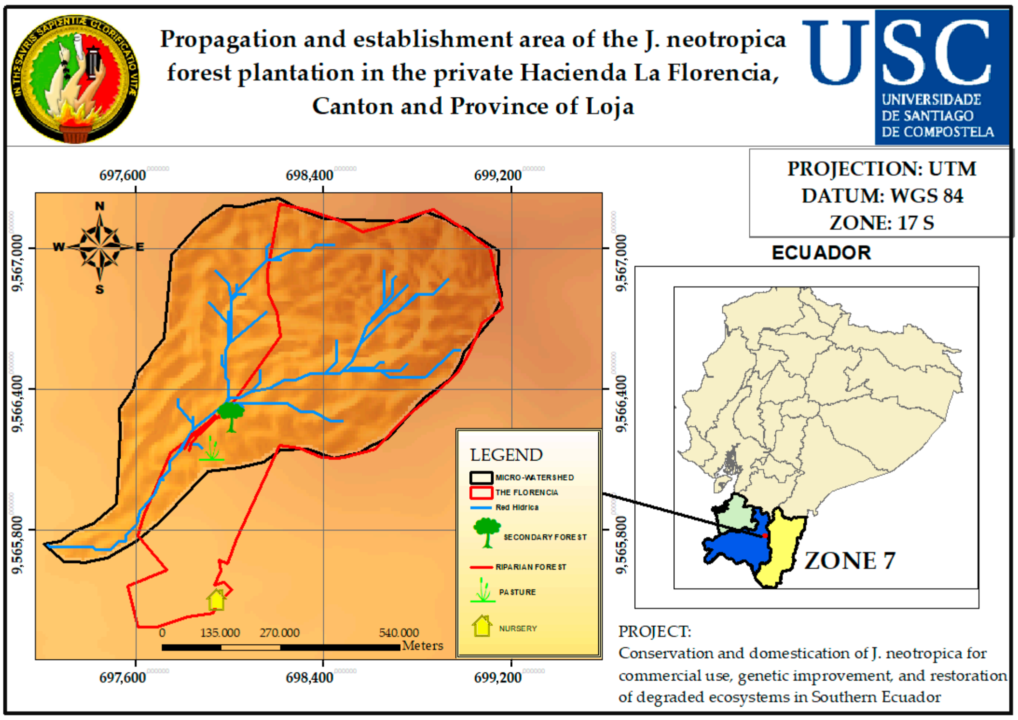


Figure 1. Locality map of the propagation and establishment of *Juglans neotropica* Diels in three stages of plant succession: secondary forest, riparian forest, and pasture.

2.3. First Phase: At the Nursery Level

To comply with the nursery phase of this research, the methodology proposed by [9] was followed. During this stage, the primary objective was to propagate, observe, and monitor the vegetative development of seedlings from three different localities before transferring them to the field or final planting site. To achieve this, various pre-germination treatments were implemented to assess their impact on germination percentage, growth, and development.

2.3.1. Quality Parameters of *J. neotropica* Seeds

A representative sample of the batch was selected for the proposed methodology in the quality analysis of *J. neotropica* seeds, strictly following the procedures established by the International Seed Testing Association (ISTA) [10].

1. Purity Percentage: To evaluate seed purity, a comprehensive physical analysis was conducted. First, a physical test was performed, involving the meticulous separation of seeds from possible impurities such as sand, soil, stones, plant debris, and other waste. This process aimed to ensure sample cleanliness and quality by removing any undesired elements. Subsequently, the genetic purification stage was carried out, with the objective of separating the analyzed seeds from other crops or weeds present. This phase is crucial to ensure sample homogeneity and obtain precise results regarding seed purity. Purity was quantified as the percentage by weight of pure

seeds in relation to the total sample analyzed. This comprehensive methodology guaranteed an exhaustive evaluation of seed purity, which is essential for quality and performance in agroforestry projects. To determine seed purity, five seed lots of one kilogram each were randomly selected, containing impurities. The following formula was applied for the assessment (Figure 2).

2. The number of seeds per kilogram was determined by randomly selecting seeds until reaching one kilogram. This process was repeated five times, and an average number of seeds per kilogram was subsequently calculated (Figure 3). To ensure consistency across all samples, seeds were weighed using a digital precision scale (Camry Electronic Scale Model EK5350, Zhongshan, Guangdong, China).
3. Moisture Content Percentage (% MC): For the determination of moisture content in *J. neotropica* seeds, 25 seeds were selected as samples for each locality. Subsequently, the initial weight of each seed was recorded before subjecting them to a storage process. Since these are recalcitrant seeds, they have a hard appearance but are delicate and lose their viability quickly after being extracted from the fruit. This type of seed typically requires specific conditions and special care for storage and preservation. For this reason, they were stored for a period of six months at an ambient temperature of 18 °C. Gradual weighing was carried out at the beginning (time 0) and six months after collection to determine the percentage of moisture lost during the established period (Figure 4).

Figure 2. *J. neotropica* seeds with impurities (**a**) and without impurities (**b**).

Figure 3. Average number of *J. neotropica* seeds per kilogram.

Figure 4. Moisture content of *J. neotropica* seeds: (**a**) 0 months; (**b**) 6 months.

The moisture content was calculated using the following equation:

$$MC = \left(\frac{Imw - Fmw}{Imw}\right) * 100 \quad (1)$$

where the variables are as follows:

MC = Moisture content (%);
Imw = Initial moisture weight of the samples (g);
Fmw = Final moisture weight of the samples (g).

4. Germination Percentage: The methodology for determining the germination percentage, following the standards of the International Seed Testing Association, adhered to a standardized procedure that ensured both accuracy and reproducibility of results. For this study, a representative sample of seeds was selected based on criteria of uniformity in size, maturity, and physiological state. These seeds were stored under controlled conditions, maintaining an average temperature of 18 °C and a relative humidity of 70%, parameters defined from previous studies and adjusted to the physiological requirements of *J. neotropica* in its natural habitat. During the storage period, systematic monitoring of viability was conducted, recording variations in moisture and physiological state to minimize the influence of external environmental factors. These conditions allowed for the collection of precise data on conservation and contributed to promoting germination. Subsequently, the germinated seeds were evaluated and classified according to defined criteria, such as normal or abnormal development. The germination percentage was calculated by dividing the number of normal seedlings by the total number of seeds sown and multiplying the result by 100, thus providing a reliable indicator of seed quality. This internationally recognized and adopted method ensured uniformity in assessing seed viability on a global scale.

In this study, four pre-germination treatments were conducted to evaluate the effectiveness of each method:

a. **Mechanical treatment:** The seeds were placed on a solid surface and struck with a hammer until they cracked.
b. **Hot water imbibition:** The seeds were placed in a container with hot water at 100 °C, at a ratio of 4 to 5 times their volume, and removed after two minutes of immersion in the heat source.
c. **Cold water imbibition and sun exposure:** To remove inhibitors, the seeds were exposed to sunlight during the day and soaked in water at night. This process was repeated for three consecutive days and nights.
d. **Control treatment:** This method served as a baseline for comparing the effectiveness of the other treatments.

The number of germinated seeds was recorded daily, and the germination percentage was calculated. This process was repeated with different seed samples corresponding to each repetition of the applied experimental treatment, ensuring that each represented a specific condition of the study. The treatments were conducted under natural environmental conditions, allowing for the collection of representative and reliable data on germination performance in response to the evaluated variables.

2.3.2. Phenotypic Characteristics of *J. neotropica*

a. **Seed size and weight:** To determine the size of *J. neotropica* seeds, a detailed methodology was implemented. Seed samples from different progenies were collected from various geographical localities. Subsequently, precise measurements of each seed's size were taken using a digital caliper (Mitutoyo, Kawasaki, Japan). This process was systematically repeated for each locality, where seed samples consisting of 100 units were evaluated. These experimental samples, referred to as seed lots, allowed for the quantification of inherent variability within each sampled population. The applied methodology ensured rigorous statistical representation, facilitating the generation of consistent and reproducible data on germination performance under diverse environmental conditions (Figure 5).

Figure 5. Measurement of the diameter (**a**) and measurement of the height (**b**) of the *J. neotropica* seed.

b. **Seedling height at the nursery level (Th, cm):** This morphological parameter is related to the plant's photosynthetic capacity and transpiration surface. It corresponds to the length from the root collar to the apex of the main stem, measured in cm. It was measured for all living plants in the experimental unit six months after germination for all localities.

c. **Basal diameter of seedlings (Bd, mm):** The basal diameter is a key indicator of the plant's ability to transport water to the aerial parts, as well as its structural resistance and relative tolerance to high-temperature conditions. This parameter was measured at the height of the root collar, at the transition point between the root system and the base of the stem, in all living plants of the experimental unit. Measurements were conducted six months after germination, covering all the localities included in the study.

d. **Number of leaves per treatment:** This morphological parameter was evaluated in all living individuals of the experimental unit propagated in the nursery under the different treatments. Measurements were conducted six months after germination, coinciding with the scheduled evaluations of the other morphological variables and covering all localities included in the study. In each case, the number of leaves was recorded using the same assessment framework, allowing for comparative analysis of foliar development among the different origin localities [11,12] (Figure 6).

Figure 6. Measurement of dasometric variables at the nursery level, such as (**a**) total height (Th, cm) and (**b**) basal diameter (Bd, cm) of *J. neotropica* from different localities.

2.3.3. Experimental Design at Nursery Level

A completely randomized block design (CRBD) with a bifactorial arrangement and three replications was used (Figure 7).

- **Functional analysis:** The coefficient of variation was calculated to assess data dispersion. Additionally, mean separation was analyzed using Tukey's test at a 5% significance level to identify statistical differences among treatments and localities.
- **Factors under study:**

  Factor 1 (pre-germination treatments):
  T0 = Control (seeds without any treatment);
  T1 = Immersion in boiling water at 100 °C (2 min);
  T2 = Mechanical (cracked with a hammer);
  T3 = Immersion in water and exposure to sunlight (three days in ambient water and three days in the sun).
  Factor 2 (localities):
  L1 = The Tundo;
  L2 = The Victoria;
  L3 = The Argelia.
- **Treatments under study:** The combination of the factors under study resulted in 12 treatments, which are detailed below (Table 1).
- **Experimental field specifications:**

  Number of treatments: 12;
  Number of replications: 3;
  Total number of units: 36;
  Total trial area: 40 m^2;
  Total number of seeds per plot: 100;
  Total number of seeds per treatment: 25.

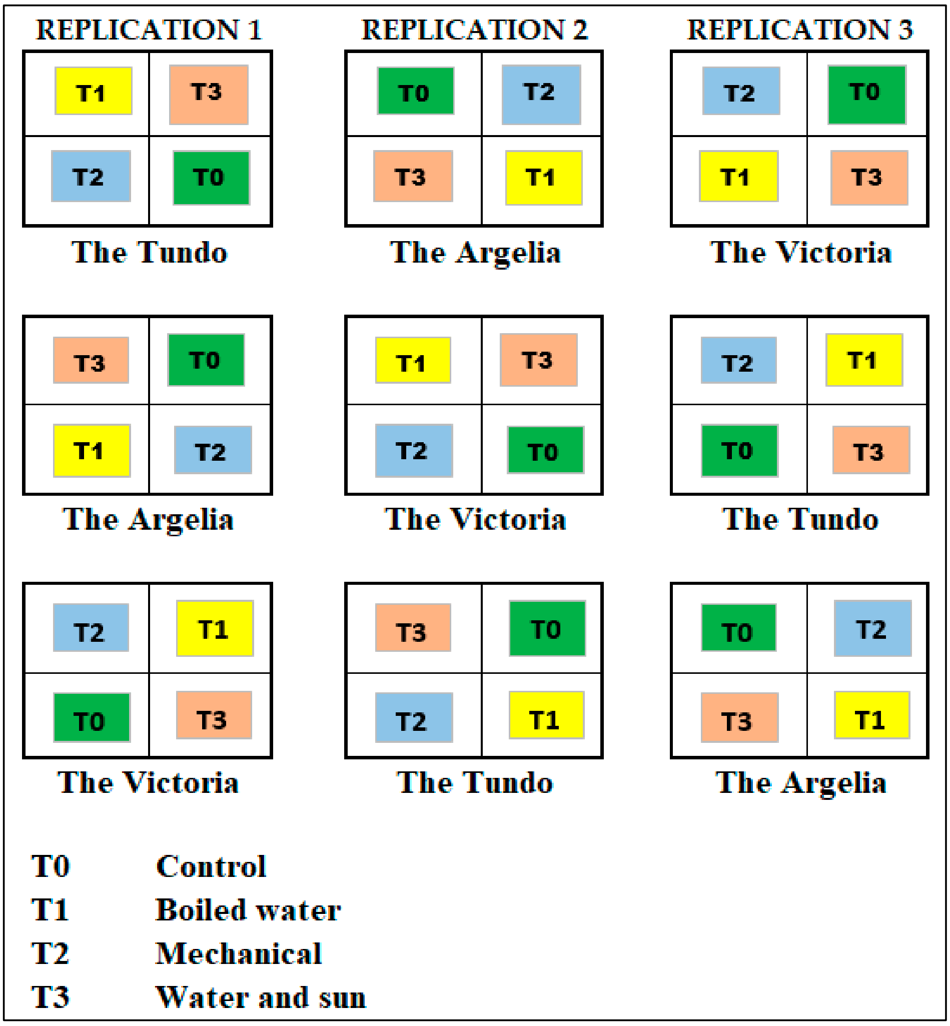


Figure 7. Experimental design of pre-germination treatments by localities.

- **Dependent variables used in the statistical analysis:**

In this study, the main dependent variable in the germination analysis was the germination percentage, which was measured for each treatment and locality. Additionally, other seed traits such as weight, height, and diameter were evaluated using the same experimental design, and separate statistical analyses were conducted to identify significant differences among treatments and origin localities.

- **Mathematical model for the statistical design:**

$$Y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \gamma_k + \epsilon_{ijk} \quad (2)$$

Y_{ijk} : the dependent variable;
μ: the global mean of all treatments;
α_i : (alpha) factor 1 under study;
i: the levels of factor;
β_j : (beta) factor 2 under study;
j : the levels of factor 2;
$(\alpha\beta)_{ij}$: the interaction between the i-th level of the pre-germination treatment and the j-th level of the locality of origin;
γ_k : random effect of replication;
ϵ_{ijk} : the experimental error of the ijk observation.

Table 1. Germination treatments of *Juglans neotropica* Diels seeds evaluated from three study areas in the nursery.

N° Treatments	Code	Description
1	T0L1	Control—The Tundo
2	T0L2	Control—The Victoria
3	T0L3	Control—The Argelia
4	T1L1	Boiling water—The Tundo
5	T1L2	Boiling water—The Victoria
6	T1L3	Boiling water—The Argelia
7	T2L1	Mechanical—The Tundo
8	T2L2	Mechanical—The Victoria
9	T2L3	Mechanical—The Argelia
10	T3L1	Water and sun—The Tundo
11	T3L2	Water and sun—The Victoria
12	T3L3	Water and sun—The Argelia

In addition to germination percentage, other morphological and seed quality variables were evaluated during Phase I, including seed size and weight, moisture content, purity, and number of seeds per kilogram, as well as seedling height, basal diameter, and number of leaves. These variables were measured six months after sowing, using the same experimental design and statistical methods described for germination analysis.

2.4. Second Phase: At the Level of Forest Plantation

In the second phase, a plantation trial of *J. neotropica* was established using germinated plants from two distinct localities of origin (The Tundo and The Victoria), under uniform planting conditions. These belong to a Piedmont Semi-deciduous Forest ecosystem of Catamayo-Alamor, differing from a Lower Montane Evergreen Forest ecosystem in the southern part of the eastern Andes mountain range, with an altitudinal range of 1660–2200 m.a.s.l. This activity was carried out following [13] methodology, which consisted of applying the following steps:

2.4.1. Selection of the Area to Be Planted

The selection of the planting site was based on the edaphoclimatic suitability for *J. neotropica*, prioritizing areas historically occupied by the species but currently degraded due to deforestation, land-use changes, landslides, and livestock grazing. To support ecological restoration efforts, three types of environments—referred to as strata in the study—were selected: secondary forest, riparian forest, and pasture. Prior to planting, detailed soil analyses were conducted to assess their physicochemical properties.

In the secondary and riparian forest sites, the soil exhibited moderately acidic conditions (pH = 5.32), high nitrogen content (51 ppm), and medium levels of phosphorus (19 ppm), potassium (0.3 meq/100 mL), calcium (5 meq/100 mL), and magnesium (0.9 meq/100 mL). These results indicate moderate fertility, with potential phosphorus limitations and a soil reaction that may require liming to optimize nutrient uptake.

In contrast, the pasture sector showed a slightly less acidic pH (5.63), greater nitrogen availability (54 ppm), medium phosphorus levels (14 ppm), and an adequate concentration of exchangeable bases, with a notably high magnesium value (1.5 meq/100 mL).

Climatic conditions across both sites were relatively homogeneous, which favored the standardization of the planting trial.

Additional selection criteria included local biodiversity, ecological threats, and interspecific competition, all of which were considered in the restoration design.

2.4.2. Selection and Field Establishment of Plants

Selected *J. neotropica* plants propagated in the nursery were chosen for transplanting based on vigor, root development, stem lignification, foliar health, and absence of pests or diseases. For their establishment, a square planting layout (5 × 5 m) was manually implemented over a 2500 m^2 area per stratum. Standard silvicultural practices were followed for plot delineation, seedling positioning, and hole excavation (30 × 30 × 30 cm). Seedlings were carefully transplanted to ensure optimal root positioning and soil contact, which facilitated uniform establishment and subsequent monitoring across the plantation trials.

2.4.3. Fertilization

Finally, based on the results of prior soil analyses conducted in the three selected strata, a fertilization scheme was designed to evaluate the performance of *J. neotropica* under different levels of nutrient availability. The analyses revealed soils with moderately acidic pH, medium fertility, and potential phosphorus deficiencies, which justified the implementation of differentiated nutritional treatments. Three fertilization levels were established using combinations of NPK (13-40-13) and urea, corresponding to low, medium, and high doses, applied in liquid form directly into each planting hole. This method aimed to optimize nutrient uptake by the seedlings and reduce leaching losses, considering the high rainfall in the study area. The methodological objective was to identify the most efficient fertilization regime for the early establishment of the species under ecological restoration conditions.

2.4.4. Management

The management of a forest plantation during the first year included essential activities such as regular irrigation to ensure proper root establishment and initial growth, weed control to prevent competition for resources, constant protection against pests and diseases through monitoring and appropriate treatments, fertilization to provide necessary nutrients, replacement of non-surviving seedlings to maintain the planned density, and continuous supervision of the plantation's condition to adjust management practices as needed, thus ensuring the successful establishment and healthy development of the seedlings.

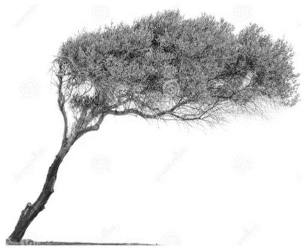
Subsequently, adaptability parameters were evaluated, such as survival rate and stem straightness of the plants in the final site, as well as phenotypic characteristics of dendrometric variables such as total height and basal diameter of the plants at the first year of planting, following the methodology proposed by [13].

2.4.5. Plant Response to Plantation Conditions

a. **Survival rate (%):** The survival rate (%) was determined based on an evaluation conducted 60 days after the trial establishment. To achieve this, the number of established plants in each experimental unit was quantified and calculated as the ratio of surviving individuals to the total number of planted trees. This calculation was performed using the following equation: (number of established plants/total number of planted trees) × 100. The evaluation was carried out under standardized conditions, ensuring uniformity in the application of establishment criteria, which allows for the interpretation of the plants' adaptability to the planting site and their response to the environmental conditions of the study area.

b. **Stem straightness at 12 months:** To carry out the phenotypic development assessment, a methodology based on shape codes was implemented, following the guidelines proposed by [14,15]. The individuals under study were evaluated at twelve months to determine their physical characteristics. These categories provided a comprehensive framework for quantitatively describing stem shape, allowing for a more precise evaluation of phenotypic characteristics across four categories (Table 2).

Table 2. Classification of stem morphology into four categories.

Category	Interpretation	Illustration
Sinuous	Twisted, tortuous, or crooked, with curved and serpentine shapes	
Inclined	Indicates an inclination or slope	
Bifurcated	Divided into two branches or parts	
Straight	A line or surface without curves or angles	

2.4.6. Phenotypic Traits Based on Dendrometric Variables

1. Basal diameter (BD, cm)

The stem diameter (cm) was measured at the base of 12-month-old *J. neotropica* plants using a caliper.

2. Total height (m)

The total height of the plant (m) was measured with a graduated ruler, from the base at ground level to the apex, at 12 months after establishment in the definitive site.

2.4.7. Experimental Design at Plantation Level

In the study area, three stages of natural succession were selected, which in this research were identified as strata (secondary forest, riparian forest, and pasture). The purpose was to group units with similar conditions into strata so that the sampling units within each stratum were as homogeneous as possible, while the strata themselves remained heterogeneous [16].

A completely randomized block design (CRBD) was used in each stratum with a factorial arrangement, with five replications, considering each plant as the sampling unit (Figure 8).

1. **Functional analysis:** The coefficient of variation was determined, and the mean separation was analyzed using Tukey's test at a 5% error level with a 95% confidence interval.
2. **Factors under study:** Two study factors were analyzed for each of the three strata (secondary forest, riparian forest, and pasture), as detailed below.

   Factor A: Localities

   L1 = The Tundo;
   L2 = The Victoria.

   Factor B: Fertilizers

   F0 = Control;
   F1 = Urea;
   F2 = NPK.
3. **Treatments under study:** The combination of the factors under study resulted in 8 treatments, which are detailed below (Table 3).
4. **Experimental unit:** A 50 × 50 m (2500 m^2) plot was used in each stratum, with four rectangular subplots of 25 × 25 m (625 m^2). Two subplots corresponded to the forest site of The Tundo and the other two to The Victoria. Each subplot contained five experimental units measuring 5 × 25 m (125 m^2), with each unit including five plants, where each plant was considered a replicate. This resulted in a subtotal of 10 experimental units per forest site and a total of 20 experimental units across both sites.
5. **Localities:** Two localities were evaluated, one from the Sozoranga canton and the other from the Macará canton, both belonging to the Loja province in southern Ecuador.

   L1 = The Tundo
   L2 = The Victoria
6. **Mathematical model for the statistical design:** To statistically analyze and determine whether there are significant differences among the treatments tested in *J. neotropica*, an ANOVA (analysis of variance) was applied.

$$Y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \gamma_k + \epsilon_{ijk} \quad (3)$$

Y_{ijk} : the dependent variable;
μ: the global mean of all treatments;
α_i : (alpha) factor 1 under study;
i: the levels of factor;
β_j : (beta) factor 2 under study;
j : the levels of factor 2;
$(\alpha\beta)_{ij}$: the interaction between the i-th level of the locality of origin and the j-th level of the fertilizer;

γ_k : random effect of replication;
ϵ_{ijk} : the experimental error of the *ijk* observation.

7. **Data analysis**

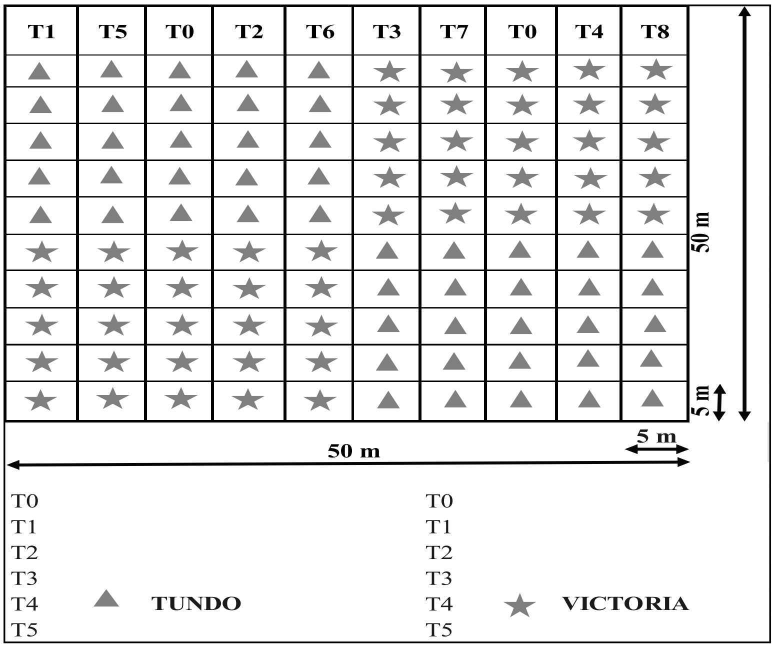


Figure 8. Completely randomized block experimental design in the lands of The Hacienda "The Florencia" to evaluate the behavior of two provenances of *J. neotropica* plants.

Table 3. Treatments evaluated in the present research at the plantation level in the strata: secondary forest, riparian forest, and pasture.

FACTORS		Levels	Treatment
F1: Location	**F2: Fertilizer**		
L1: The Tundo	Fert 0:	**Control**	T0
	Fert 1: NPK (13-40-13)	**NPK 1:** 100 gr	T1
		NPK 2: 150 gr	T2
		NPK 3: 200 gr	T3
		NPK 4: 250 gr	T4
	Fert 2: Urea	**Urea:** 100 gr	T5
		Urea: 150 gr	T6
		Urea: 200 gr	T7
		Urea: 250 gr	T8
L2: The Victoria	Fert 0: 0	**Control**	T0
	Fert 1: NPK (13-40-13)	**NPK 1:** 100 gr	T1
		NPK 2: 150 gr	T2
		NPK 3: 200 gr	T3
		NPK 4: 250 gr	T4
	Fert 2: Urea	**Urea:** 100 gr	T5
		Urea: 150 gr	T6
		Urea: 200 gr	T7
		Urea: 250 gr	T8

To evaluate significant differences ($p < 0.05$) among the different treatments, a mean comparison was performed using Tukey's test with InfoStat Professional 2020 [17].

The statistical analysis was conducted separately for each of the three identified strata (secondary forest, riparian forest, and pasture) to maintain internal homogeneity of the sampling units within each stratum. Consequently, the stratum was not included as a factor in the model but was treated as an independent analytical structure, with a completely randomized block design and factorial arrangement applied to each one.

3. Results

3.1. Phase 1: At the Nursery Level

3.1.1. Quality Parameters of *Juglans neotropica* Diels Seeds

1. Purity percentage

The physical purity of *J. neotropica* seeds showed a high proportion of pure seeds relative to total sample weight, indicating good seed lot quality. The results revealed clear differences in the composition of seed components, as shown in Table 4.

Table 4. Mean ± standard deviation of seed impurity and number of seeds per kilogram of *J. neotropica* by provenance.

Locality	Impurity (%) ± SD	Seeds kg^{-1} ± SD	CV Seeds (%)
The Tundo	1.08 ± 0.22	30.0 ± 1.87	6.23
The Victoria	0.88 ± 0.22	32.0 ± 2.24	7.00
The Argelia	1.04 ± 0.29	35.0 ± 1.87	5.34

Legend: Summary of physical purity and seed count per kilogram for *J. neotropica* seeds collected from three localities. Values represent the mean ± standard deviation based on five replicates.

2. Number of seeds per kilogram (kg)

The results revealed significant variations in seed density per kilogram among the different localities of *J. neotropica*, with a value of 30 seeds per kilogram in The Tundo, which had the largest seed sizes, followed by The Victoria with 32 seeds kg^{-1}, and finally The Argelia with 35 seeds kg^{-1} (Table 4).

3. Percentage of moisture content (MC %)

The results clearly show that seeds from the three localities gradually lose moisture over time in months, and their 100% viability has been confirmed up to six months of storage. Beyond that period, it has been demonstrated that even a 2% moisture loss leads to a loss of viability (Table 5).

4. Germination percentage

The analysis of variance (ANOVA) revealed a significant interaction between pre-germination treatment and locality of origin ($p \leq 0.05$). This interaction was mainly evident in the control treatment (T0), where The Victoria exhibited a significantly higher germination percentage compared to The Tundo and The Argelia, indicating a differential response in the absence of pre-germination treatments.

In contrast, treatments T1, T2, and T3 showed no significant differences among localities, as confirmed by the post hoc analysis, suggesting that the pre-germination treatments produced a more uniform germination response across environments (Figure 9).

Table 5. Changes in the moisture content and viability of *J. neotropica* seeds over time by locality. Mean values ± SD.

Sampling Time	Locality	N° Seeds	Wws (g)	Dws (g)	Mc (%)	Viability
Measurement 1 (starting month)	The Tundo	25	31.3 ± 0.2	31.1 ± 0.2	0.64 ± 0.03	Viable
	The Victoria	25	28.7 ± 0.3	28.5 ± 0.3	0.73 ± 0.04	Viable
	The Argelia	25	25.6 ± 0.2	25.4 ± 0.2	0.51 ± 0.02	Viable
Measurement 2 (3 months)	The Tundo	25	31.3 ± 0.2	30.9 ± 0.2	1.34 ± 0.05	Viable
	The Victoria	25	28.7 ± 0.3	28.3 ± 0.3	1.46 ± 0.06	Viable
	The Argelia	25	25.6 ± 0.2	25.2 ± 0.2	1.37 ± 0.05	Viable
Measurement 3 (6 months)	The Tundo	25	31.3 ± 0.2	30.6 ± 0.3	2.17 ± 0.07	Not viable
	The Victoria	25	28.7 ± 0.3	28.0 ± 0.3	2.37 ± 0.08	Not viable
	The Argelia	25	25.6 ± 0.2	24.9 ± 0.2	2.58 ± 0.09	Not viable

Wws: fresh weight; Dws: dry weight; Mc: moisture content.

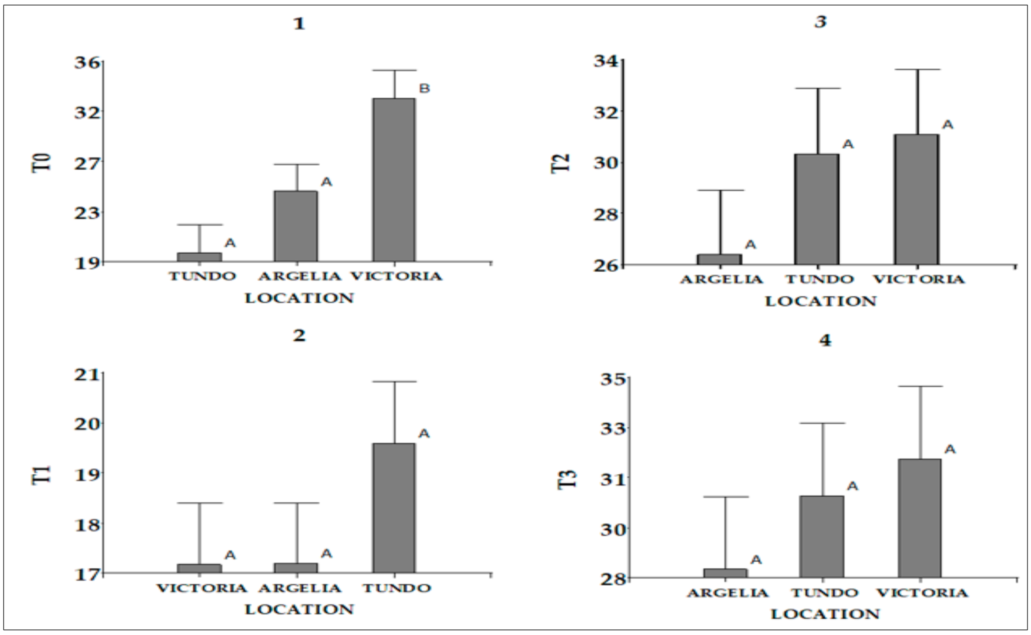


Figure 9. Analysis of variance (ANOVA) of germination percentage for each pre-germination treatment across all localities. A significant interaction between treatment and locality was detected ($p \leq 0.05$). Different letters indicate statistically significant differences among localities within each treatment. Numbers (**1**–**4**) correspond to the pre-germination treatments: 1 = T0, 2 = T1, 3 = T2, 4 = T3.

3.1.2. Germination Percentage Among Treatments and Localities

Statistically significant differences were observed among localities at each time point (T0–T3), as indicated by non-overlapping letters in the post hoc analysis. At T0, The Victoria exhibited the highest value, significantly greater than The Argelia and The Tundo. At T1, although values were closer, The Tundo remained significantly higher than the other two localities. During T2 and T3, all three localities differed significantly, with The Victoria maintaining the highest mean values (Figure 10).

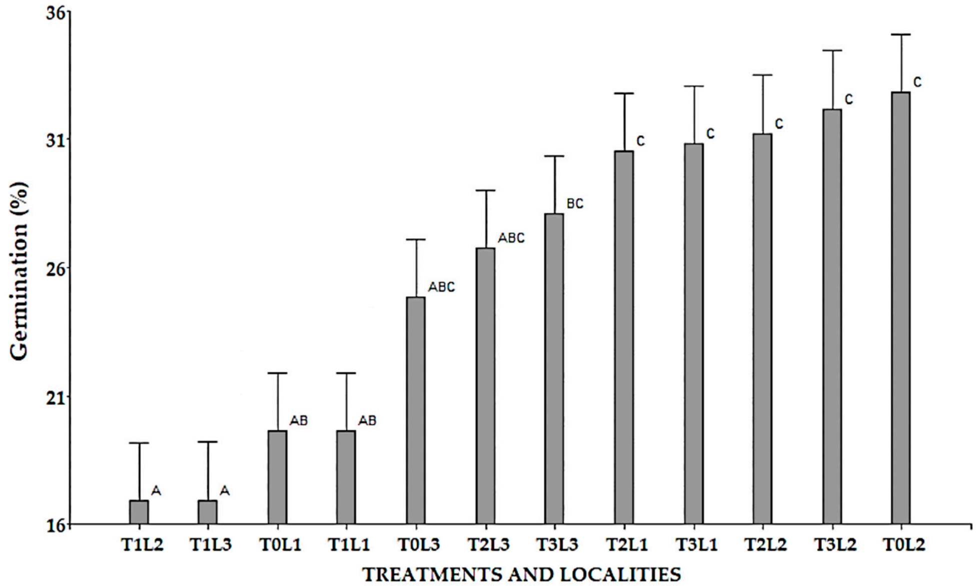


Figure 10. Analysis of variance of the average germination percentage across treatments and localities. Different letters indicate significant differences ($p \leq 0.05$).

5. Phenotypic Characteristics of *J. neotropica* Seeds

3.1.3. Size and Weight of the Seeds

Clear phenotypic differences were observed in the size and weight of *J. neotropica* seeds depending on their locality of origin. Seeds from The Tundo exhibited the highest average values, with a weight of 29.55 ± 6.15 g, a diameter of 40.70 ± 3.30 mm, and a height of 39.75 ± 3.68 mm. These were followed by seeds from The Victoria, with an average weight of 24.39 ± 4.67 g, a diameter of 36.88 ± 3.01 mm, and a height of 37.40 ± 3.23 mm. The smallest seeds were recorded from the locality of The Argelia, with average values of 20.93 ± 6.06 g in weight, 35.99 ± 3.88 mm in diameter, and 32.81 ± 4.47 mm in height. This variability suggests possible differences in the quality of genetic material or in local environmental conditions that may be influencing seed development (Table 6).

Table 6. Descriptive statistics of seed weight, diameter, and height of *J. neotropica* collected from three localities.

Locality	**Variable**	***n***	**Mean ± SD**	**Min–Max**
The Argelia	Weight (g)	331	20.93 ± 6.06	(8.00–40.00)
	Diameter (mm)	331	35.99 ± 3.88	(25.70–46.70)
	Height (mm)	331	32.81 ± 4.47	(24.90–79.10)
The Tundo	Weight (g)	333	29.55 ± 6.15	(14.00–46.00)
	Diameter (mm)	333	40.70 ± 3.30	(29.80–48.50)
	Height (mm)	333	39.75 ± 3.68	(25.30–49.20)
The Victoria	Weight (g)	101	24.39 ± 4.67	(13.00–38.00)
	Diameter (mm)	101	36.88 ± 3.01	(30.40–58.20)
	Height (mm)	101	37.40 ± 3.23	(27.20–45.20)

Values are expressed as mean ± standard deviation, with minimum and maximum in parentheses.

The summarized results of seed size and weight for each locality are shown in Table 6 and Figure 11, where significant differences can be observed.

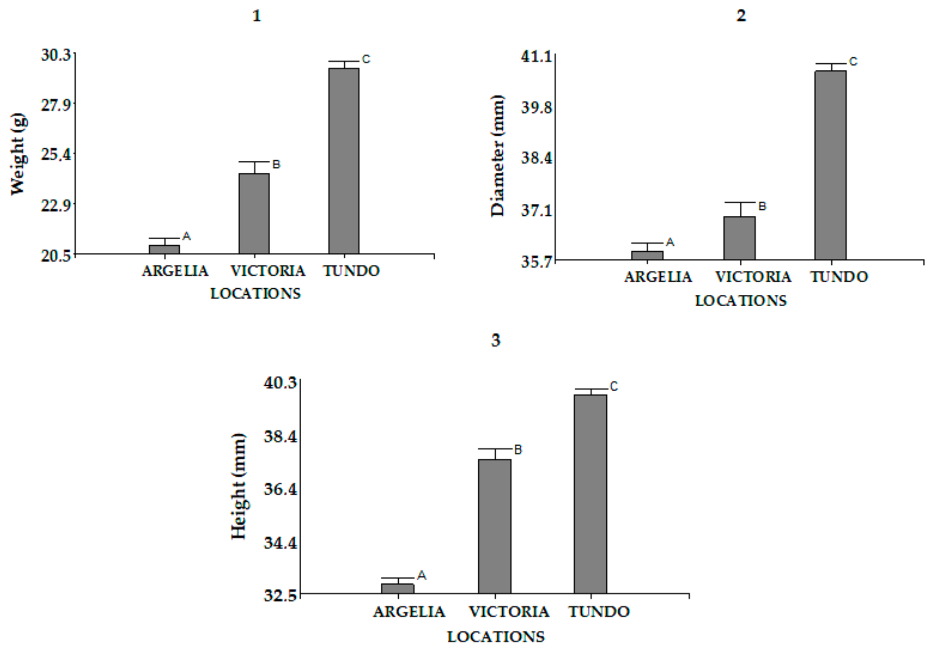


Figure 11. Analysis of variance of (**1**) weight (g), (**2**) diameter (mm), and (**3**) height (mm) of *J. neotropica* seeds across different localities. Different letters (A, B, C) indicate statistically significant differences among the evaluated localities ($p \leq 0.05$).

3.1.4. Basal Diameter, Total Height, and Number of Leaves of the Nursery Plants

Significant differences were observed in the basal diameter, total height, and number of leaves of nursery plants across the evaluated localities. Seedlings from The Victoria exhibited the highest total height (38.35 cm) and a relatively large basal diameter (0.91 cm), while The Tundo showed the highest average number of leaves (7). In contrast, seedlings from The Argelia consistently showed the lowest values for all traits. These differences were statistically significant ($p \leq 0.05$), as indicated by the distinct letters above each bar in Figure 12, confirming that locality has a notable effect on early vegetative development.

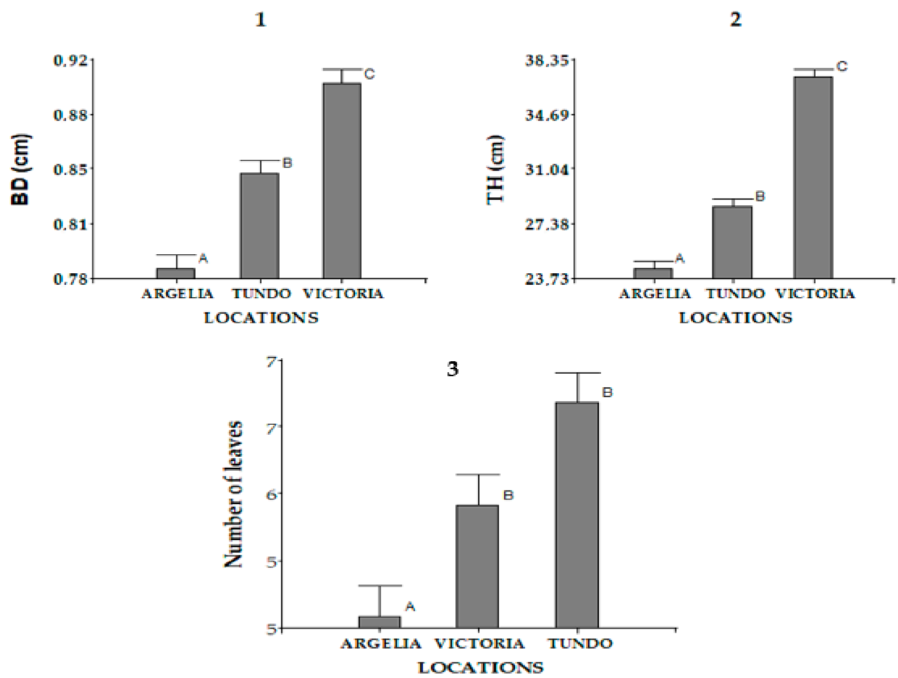


Figure 12. Analysis of variance of basal diameter (**1**), total height (**2**), and number of leaves of the plants by locality (**3**). Different letters indicate significant differences ($p \leq 0.05$).

3.2. Phase II: At the Level of Forest Plantation

3.2.1. Adaptability Parameters

1. Survival %. During the first year of establishment, *J. neotropica* exhibited a high overall survival rate of 92% across the plantation trial. However, stratified and locality-based analyses revealed important differences that highlight environmental influences on early survival.

Among the evaluated strata, the secondary forest showed the highest survival rate (100%), followed by the riparian forest (92%) and pasture (84%). At the locality level, plantations from The Tundo recorded a slightly higher survival rate (94%) than those from The Victoria (90%).

When examining survival by locality within each stratum, more nuanced patterns emerge (Table 7). Both The Tundo and The Victoria achieved 100% survival in the secondary forest. In contrast, the riparian forest showed 96% survival from The Tundo and 88% from The Victoria. The lowest survival percentages occurred in the pasture, with 90% in The Tundo and only 78% from The Victoria.

Table 7. Survival percentage of *J. neotropica* one year after planting by stratum and locality.

Stratum	Locality	Planted	Living	Survival (%)
Secondary Forest	The Tundo	50	50	100
	The Victoria	50	50	100
Subtotal		100	100	100
Riparian Forest	The Tundo	50	48	96
	The Victoria	50	44	88
Subtotal		100	92	92
Pasture	The Tundo	50	45	90
	The Victoria	50	39	78
Subtotal		100	84	84
General Total		300	276	92

Survival percentages recorded during the first year of evaluation for *J. neotropica* plants established in three vegetation types (secondary forest, riparian forest, and pasture) are shown according to fertilization treatment and plant origin (L1: The Tundo; L2: The Victoria).

Plants from L1 (The Tundo) exhibited 100% survival in secondary forest across all treatments, including the unfertilized control (T0), indicating high adaptability to this environment. In contrast, survival rates in riparian forest and pasture under T0 were reduced to 70% and 56%, respectively. The application of NPK significantly improved survival, particularly at 200 and 250 g (T3 and T4), where values exceeded 98% across all cover types. Similarly, urea was highly effective from 150 g onwards (T6–T8), achieving 100% survival in all vegetation types.

For plants from L2 (The Victoria), the response to fertilization was more variable. In the absence of fertilizer (T0), survival dropped notably in pasture (39%) and moderately in riparian forest (67%). The use of NPK led to consistent improvements, especially in secondary and riparian forests, though survival in pasture did not exceed 90%. Urea displayed less stability at intermediate doses, particularly at 150 g (T6), where survival declined in RF (66%) and P (58%). However, higher doses (200 and 250 g; T7 and T8) restored survival to 100% across all cover types (Table 8).

2. Stem straightness at 12 months. It is important to note that the bifurcation caused by the borer in the planted individuals is not considered a genetic phenotypic trait of the species *J. neotropico* (Table 9).

Table 8. Survival percentage of *J. neotropica* plants by ecological stratum and locality.

F1: Localities	F2: Fertilizer	Levels	Treatment	Survival %		
				SF	RF	P
L1: The Tundo	Fert 0: 0	**L1**	T0	100	70	56
	Fert 1: NPK (13-40-13)	**NPK 1:** 100 gr	T1	100	96	95
		NPK 2: 150 gr	T2	100	100	93
		NPK 3: 200 gr	T3	100	100	98
		NPK 4: 250 gr	T4	100	100	99
	Fert 2 = Urea	**Urea:** 100 gr	T5	100	95	65
		Urea: 150 gr	T6	100	100	100
		Urea: 200 gr	T7	100	100	100
		Urea: 250 gr	T8	100	100	100
L2: The Victoria	Fert 0: 0	**L2**	T0	100	67	39
	Fert 1: NPK (13-40-13)	**NPK 1:** 100 gr	T1	100	92	90
		NPK 2: 150 gr	T2	100	80	85
		NPK 3: 200 gr	T3	100	90	90
		NPK 4: 250 gr	T4	100	100	89
	Fert 2 = Urea	**Urea:** 100 gr	T5	100	100	55
		Urea: 150 gr	T6	100	66	58
		Urea: 200 gr	T7	100	100	100
		Urea: 250 gr	T8	100	100	100

Table 9. Percentage of stem shape categories at 12 months for *J. neotropica* by stratum and locality.

Category	No. of Individuals	Sinous (%)	Inclined (%)	Forked (%)	Straight (%)
Strata					
Secondary Forest	100	0.00	0.00	0.00	100.00
Riparian Forest	99	0.00	0.00	0.00	99.00
Pasture	100	0.00	0.00	0.00	100.00
Localities					
The Tundo	150	0.00	0.00	0.00	100.00
The Victoria	149	0.00	0.00	0.67	99.33

Across the three evaluated strata (secondary forest, riparian forest, and pasture), nearly all individuals exhibited straight stems, with 100.00% in both the secondary forest and pasture and 99.00% in the riparian forest.

No individuals with sinuous, inclined, or forked stem shapes were recorded in any of the strata.

Regarding provenance, individuals from The Tundo exhibited a 100% straight stem rate.

In contrast, individuals from The Victoria showed a slightly lower percentage, with 99.33% presenting straight stems and a single individual (0.67%) classified as forked. It is important to note that the bifurcation caused by the borer in the planted individuals is not considered a genetic phenotypic trait of the species *J. neotropica*.

These observations reflect a consistently high occurrence of straight stems across all planting conditions and localities by the 12-month evaluation point.

3.2.2. Phenotypic Characteristics Based on Dasometric Variables

Basal diameter (Bd mm) and total height (Th cm): The average basal diameter and total height are presented for plants from different localities of origin, evaluated across various strata. Among the evaluated localities, The Tundo consistently exhibited the highest mean basal diameters across all three strata, along with the tallest average plant heights (Table 10).

Table 10. Growth of the dasometric variables diameter and height across all strata by locality.

Localities	Strata	Variable	Min	Mean	Max	SD	CV (%)
The Tundo	Secondary Forest	Diameter (mm)	6.39	11.47	20.75	2.87	15.04
		Height (cm)	32.00	54.74	101.00	15.04	27.48
	Riparian Forest	Diameter (mm)	6.83	8.81	11.08	1.12	12.71
		Height (cm)	17.00	49.25	67.00	11.00	22.34
	Pasture	Diameter (mm)	6.24	12.32	20.67	2.68	21.75
		Height (cm)	14.00	41.32	74.00	14.25	34.49
The Victoria	Secondary Forest	Diameter (mm)	6.12	12.08	19.77	3.66	30.30
		Height (cm)	28.00	54.89	108.00	19.97	36.38
	Riparian Forest	Diameter (mm)	5.70	9.57	16.25	2.15	22.47
		Height (cm)	20.00	47.60	87.00	14.80	31.09
	Pasture	Diameter (mm)	5.85	13.86	20.45	3.20	23.09
		Height (cm)	20.00	44.58	76.00	14.29	32.05

Variables represent basal diameter (Diameter) in millimeters and total height (Height) in centimeters, measured 12 months after planting. SD = standard deviation; CV (%) = coefficient of variation.

The average values of the dasometric variables Bd (mm) and Th (cm) are summarized according to strata, localities, and treatments.

Statistically significant differences between strata were found for the mean growth of the dasometric variables, with $p \leq 0.05$ for both diameter and height.

On the other hand, it can be observed that there are no statistically significant differences between the mean growth values of the dasometric variables under study with respect to localities, yielding a *p*-value of 0.2587 for diameter and a *p*-value of 0.5681 for height.

Finally, the fertilization treatments applied to the three strata also show no statistically significant differences among them, yielding a *p*-value of 0.1692 for diameter and 0.7183 for height (Table 11).

Table 12 summarizes the interaction effects between locality, fertilization treatment, and stratum on basal diameter and total height of *J. neotropica* plants.

Table 11. ANOVA of dasometric variables by locality, strata, and treatments.

Category	Factor	Diameter (mm)	SE (mm)	CV Diameter (%)	*p*-Value	Height (cm)	SE (cm)	CV Height (%)	*p*-Value
Locality	The Tundo	11.80	0.27	49.29	0.2587	49.29	1.38	2.8	0.5681
	The Victoria	11.35	0.29	48.14		48.14	1.46	3.03	
Stratum	Secondary Forest	11.78	0.29	54.81	0.0001	54.81	1.55	2.83	0.0001
	Riparian Forest	9.33	0.35	48.13		48.13	1.88	3.91	
	Pasture	13.02	0.30	42.8		42.80	1.59	3.71	
Treatment	T0 (Control)	10.89	0.44	46.32	0.1692	46.32	2.27	4.9	0.7183
	T1 (100 g)	10.91	0.59	49.78		49.78	3.04	6.11	
	T2 (150 g)	11.79	0.61	49.85		49.85	3.15	6.32	
	T3 (200 g)	12.54	0.61	50.15		50.15	3.15	6.28	
	T4 (250 g)	11.68	0.67	50.22		50.22	3.41	6.79	
	T5 (100 g)	10.62	0.63	44.37		44.37	3.21	7.23	
	T6 (150 g)	12.09	0.60	48.61		48.61	3.09	6.36	
	T7 (200 g)	12.19	0.63	52.94		52.94	3.21	6.06	
	T8 (250 g)	12.34	0.64	48.88		48.88	3.27	6.69	

Table 12. Interaction between locality, fertilization treatment, and stratum (CODE) on basal diameter (BD) and total height (TH) of *J. neotropica* plants. Each CODE represents a unique treatment × locality × stratum combination. Tukey groups (α = 0.05) indicate statistically significant differences. For complete statistical data across all 55 combinations, refer to Supplementary Table S1.

Code	Locality	Treatment	Stratum	BD (mm)	SE	Tukey Group (BD)	TH (cm)	SE	Tukey Group (TH)
L2 T3–RF	L2	T3	Riparian forest	7.58	1.56	A	47.00	8.73	A–B
L1 T6–RF	L1	T6	Riparian forest	7.74	2.69	A	51.00	15.10	A–B
L1 T1–RF	L1	T1	Riparian forest	8.11	1.91	A–B	26.00	10.67	A
L2 T5–P	L2	T5	Pasture	16.66	1.21	C	45.80	6.75	A–B
L2 T0–P	L2	T0	Pasture	15.89	1.35	B–C	60.75	7.55	A–B
L1 T0–SF	L1	T0	Secondary forest	13.07	1.21	A–B–C	72.56	6.75	B
L2 T8–SF	L2	T8	Secondary forest	13.14	0.85	A–B–C	52.60	4.77	A–B
L1 T1–SF	L1	T1	Secondary forest	11.07	1.21	A–B–C	66.40	6.75	A–B
L2 T3–SF	L2	T3	Secondary forest	13.31	1.21	A–B–C	69.40	6.75	A–B
L2 T4–SF	L2	T4	Secondary forest	9.23	1.21	A–B–C	42.20	6.75	A–B

Note: Means with the same letter are not significantly different according to Tukey's HSD test (α = 0.05). SE = standard error; BD = basal diameter; TH = total height.

4. Discussion

4.1. Phase I: Influence of Seed Provenance on Early Performance of Juglans neotropica Diels in the Nursery

The results obtained in Phase I reveal a clear effect of seed provenance on various physiological and dasometric traits of *J. neotropica*. In terms of seed quality, high levels of genetic purity were recorded across all provenances: 98.92% for The Tundo, 99.12% for The Victoria, and 98.96% for The Argelia, aligning with values reported by [18] (97.66%). These figures indicate that the seeds were largely free of impurities, supporting effective sexual propagation and the preservation of desirable genetic traits for silvicultural or restoration purposes.

Variations in seed density per unit of mass were also observed: The Tundo presented 30 seeds kg^{-1}, The Victoria 32 seeds kg^{-1}, and The Argelia 35 seeds kg^{-1}. These figures are consistent with reports by [18,19], who documented between 34 and 60 seeds kg^{-1}.

The variability observed among provenances suggests underlying genetic differences with direct and practical implications for forest nursery planning and seed lot selection. From an operational standpoint, the results—particularly those related to growth and survival by locality of origin—allow for the identification of seed sources with superior performance under specific site conditions. This is critical for optimizing production resources, designing tailored fertilization regimes, and adjusting nursery management schedules accordingly. As highlighted by [20], the genetic origin of planting material has a direct influence on its adaptability and field establishment potential, making provenance selection a key step in nursery operations. Complementarily, ref. [21] emphasizes that taking provenance-specific responses into account during nursery phases enhances the compatibility of planting stock with reforestation objectives. The findings of this study reinforce the need to use genetically adapted seed lots for each environment to maximize silvicultural efficiency and ensure the successful production and establishment of *J. neotropica*. These considerations should be integrated into future restoration and forest management programs involving the propagation and deployment of native species such as *J. neotropica*.

During storage, a drop of more than 2% in seed moisture content was recorded after six months at 15–18 °C, compromising seed viability. These findings are supported by [18], who emphasized the critical role of initial seed moisture for germination.

The pre-germination treatments applied—primarily physical and substrate-related—enhanced the uniformity and germination percentage of *J. neotropica* seeds, particularly when compared to the variability observed in the control (T0). Although viability declined after six months of storage, the implemented techniques helped partially mitigate this effect. Previous studies have confirmed that non-chemical pre-germination strategies can improve germination efficiency in native forest species [21,22]. Additionally, ref. [23] emphasized that morphological and biochemical seed evaluation is essential for understanding germination behavior and designing species-specific nursery protocols. In this context, the findings of the present study reinforce the value of simple physical treatments as a practical tool for improving nursery performance when working with limited-quality seed lots.

Germination behavior also varied among provenances and responded differently to pre-sowing treatments. This study observed a germination range consistent with previous reports in the genus *Juglans*, with percentages between 40% and 80% [19,24]. These findings reinforce the importance of tailoring propagation strategies to the genetic origin of the seed material.

In terms of seedling development, The Victoria showed the highest values in both average height (37.20 cm) and basal diameter (9 mm) after six months, followed by The Tundo (28.56 cm, 8 mm) and The Argelia (24.39 cm, 7 mm), which exhibited contrasting growth responses, which align with the provenance-specific patterns previously reported by [25,26]. These studies describe how seed origin influences early vegetative traits such as basal diameter and total height, with certain localities consistently outperforming others under similar nursery conditions. As for foliar development, The Tundo exhibited the highest average number of leaves (7), compared with The Victoria (6) and The Argelia (5), which may indicate initial growth vigor linked to local environmental or genetic factors.

Furthermore, seed size variability—also documented by [27–29]—could be attributed not only to inherent genetic characteristics but also to ecological pressures and dispersal mechanisms, underscoring its importance in shaping early seedling performance. Larger seeds from The Tundo accumulate more reserves, enhancing germination and early seedling vigor, while smaller seeds from The Argelia may be better adapted for greater dispersal in their environment. This contrast may reflect divergent adaptive strategies shaped by local environmental conditions.

Together, these results highlight that seed provenance is a determining factor for seed quality, germination potential, and early seedling growth of *J. neotropica*, offering essential insights for seed sourcing decisions in forest production and restoration programs.

4.2. Phase II: Influence of Ecosystem and Provenance on the Establishment of J. neotropica in Field Conditions

The establishment success of *J. neotropica* was closely linked to both the type of ecosystem and the provenance of the seedlings. Survival rates were remarkably high across sites, with a total average of 92%, aligning with previous findings such as those reported by [30], who documented a 99.40% survival rate under similar conditions. Notably, survival reached 100% in secondary forests, 92% in riparian forests, and declined to 84% in pastures. This gradient highlights the protective role that forest cover may offer in early plantation stages. These findings reinforce the notion that forested environments, particularly secondary forests, offer more conducive conditions for early species establishment. This suggests greater adaptability of *J. neotropica* under forested conditions, likely due to favorable edaphic and microclimatic factors.

The slightly higher survival rate of plants from The Tundo (94%) compared to The Victoria (90%) may reflect better site adaptation. Ref. [31] found that climatic similarity between seed source and planting site significantly influences performance in tropical pines. Thus, The Tundo's ecological affinity with the local conditions could explain its greater stress tolerance and superior outcome.

Stem form was another key indicator of early vigor. Straightness—a desirable silvicultural trait—was particularly pronounced, with The Tundo reaching 100% of individuals displaying straight, dominant stems, and The Victoria registering 99.33%. It is worth noting that these values may partly reflect a selection effect, as the most vigorous individuals were chosen for outplanting. Nonetheless, the consistently high proportion of straight stems across provenances suggests that this trait may also be influenced by genetic factors and initial morphological quality expressed at the nursery stage.

This pattern highlights the silvicultural relevance of stem architecture and reinforces the importance of parental selection in breeding and domestication programs. While the straight stems observed in The Tundo and The Victoria may reflect both provenance effects and the selection of vigorous individuals at the nursery stage, the results do not allow us to distinguish genetic heritability from environmental or management influences. Nonetheless, these findings are consistent with those of [32], who emphasized the direct relationship between stem form and wood quality.

In terms of growth performance, the basal diameter and total height of plants were influenced by both stratum and provenance. Individuals from The Tundo reached an average diameter of 11.80 mm and 49.29 cm in height, while those from The Victoria showed slightly lower values (11.35 mm and 48.14 cm, respectively).

While these figures are consistent with reports by [30] (12.42 mm Bd; 39.68 cm Th), it was observed that plants grown in open pastures showed reduced growth compared to those in secondary or riparian forests. This is likely due to increased exposure to radiation, limited soil cover, and competition with grasses. Ref. [25] also reported that seedlings surrounded by taller vegetation exhibited better height and diameter growth, likely due to moderated microclimates and reduced competition. These results highlight the importance of considering the interactions between the origin of the plant material and the applied treatments, especially when pre-germination methods are not used, as inherent differences in seed quality or adaptation among localities may become evident.

Collectively, these findings underscore the importance of carefully selecting planting environments and seed sources. Forested sites—particularly secondary and riparian forests—promote better survival and early development, while provenances such as The Tundo may offer advantages in structural form and growth under diverse conditions. Such insights are crucial for designing effective silvicultural strategies and optimizing reforestation outcomes with *J. neotropica* [33].

5. Conclusions

The high physical purity percentage of *Juglans neotropica* Diels seeds (98%) confirms efficient handling and processing, promoting the production of certified seeds and the planning of reforestation programs.

Seed viability is maintained for up to six months but declines with moisture loss exceeding 2%. Implementing optimal storage conditions with controlled temperature and humidity is essential to extending viability beyond this period.

Germination rates vary depending on seed origin and environmental conditions, highlighting the need to select seeds with higher adaptive potential. Additionally, the highest germination percentages for *J. neotropica* were obtained through the control treatment (no pre-germination), immersion in boiling water, mechanical cracking with a hammer, and immersion in water with sunlight exposure. All showed statistically significant differences compared to the other methods evaluated.

However, their effectiveness varied depending on the seed provenance, highlighting an interaction between treatment and locality of origin. This underscores the need to tailor propagation strategies to both the biological characteristics of the seed and the applied treatment. Additionally, nursery conditions—partial shade, controlled irrigation, and well-drained substrate—proved essential for successful seedling establishment. These findings provide practical guidelines for optimizing propagation protocols in restoration and forest production programs.

J. neotropica demonstrated strong establishment capacity during the first year of planting, with an overall survival rate of 92%. The highest survival occurred in secondary forest conditions (100%), suggesting that this environment provides optimal conditions for early establishment. In comparison, riparian forest and grassland sites showed slightly lower survival rates (92% and 84%, respectively), indicating that microenvironmental factors significantly influence planting success. These findings support prioritizing forested sites—particularly secondary forests—for restoration efforts involving this species.

Fertilization played a decisive role in the establishment of *J. neotropica*, particularly under unfavorable conditions such as grasslands. The most effective doses were 200 g and 250 g per plant of both NPK (13-40-13) and urea, which achieved 100% survival across all evaluated sites. These results demonstrate that appropriate fertilization not only enhances early survival but also mitigates site limitations related to soil and microclimate. Therefore, strategic fertilization should be considered an essential practice in ecological restoration and reforestation programs involving this species.

J. neotropica exhibited excellent structural quality at 12 months of establishment, with 99%–100% of individuals displaying straight stems across all evaluated strata and localities. No sinuous or inclined individuals were recorded, and forked stems were virtually absent (0.67% in only one site). These results indicate that, under proper management conditions, this species has strong potential for high-quality timber production, reinforcing its value in both ecological restoration and productive reforestation programs.

Growth in basal diameter and total height was highest in secondary forests and from The Tundo, suggesting better adaptation of the plants from this locality. However, statistical analysis indicated no significant differences between localities or fertilization treatments. highlighting the importance of site conditions in species development.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f16071141/s1, Table S1: Complete statistical dataset showing the interaction between locality, fertilization treatment, and stratum on basal diameter (BD) and total height (TH) of *J. neotropica* plants across 55 treatment combinations. Includes means, standard errors, and Tukey groupings (α = 0.05) for each combination.

Author Contributions: Conceptualization, investigation, methodology, writing—review and editing, B.P.-H.; formal analysis and writing—original draft, S.P.-L. and D.P.-C. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

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Conflicts of Interest: The authors declare no conflicts of interest.

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5. DISCUSIÓN GENERAL

5.1 INTRODUCCIÓN

5.1.1 Justificación del enfoque por compendio

La presentación de esta Tesis Doctoral como compendio de publicaciones responde a una estrategia metodológica que permite abordar de manera holística y profunda el estudio de *Juglans neotropica* Diels, una especie forestal de distribución restringida en los Andes tropicales, cuya conservación y manejo sostenible requieren enfoques interdisciplinarios. Este formato, contemplado por la Universidad de Santiago de Compostela, permite integrar investigaciones publicadas en revistas científicas indexadas, dotando a la Tesis Doctoral de validez empírica, visibilidad académica y coherencia temática.

El enfoque por compendio se justifica no solo por la calidad científica de los artículos incluidos, sino también por la necesidad de abordar múltiples dimensiones ecológicas y silviculturales de la especie. Como señalan Niinemets (2010) y Hasenauer (2006), los árboles forestales responden a múltiples estresores ambientales, y su estudio requiere metodologías que integren datos estructurales, fenológicos, genéticos y climáticos. En este sentido, el compendio permite articular estudios que, aunque distintos en su enfoque específico, convergen en el objetivo común de comprender la dinámica ecológica de *J. neotropica* en el sur de Ecuador.

Además, el formato por compendio facilita la transferencia del conocimiento generado hacia la comunidad científica y los tomadores de decisiones. Al estar los artículos sometidos a revisión por pares y publicados en revistas de acceso abierto como Agronomy, Diversity y Forests, se garantiza la transparencia metodológica y la replicabilidad de los resultados (Leal Carretero, 2017). Esta característica es especialmente relevante en el contexto de especies amenazadas, donde la disponibilidad de información científica confiable puede incidir directamente en las políticas de conservación y restauración ecológica (IUCN, 2022; Bellard et al., 2012).

Desde una perspectiva formativa, el compendio también refleja el proceso de maduración académica del doctorando, quien ha participado activamente en todas las etapas de investigación, redacción y publicación. Este proceso, además de fortalecer las competencias investigativas, permite establecer redes de colaboración científica y posicionar la investigación forestal ecuatoriana en el contexto internacional (Gómez-Guerrero et al., 2021).

El enfoque por compendio de publicaciones responde a la necesidad de abordar la complejidad ecológica de *J. neotropica* desde múltiples escalas: desde la estructura poblacional en bosques naturales y plantaciones, hasta la respuesta fenológica frente a gradientes climáticos y edáficos, y la variabilidad fenotípica en vivero y campo. Esta integración temática permite construir una narrativa científica coherente, que dota de unidad a la Tesis Doctoral y contribuye al conocimiento aplicado en silvicultura tropical.

En conjunto, los tres artículos permiten construir una visión integral de *J. neotropica* como especie clave en los bosques montanos del sur de Ecuador, aportando evidencia científica para su conservación, manejo y aprovechamiento sostenible.

5.2 DISCUSIÓN

La integración de los tres artículos científicos incluidos en esta Tesis Doctoral permite construir una narrativa científica sólida sobre la ecología funcional, la variabilidad fenotípica y la dinámica fenológica de *J. neotropica* en el sur de Ecuador. Cada estudio aporta evidencia científica basada en datos empíricos obtenidos mediante enfoques complementarios, que al ser analizados de forma conjunta revelan patrones ecológicos, silviculturales y adaptativos de gran relevancia para la conservación y el manejo sostenible de esta especie en peligro de extinción.

5.2.1 Ocurrencia y distribución espacial

El primer artículo, titulado *Natural and Artificial Occurrence, Structure, and Abundance of Juglans neotropica Diels in Southern Ecuador*, publicado en la revista *Agronomy*, fue elaborado por Palacios-Herrera et al. (2023). Este estudio abordó la distribución natural y artificial de la especie en seis localidades de las provincias de Loja y Zamora Chinchipe. El estudio identificó patrones de agregación espacial, diferencias en densidad entre bosques naturales y plantaciones, y destacó la influencia de factores topográficos en la ocurrencia de la especie. Se emplearon índices estructurales como el de Morisita y se analizaron variables dendrométricas, evidenciando que *J. neotropica* presenta una distribución no aleatoria, con preferencia por sectores específicos del ecosistema, especialmente en altitudes entre 2200 y 3000 m s.n.m.

Palacios-Herrera et al. (2023) documentaron la ocurrencia natural y artificial de *J. neotropica* en seis localidades de las provincias de Loja y Zamora Chinchipe, excluyendo la provincia de El Oro. Se identificaron áreas con más de 5.000 m² donde la especie se ha establecido de forma natural o mediante plantaciones, lo que representa un avance significativo en el conocimiento de su distribución geográfica. Los hallazgos en sitios como Cerro El Zañe, La Victoria, La Merced y El Tibio generaron nuevos registros de la especie, ampliando su rango de distribución conocido y evidenciando su capacidad de adaptación a condiciones altitudinales diversas (entre 1400 y 2800 m s.n.m.).

Estos hallazgos coinciden con estudios previos que señalan la gregariedad relativa de las especies del género *Juglans* en bosques maduros, lo que explica su escasa representación en ecosistemas naturales fragmentados (García, 2002). La agregación espacial observada, medida mediante el índice de Morisita ($I > 1$), indica una distribución no aleatoria, influenciada por microhábitats y patrones de dispersión de semillas cercanos al árbol madre (Morláns & María, 2014). Este comportamiento es común en especies que presentan limitaciones en la dispersión anemócora o zoócora, y que dependen de condiciones edáficas y topográficas específicas para su establecimiento (Xue et al., 2024).

La identificación de nuevos sitios de ocurrencia natural y artificial no solo amplía el conocimiento biogeográfico de la especie, sino que también permite establecer zonas prioritarias para su conservación *in situ* y *ex situ*. En este sentido, la presencia de *J. neotropica* en áreas con fuerte pendiente y cobertura vegetal residual sugiere que la especie puede actuar como indicador ecológico de bosques montanos resilientes, tal como lo han propuesto estudios sobre especies arbóreas de distribución restringida en los Andes tropicales (Githumbi et al., 2025).

5.2.1.1 Estructura poblacional y atributos dendrométricos

Los estudios revelaron que *J. neotropica* presenta una estructura poblacional variable según el tipo de ecosistema. En bosques naturales como El Tibio y Tundo, se observaron individuos con diámetros a la altura del pecho (DAP) superiores a 90 cm y alturas de hasta 30 m, lo que evidencia un alto potencial de crecimiento vertical (Barreto & Herrera, 1990). En contraste, las plantaciones como La Argelia, aunque con menor extensión (0.7 ha), presentaron alta densidad de individuos por hectárea, lo que sugiere un manejo silvicultural exitoso y adaptación a las condiciones locales (Palacios-Herrera et al., 2023).

La edad estimada de los individuos varió entre 11,8 y 355 años, con los árboles más longevos ubicados en Tundo. Esta diversidad etaria se asocia con una mayor resiliencia fenológica, como lo señalan Zuo et al. (2024), quienes destacan que las estructuras de edad heterogéneas permiten una mejor respuesta ante variabilidad climática. Además, la presencia de individuos jóvenes en sitios como La Merced y La Argelia indica procesos de regeneración natural y artificial que podrían ser aprovechados en programas de restauración ecológica.

El análisis de la estructura poblacional también revela que la especie presenta una tendencia a la agregación en sectores específicos del ecosistema, lo que puede estar relacionado con la dispersión limitada de semillas y la preferencia por microhábitats con condiciones edáficas favorables. Este patrón ha sido observado en otras especies de *Juglans* en América Latina, como *J. olanchana* en Honduras (García, 2002), y sugiere que la planificación silvicultural debe considerar la heterogeneidad espacial de las poblaciones para garantizar su sostenibilidad.

5.2.2 Dinámica fenológica y sensibilidad climática

El segundo artículo, titulado *Phenological Variation of Native and Reforested Juglans neotropica Diels in Response to Edaphic and Orographic Gradients in Southern Ecuador*, publicado en la revista *Diversity* por Palacios-Herrera et al. (2025a), se enfocó en la dinámica fenológica de la especie en relación con variables climáticas (temperatura, precipitación, humedad relativa) y edáficas (humedad del suelo, pH, capacidad de intercambio catiónico). El estudio reveló que la fenología reproductiva de *J. neotropica* está modulada por la altitud, la pendiente y la disponibilidad hídrica, con eventos de floración y fructificación más sincronizados en sitios con mayor estabilidad edáfica. Se destaca la influencia de fenómenos globales como El Niño en la variabilidad fenológica, y se propone la incorporación de sensores microclimáticos para mejorar los modelos predictivos.

Palacios-Herrera et al. (2025a) demostraron que la fenología de *J. neotropica* estaba fuertemente influenciada por variables climáticas como temperatura, precipitación y humedad relativa. Se confirmó un aumento sostenido de la temperatura en la región Loja–Zamora, lo que ha generado adelantos en la floración y maduración de frutos, en concordancia con estudios regionales (León Baque et al., 2021; Tang et al., 2023). Este fenómeno se asocia con el cambio climático global y con eventos como El Niño, que intensifican las anomalías térmicas y pluviométricas en la región (Vincenti et al., 2016).

La humedad relativa mostró variaciones altitudinales, con valores inferiores al 60% en zonas como Sozoranga, lo que afectó la sincronía reproductiva y la expansión foliar. Estos resultados coinciden con los de Park et al. (2024) y Dong & Wang (2024), quienes señalan que la disminución de la humedad atmosférica puede alterar los ciclos fenológicos en especies de hoja ancha. La interacción entre temperatura, humedad y pendiente genera efectos no lineales en el inicio y fin de la temporada de crecimiento, lo que se traduce en divergencias fenológicas entre laderas sombreadas y expuestas (Tian et al., 2025).

La humedad edáfica a un metro de profundidad se mantiene estable en sitios como Zañe y Merced (>60%), lo que favoreció la expresión fenológica sincronizada. Esta relación entre humedad del suelo y fenología ha sido documentada por Cui et al. (2022) y Zhang et al. (2024), quienes destacan el papel modulador de la disponibilidad hídrica en el comportamiento reproductivo de especies de bosques montanos. La estabilidad hídrica subterránea, especialmente en años con picos de humedad (1983, 1989, 1998), coincide con eventos fenológicos intensos, lo que sugiere la existencia de umbrales ecológicos relevantes para la planificación silvicultural.

5.2.2.1 Influencia edáfica y topográfica

Los atributos físicos y químicos del suelo también incidieron en la viabilidad y fenología de *J. neotropica*. Localidades como La Victoria y Zañe presentaron suelos con pH neutro (7,0), alta capacidad de intercambio catiónico (22–25 meq/100 g) y fertilidad media, lo que se asocia con mayor éxito en la expresión fenológica y el crecimiento estructural (Meng et al., 2023; Weil & Brady, 2016). En contraste, sitios como La Merced y El Tibio presentaron suelos ácidos (pH 6,75), baja fertilidad y textura arcillosa, lo que podría limitar el desarrollo radicular y la retención hídrica.

La pendiente del terreno (>40%) se reveló como un factor determinante en la distribución de la especie. Todas las microcuencas estudiadas superaron el 45% de inclinación, lo que influye en el drenaje, la erosión y la variabilidad microclimática (Liang et al., 2024). Aunque no se correlacionaron directamente los rasgos fenológicos con la pendiente, se sugiere que estas zonas podrían representar nichos ecológicos prioritarios para la conservación. La orientación de la pendiente, la cobertura vegetal y la estructura del dosel también modulan el microclima, afectando la evapotranspiración y la radiación solar (Tian et al., 2025).

5.2.3 Variabilidad fenotípica y desempeño por procedencia

El tercer artículo, titulado *Phenotypic Variability of Juglans neotropica Diels from Different Provenances During Nursery and Plantation Stages in Southern Ecuador*, publicado en la revista *Forests* por Palacios-Herrera et al. (2025b), analiza el desempeño de la especie en vivero y campo según tres procedencias: Tundo, Victoria y Argelia. Se evalúan variables como germinación, crecimiento, forma del fuste y supervivencia, encontrando diferencias significativas entre las procedencias. Las semillas de Tundo y Victoria muestran mayor vigor y adaptabilidad, mientras que Argelia presenta menor desarrollo inicial. Estos resultados resaltan la importancia de la selección de procedencias en programas de restauración ecológica y manejo forestal, y se propone el diseño de ensayos silviculturales con material genético contrastante.

Palacios-Herrera et al. (2025b) evidenciaron que la procedencia de la semilla influyó significativamente en el desempeño de *J. neotropica* en vivero y campo. Las semillas de Tundo y Victoria presentaron un mayor vigor, con tasas de germinación entre 40% y 80%, y un desarrollo superior en altura y diámetro basal. Estos resultados coinciden con estudios sobre la influencia del origen genético en el crecimiento inicial de especies forestales (Leibing et al., 2013; Martinez & Hernández, 2004).

La forma del fuste, evaluada como rectitud y dominancia, fue superior en individuos de Tundo (100%) y Victoria (99.33%), lo que sugiere una combinación de factores genéticos y selección morfológica en vivero. La supervivencia en campo alcanzó el 92% en promedio, con valores más altos en bosques secundarios y riparios, lo que confirma la importancia del entorno ecológico en el establecimiento exitoso (Haase et al., 2021).

La variabilidad fenotípica observada entre procedencias también se reflejó en el número de hojas, el tamaño de la semilla y la respuesta a tratamientos pregerminativos. Estos rasgos, determinados por la interacción de factores genéticos y ambientales de origen, deben ser considerados en programas de restauración ecológica, especialmente en territorios con alta variabilidad climática y edáfica.

5.3 INTEGRACIÓN CONCEPTUAL

La integración conceptual de los tres artículos incluidos en esta Tesis Doctoral permite establecer conexiones entre los distintos niveles de análisis abordados: la estructura poblacional, la dinámica fenológica, la variabilidad fenotípica y los factores ambientales que modulan el comportamiento ecológico de *J. neotropica*. Esta sección busca articular los hallazgos desde una perspectiva sistémica, reconociendo que la especie responde a una compleja interacción entre factores bióticos y abióticos, y que su estudio requiere enfoques multiescalares y transdisciplinarios.

5.3.1 Relación entre estructura poblacional y fenología

La estructura poblacional condiciona la expresión fenológica de *J. neotropica*. Localidades como El Tundo y La Victoria mostraron mayor sincronía fenológica en brotación y floración, lo que refleja un desempeño reproductivo más consistente bajo gradientes ambientales favorables. En contraste, La Argelia presentó patrones fenológicos diferenciados, evidenciando la influencia de la heterogeneidad ecológica en la dinámica reproductiva.

Los resultados obtenidos en los tres estudios revelaron una estrecha relación entre la estructura poblacional de *J. neotropica* y su comportamiento fenológico. En localidades como Tundo y Victoria, donde se registraron individuos de gran porte (DAP > 90 cm) y edades superiores a los 300 años, se observaron fenofases más sincronizadas y prolongadas, especialmente en floración y fructificación (Palacios-Herrera et al., 2025a). Esta asociación sugiere que los árboles más longevos, con sistemas radiculares más profundos y mayor capacidad de almacenamiento de carbono, actúan como estabilizadores ecológicos frente a la variabilidad climática (Zuo et al., 2024; Silvestro et al., 2025).

La diversidad estructural, entendida como la coexistencia de múltiples clases diamétricas y etarias, parece favorecer la resiliencia fenológica de las poblaciones. Este patrón ha sido documentado en bosques templados y tropicales, donde la heterogeneidad estructural permite amortiguar los efectos de eventos extremos como sequías o heladas (Allen et al., 2010; Reichstein et al., 2013). En el caso de *J. neotropica*, la coexistencia de individuos jóvenes y adultos en sitios como Zañe y Merced podría explicar la persistencia de la especie en paisajes fragmentados y sometidos a presión antrópica.

5.3.2 Influencia de los factores edáficos y topográficos en la expresión fenológica

La expresión fenológica de *J. neotropica* está modulada por una combinación de factores edáficos y topográficos que interactúan con las condiciones climáticas locales. Los suelos con alta capacidad de intercambio catiónico (CEC), pH neutro y fertilidad media, como los encontrados en Victoria y Zañe, se asociaron con una mayor sincronía en las fenofases reproductivas y vegetativas (Palacios-Herrera et al., 2025a). Estos atributos edáficos permiten una mejor retención de nutrientes esenciales como nitrógeno, fósforo y potasio, que son críticos durante la floración y el desarrollo de frutos (Marschner, 2011; Weil & Brady, 2016).

La pendiente del terreno (>45%) también influye en la distribución y comportamiento fenológico de la especie. Aunque no se realizó un análisis específico de la orientación de las laderas, estudios previos han demostrado que las pendientes expuestas al norte o sur pueden generar microclimas diferenciados, afectando la temperatura del suelo, la radiación solar y la evapotranspiración (Tian et al., 2025; Liang et al., 2024). En este contexto, la persistencia de *J. neotropica* en zonas de fuerte pendiente sugiere una adaptación morfofisiológica que le permite tolerar condiciones de drenaje rápido, erosión y estrés hídrico.

La interacción entre suelo y pendiente genera lo que algunos autores denominan "envoltura edáfica-topográfica", es decir, un conjunto de condiciones que definen el nicho ecológico de la especie (Xue et al., 2024). En el caso de *J. neotropica*, esta envoltura parece estar caracterizada por suelos alfisoles, pendientes superiores al 40%, pH neutro a ligeramente ácido, y cobertura vegetal residual, lo que delimita su distribución potencial en los Andes tropicales (Palacios-Herrera et al., 2025a).

5.3.3 Procedencia genética y plasticidad fenotípica

La procedencia genética influye directamente en la expresión de los rasgos fenotípicos de *J. neotropica*. Los individuos provenientes de El Tundo y La Victoria mostraron mayor desempeño en altura y supervivencia, mientras que La Argelia presentó valores diferenciados, reflejando la interacción entre origen genético y condiciones ambientales.

La variabilidad fenotípica observada entre las procedencias estudiadas (Tundo, Victoria y Argelia) revela que *J. neotropica* posee una notable plasticidad adaptativa, especialmente durante las etapas de vivero y establecimiento en campo (Palacios-Herrera et al., 2025b). Las diferencias en germinación, crecimiento, forma del fuste y número de hojas entre procedencias sugieren que el origen genético influye en la expresión de rasgos funcionales clave para la supervivencia y el desempeño silvícola. Esta plasticidad fenotípica ha sido ampliamente documentada en especies forestales de distribución amplia, donde las poblaciones locales desarrollan adaptaciones específicas a las condiciones ambientales de su sitio de origen (Nicotra et al., 2010; Hansen & Pelabon, 2021). En el caso de *J. neotropica*, las semillas provenientes de Tundo y Victoria mostraron mayor vigor y rectitud del fuste, lo que podría estar relacionado con procesos de selección natural en ambientes más estables y menos perturbados. La plasticidad observada también tiene implicaciones para la restauración ecológica y el mejoramiento genético. La selección de procedencias con alto desempeño estructural y fenológico permite optimizar los programas de reforestación, especialmente en zonas vulnerables al cambio climático. Además, el diseño de ensayos silviculturales con material genético contrastante puede contribuir a identificar genotipos con mayor tolerancia a estrés hídrico, térmico o edáfico (Ektvedt et al., 2025).

En conjunto, estos resultados confirman que la plasticidad fenotípica de J. neotropica constituye un mecanismo de resiliencia forestal, capaz de amortiguar los efectos de la variabilidad ambiental y de sostener la persistencia poblacional en escenarios de fragmentación y cambio climático (Allen et al., 2010; Reichstein et al., 2013).

5.3.4 Interacciones multiescalares y enfoque ecosistémico

La integración de los tres niveles de análisis —estructura poblacional, fenología y rasgos fenotípicos— permite comprender la respuesta adaptativa de *Juglans neotropica* en distintos contextos ecológicos. La estructura poblacional define la base demográfica y la capacidad de resiliencia de las comunidades; la fenología refleja la sincronía temporal de los procesos reproductivos y su sensibilidad frente a gradientes ambientales; mientras que los rasgos fenotípicos cuantifican la plasticidad morfológica y funcional de los individuos en vivero y plantación.

Esta visión multiescalar evidencia que la especie responde de manera integrada a factores genéticos, edáficos y climáticos, lo que refuerza su potencial como recurso estratégico para programas de restauración ecológica en ecosistemas montanos de alta fragilidad. La combinación de individuos longevos con alta sincronía fenológica y procedencias con rasgos fenotípicos vigorosos constituye un modelo de manejo forestal sostenible, capaz de enfrentar escenarios de cambio climático y fragmentación del paisaje. En consecuencia, la tesis aporta un marco conceptual y técnico que vincula la dinámica poblacional con la variabilidad fenológica y fenotípica, ofreciendo criterios aplicables tanto a la conservación *in situ* como al diseño de ensayos silviculturales orientados al mejoramiento genético y la resiliencia ecosistémica.

Los resultados de los tres estudios evidencian que el comportamiento ecológico de *J. neotropica* no puede ser explicado por una sola variable, sino que responde a interacciones multiescalares entre clima, suelo, topografía, estructura poblacional y genética. Esta complejidad requiere un enfoque ecosistémico que considere simultáneamente los procesos biofísicos, ecológicos y silviculturales que afectan a la especie. Por ejemplo, la sincronía fenológica observada en Tundo y Victoria no solo se explica por la edad de los individuos o la calidad del suelo, sino también por la estabilidad microclimática, la cobertura vegetal y la historia de uso del suelo. De igual forma, la agregación espacial en La Argelia puede estar influenciada por prácticas de manejo forestal, densidad de plantación y selección de material genético.

Este enfoque ecosistémico ha sido promovido por autores como Anderegg et al. (2020) y Lindner et al. (2010), quienes destacaron que la resiliencia de los bosques frente al cambio climático depende de la capacidad de integrar múltiples dimensiones del funcionamiento forestal. En el caso de *J. neotropica*, esta integración permite identificar sitios prioritarios para la conservación, diseñar estrategias de manejo adaptativo y proyectar escenarios de restauración bajo condiciones de alta incertidumbre ambiental.

5.4 IMPLICACIONES ECOLÓGICAS Y SILVICULTURALES

Los resultados integrados de los tres artículos incluidos en esta Tesis Doctoral permiten identificar una serie de implicaciones ecológicas y silviculturales de gran relevancia para la conservación, restauración y manejo sostenible de *J. neotropica* en los Andes tropicales del sur de Ecuador. Estas implicaciones se derivan de la comprensión profunda de los patrones de ocurrencia, estructura poblacional, variabilidad fenotípica y dinámica fenológica de la especie, y se articulan en torno a tres ejes fundamentales: la conservación adaptativa, la planificación silvicultural diferenciada y el diseño de estrategias de restauración ecológica resiliente.

5.4.1 Conservación adaptativa de una especie amenazada

J. neotropica ha sido categorizada como “En peligro” por la Unión Internacional para la Conservación de la Naturaleza (IUCN, 2022), debido a la reducción de sus poblaciones naturales, la fragmentación de su hábitat y la presión antrópica derivada de actividades como la ganadería extensiva, la agricultura migratoria y la expansión urbana (Palacios-Herrera et al., 2023). En este contexto, los hallazgos de esta Tesis Doctoral aportan información crítica para el diseño de estrategias de conservación adaptativa, basadas en el conocimiento empírico de la ecología funcional de la especie.

La identificación de localidades con alta densidad poblacional, diversidad estructural y sincronía fenológica, como Tundo y Victoria, permite establecer zonas núcleo para la conservación *in situ*, que podrían funcionar como reservorios genéticos y centros de dispersión natural. Estas áreas presentan condiciones edáficas y microclimáticas favorables, como suelos con alta capacidad de intercambio catiónico, pH neutro y humedad edáfica estable, que favorecen el crecimiento y la reproducción de la especie (Weil & Brady, 2016; Marschner, 2011).

Además, la variabilidad fenotípica observada entre procedencias sugiere que ciertas poblaciones locales han desarrollado adaptaciones específicas a sus entornos, lo que refuerza la necesidad de conservar la diversidad genética intraespecífica como mecanismo de resiliencia frente al cambio climático (Nicotra et al., 2010; Hansen & Pelabon, 2021). La conservación de esta variabilidad es esencial para garantizar la capacidad de respuesta de la especie ante escenarios de estrés hídrico, térmico o edáfico, especialmente en zonas de transición altitudinal y paisajes fragmentados.

5.4.2 Planificación silvicultural diferenciada y basada en evidencia

Los resultados de los estudios sobre estructura poblacional, fenología y desempeño por procedencia permiten establecer criterios técnicos para la planificación silvicultural diferenciada de *J. neotropica*, adaptada a las condiciones específicas de cada sitio. Esta planificación debe considerar variables como altitud, pendiente, tipo de suelo, cobertura vegetal, orientación de la ladera y procedencia genética del material vegetal, con el fin de optimizar el crecimiento, la supervivencia y la productividad de la especie.

Por ejemplo, en sitios con pendientes superiores al 45% y suelos de fertilidad media, como Zañe y Victoria, se recomienda el uso de procedencias con alto vigor inicial y buena arquitectura del fuste, como Tundo y Victoria, que han demostrado mayor adaptabilidad y desempeño estructural (Palacios-Herrera et al., 2025b). En contraste, en zonas con suelos ácidos y baja fertilidad, como El Tibio y La Merced, se sugiere implementar prácticas de fertilización orgánica y manejo del micro-sitio para mejorar las condiciones de establecimiento.

La incorporación de calendarios fenológicos en la planificación silvicultural permite ajustar las actividades de recolección de semillas, producción de plántulas, establecimiento de viveros y plantación en campo, en función de las ventanas óptimas de floración y fructificación. Estos calendarios, validados empíricamente en los estudios incluidos en esta Tesis Doctoral, constituyen herramientas operativas para mejorar la eficiencia de los programas de reforestación y restauración ecológica (Palacios-Herrera et al., 2025a).

Asimismo, la selección de sitios con alta humedad edáfica y estabilidad microclimática como zonas prioritarias para la plantación puede aumentar significativamente las tasas de supervivencia y crecimiento, como lo han demostrado estudios sobre especies montanas en ambientes tropicales (Cui et al., 2022; Zhang et al., 2024). La planificación silvicultural debe incorporar estos criterios para maximizar el éxito de las intervenciones y reducir los costos asociados al mantenimiento y reposición de plantas.

5.4.3 Restauración ecológica resiliente y basada en procedencias

La restauración ecológica de los bosques montanos donde habita *J. neotropica* requiere enfoques resilientes que integren el conocimiento ecológico, genético y silvicultural de la especie. Los resultados de esta Tesis Doctoral permiten diseñar estrategias de restauración basadas en la selección de procedencias adaptadas, la caracterización edáfica y topográfica de los sitios, y la sincronización de las actividades de propagación y plantación con los ciclos fenológicos locales.

La alta supervivencia observada en bosques secundarios y riparios (hasta 100%) indica que estos ecosistemas ofrecen condiciones favorables para el establecimiento de *J. neotropica*, y pueden ser utilizados como zonas de restauración piloto. La compatibilidad entre el origen del material vegetal y las condiciones del sitio de plantación es un factor clave para el éxito de la restauración, como lo señalan estudios sobre pinos tropicales y especies de hoja ancha (Leibing et al., 2013; Haase et al., 2021).

Además, la variabilidad fenotípica observada en vivero y campo permite identificar genotipos con mayor plasticidad adaptativa, que podrían ser utilizados en ensayos de mejoramiento genético y producción de semilla certificada. La implementación de rodales semilleros con individuos seleccionados por su desempeño estructural y fenológico puede contribuir a garantizar la calidad del material vegetal y la sostenibilidad de los programas de restauración (Cornejo Oviedo et al., 2009; Barner et al., 1992).

La restauración ecológica también debe considerar la conectividad paisajística y la reconstitución de corredores ecológicos que faciliten el flujo genético entre poblaciones fragmentadas. La fragmentación del hábitat ha sido identificada como una de las principales amenazas para la sincronía reproductiva de *J. neotropica*, lo que refuerza la necesidad de restaurar la continuidad ecológica del paisaje (Toro Vanegas & Roldán Rojas, 2018; Ramirez & Kallarackal, 2021).

5.5 LIMITACIONES METODOLÓGICAS COMUNES

A pesar de la solidez empírica y la rigurosidad técnica de los tres estudios que conforman esta Tesis Doctoral, es necesario reconocer una serie de limitaciones metodológicas que condicionaron el alcance de los resultados y que deben ser consideradas en futuras investigaciones. Estas limitaciones se relacionan principalmente con restricciones legales y éticas para el muestreo destructivo, el uso de datos interpolados en lugar de mediciones *in situ*, la accesibilidad en terrenos de alta pendiente, y la escasa disponibilidad de estudios previos sobre la especie en la región sur del Ecuador.

5.5.1 Restricciones legales para el muestreo destructivo

Una de las principales limitaciones enfrentadas en los estudios fue la imposibilidad de realizar muestreos destructivos en individuos vivos de *J. neotropica*, debido a su categorización como especie "En peligro" por la UICN (2022) y por el Ministerio del Ambiente, Agua y Transición Ecológica de Ecuador (MAE, 2015). Esta normativa prohíbe expresamente la tala o extracción de muestras de especies amenazadas, lo que restringió la aplicación de técnicas dendrocronológicas convencionales para la estimación precisa de la edad y el crecimiento anual.

Como alternativa, se recurrió al análisis de árboles caídos de forma natural en zonas de alta pendiente y exposición al viento, lo que permitió realizar conteos de anillos de crecimiento en 12 individuos de referencia (Palacios-Herrera et al., 2025a). Aunque se aplicaron protocolos rigurosos para garantizar la representatividad de las muestras, esta estrategia presenta limitaciones inherentes, como la posible alteración de la estructura poblacional por eventos de caída no aleatorios y la dificultad para extrapolar los resultados a toda la población.

La restricción al muestreo destructivo también limitó la posibilidad de realizar análisis isotópicos y radiocarbónicos más detallados, que podrían haber aportado información sobre la sensibilidad de la especie a eventos climáticos extremos como El Niño, tal como lo han demostrado estudios en Perú (Ektvedt et al., 2025). Esta limitación metodológica subraya la necesidad de desarrollar técnicas no destructivas para el estudio de especies amenazadas, como el uso de tomografía de resistencia eléctrica, análisis de imágenes hiperespectrales o modelado de crecimiento basado en series temporales de diámetro.

5.5.2 Uso de datos interpolados en lugar de sensores *in situ*

Otra limitación importante fue el uso de datos climáticos y edáficos interpolados, obtenidos de estaciones meteorológicas regionales y modelos de estimación espacial, en lugar de mediciones directas mediante sensores instalados en los sitios de estudio. Aunque se aplicaron metodologías de interpolación validadas y se utilizaron series temporales extensas (1970–2024), esta aproximación puede ocultar variaciones microclimáticas relevantes, especialmente en zonas montanas con alta heterogeneidad topográfica (Ochoa et al., 2016; Farfán, 2018).

La ausencia de sensores de temperatura, humedad relativa y humedad edáfica en tiempo real impidió capturar fluctuaciones de corto plazo que podrían tener efectos significativos en la fenología de *J. neotropica*. Por ejemplo, eventos de sequía episódica o lluvias intensas pueden alterar la sincronía reproductiva, la expansión foliar y la caída de frutos, pero estas dinámicas no pueden ser detectadas con precisión mediante datos interpolados (Dong & Wang, 2024; Tian et al., 2025).

Asimismo, la falta de sensores de humedad del suelo a múltiples profundidades limitó la capacidad para establecer correlaciones entre la disponibilidad hídrica en el perfil edáfico y la expresión fenológica. Estudios recientes han demostrado que la humedad subterránea, especialmente en el rango de 80–100 cm, tiene un efecto modulador sobre la fenología en ecosistemas montanos (Cui et al., 2022; Zhang et al., 2024). La incorporación de redes de sensores microclimáticos, como las propuestas por Klinges et al. (2025), permitiría superar esta limitación y mejorar la resolución de los modelos ecológicos.

5.5.3 Accesibilidad limitada en terrenos de alta pendiente

La topografía abrupta de las localidades estudiadas, con pendientes superiores al 45%, representó una limitación logística para el monitoreo fenológico y la toma de datos estructurales. En varios casos, la inaccesibilidad física de ciertos sectores impidió realizar observaciones continuas, especialmente durante la temporada de lluvias, cuando el riesgo de deslizamientos y caídas aumenta significativamente (Palacios-Herrera et al., 2025a).

Esta limitación afectó la representatividad espacial de los datos, ya que las observaciones se concentraron en zonas accesibles, lo que podría generar sesgos en la caracterización fenológica y estructural de las poblaciones. Además, la falta de análisis de orientación de las pendientes (e.g., norte vs. sur) impidió evaluar el efecto de la exposición solar en la fenología, una variable que ha demostrado ser crítica en estudios de bosques templados y tropicales (Liang et al., 2024; Tian et al., 2025).

Para superar esta limitación, se recomienda el uso de tecnologías de monitoreo remoto, como drones equipados con cámaras multiespectrales, sensores LiDAR y sistemas de posicionamiento GPS, que permiten acceder a zonas de difícil tránsito y obtener datos de alta resolución sin comprometer la seguridad del equipo de campo.

5.5.4 Escasa disponibilidad de estudios previos sobre la especie en la región

La limitada disponibilidad de estudios previos sobre *J. neotropica* en los bosques naturales del sur de Ecuador representó una restricción para la comparación de resultados y la contextualización regional de los hallazgos. Aunque existen investigaciones sobre la especie en otras zonas andinas, como Colombia, Perú y Honduras (García, 2002; Toro Vanegas & Roldán Rojas, 2018; Ektvedt et al., 2025), la información específica para Loja y Zamora Chinchipe es escasa y fragmentaria.

Esta carencia obligó a desarrollar criterios interpretativos basados en observación empírica y análisis contextual, lo que aumenta el riesgo de subjetividad en la interpretación de ciertos patrones ecológicos. Además, la falta de referencias locales dificultó la validación de los calendarios fenológicos propuestos, así como la comparación de tasas de crecimiento, productividad y regeneración natural.

Para abordar esta limitación, se propone la creación de una base de datos regional sobre *J. neotropica*, que integre información estructural, fenológica, genética y climática de múltiples localidades, y que pueda ser utilizada como referencia para futuras investigaciones, planificación silvicultural y toma de decisiones en conservación.

5.6 PROPUESTAS PARA FUTURAS INVESTIGACIONES

A partir de los hallazgos integrados en esta Tesis Doctoral, se identifican múltiples líneas de investigación que pueden fortalecer el conocimiento científico sobre *J. neotropica* y contribuir al desarrollo de estrategias de conservación, restauración y manejo forestal adaptativo en los Andes tropicales. Estas propuestas se articulan en torno a la necesidad de superar las limitaciones metodológicas identificadas, profundizar en los mecanismos ecofisiológicos de la especie, incorporar herramientas tecnológicas de monitoreo y modelado, y establecer vínculos entre genética, fenología y resiliencia ecológica.

5.6.1 Implementación de redes de sensores microclimáticos

Una de las principales recomendaciones metodológicas es la instalación de redes de sensores microclimáticos en las localidades donde se ha documentado la presencia de *J. neotropica*. Estos sensores deben medir variables clave como temperatura del aire y del suelo, humedad relativa, humedad edáfica a múltiples profundidades, radiación solar y velocidad del viento, tanto a nivel del dosel como del sotobosque. Esta estrategia permitiría capturar variaciones de corto plazo que afectan directamente la fenología de la especie, como eventos de sequía, lluvias intensas o cambios bruscos de temperatura (Klinges et al., 2025; Tian et al., 2025).

La implementación de sensores inalámbricos de bajo costo, como los utilizados en bosques montanos húmedos, facilitaría el monitoreo continuo sin alterar el entorno natural. Además, la integración de estos datos con estaciones meteorológicas locales y plataformas satelitales permitiría construir modelos de alta resolución para predecir la respuesta fenológica de *J. neotropica* bajo distintos escenarios climáticos (Ochoa et al., 2016; Vincenti et al., 2016).

5.6.2 Estudios ecofisiológicos y modelado de tolerancia climática

Es necesario desarrollar estudios ecofisiológicos que evalúen la respuesta de *J. neotropica* a condiciones de estrés hídrico, térmico y edáfico, mediante el análisis de variables como tasa de fotosíntesis, conductancia estomática, eficiencia en el uso del agua, contenido de clorofila y arquitectura radicular. Estos estudios permitirían identificar los límites de tolerancia de la especie y establecer umbrales críticos para su supervivencia y reproducción (Domínguez Liévano, 2021; Freschet et al., 2021).

El modelado de tolerancia climática, utilizando simulaciones multiescenario y algoritmos de aprendizaje automático, podría proyectar la distribución potencial de *J. neotropica* en función de variables ambientales y genéticas. Este enfoque ha sido aplicado con éxito en especies forestales de zonas tropicales y templadas, y permite anticipar desplazamientos altitudinales, cambios en la fenología y riesgos de extinción local (Bellard et al., 2012; Anderegg et al., 2020).

5.6.3 Incorporación de marcadores genéticos y análisis de diversidad intraespecífica

La variabilidad fenotípica observada entre procedencias sugiere la existencia de diferencias genéticas que deben ser caracterizadas mediante el uso de marcadores moleculares, como microsatélites, SNPs o secuenciación genómica. Estos análisis permitirían evaluar la diversidad genética intraespecífica, identificar genotipos con mayor plasticidad adaptativa y establecer relaciones entre origen genético y desempeño silvícola (Aradhya et al., 2004; Buzatti et al., 2019).

Además, la caracterización genética de poblaciones naturales y plantadas permitiría detectar posibles cuellos de botella genéticos, eventos de hibridación o pérdida de variabilidad, que podrían comprometer la viabilidad a largo plazo de la especie. La integración de datos genéticos con información fenológica y estructural fortalecería los programas de mejoramiento genético, producción de semilla certificada y diseño de rodales semilleros (Barner et al., 1992; Cornejo Oviedo et al., 2009).

5.6.4 Diseño de ensayos silviculturales con procedencias contrastantes

Se recomienda el establecimiento de ensayos silviculturales en diferentes zonas ecológicas, utilizando material vegetal de procedencias contrastantes (e.g., Tundo, Victoria, Argelia), con el fin de validar los calendarios fenológicos propuestos, evaluar el desempeño estructural y reproductivo, y optimizar la selección de genotipos para programas de reforestación y restauración ecológica. Estos ensayos deben incluir tratamientos diferenciados de fertilización, manejo del micrositio, densidad de plantación y control de competencia (Palacios-Herrera et al., 2025b; Martínez & Hernández, 2004).

La evaluación de variables como crecimiento en altura y diámetro, forma del fuste, fenofases reproductivas, supervivencia y respuesta a estrés ambiental permitiría identificar combinaciones óptimas de procedencia y sitio, y generar recomendaciones técnicas para el manejo adaptativo de *J. neotropica*. Además, estos ensayos podrían ser utilizados como plataformas de investigación participativa, involucrando a comunidades locales, estudiantes y técnicos forestales en el monitoreo y análisis de resultados.

5.6.5 Restauración ecológica basada en funcionalidad y conectividad

Las futuras investigaciones deben enfocarse en el diseño de estrategias de restauración ecológica que integren criterios de funcionalidad ecosistémica y conectividad paisajística. Esto implica seleccionar sitios estratégicos para la reforestación con *J. neotropica*, considerando su papel como especie estructural y funcional en bosques montanos, su capacidad de generar sombra, retener suelos y ofrecer un hábitat para la fauna asociada (Swann et al., 2023; Githumbi et al., 2025).

La restauración debe orientarse a reconstituir corredores ecológicos que faciliten el flujo genético entre poblaciones fragmentadas, reducir la presión antrópica en zonas núcleo, y promover la regeneración natural mediante el manejo de la cobertura vegetal y la protección de individuos reproductivos. La incorporación de criterios de resiliencia, como diversidad estructural, variabilidad fenológica y adaptabilidad genética, permitirá aumentar la capacidad de respuesta de los ecosistemas frente al cambio climático y otros disturbios (SER, 2019; Allen et al., 2010).

5.7 CONCLUSIONES

La presente Tesis Doctoral, estructurada como compendio de publicaciones científicas, ha permitido desarrollar una comprensión integral de la ecología funcional, la variabilidad fenotípica y la dinámica fenológica de *J. neotropica* en los Andes tropicales del sur de Ecuador a partir de tres estudios complementarios: 1, la ocurrencia natural y artificial de la especie; 2, su estructura poblacional y su respuesta fenológica a gradientes ambientales; 3, su desempeño en vivero y campo según procedencia genética.

Los hallazgos permitieron concluir que *J. neotropica* es una especie altamente sensible a las condiciones microclimáticas, edáficas y topográficas, con una marcada plasticidad fenotípica que le permite adaptarse a entornos diversos, pero que también la hace vulnerable a perturbaciones ambientales y antrópicas. La agregación espacial, la diversidad estructural, la sincronía fenológica y la variabilidad por procedencia son rasgos clave que definen su comportamiento ecológico y su potencial silvicultural.

Desde una perspectiva ecológica, se concluye que la especie actúa como componente estructural y funcional en bosques montanos, contribuyendo a la estabilidad del ecosistema, la retención de suelos, la regulación hídrica y la provisión de hábitat para fauna asociada. Su conservación requiere enfoques adaptativos que integren el conocimiento científico con la gestión territorial, la participación comunitaria y la restauración ecológica basada en funcionalidad y conectividad.

En el ámbito silvicultural, los resultados permitieron concluir que establecer criterios técnicos para la planificación diferenciada, la selección de procedencias, el diseño de viveros, la programación de plantaciones y el monitoreo fenológico. La validación de calendarios fenológicos, la identificación de genotipos con alto desempeño, y la caracterización de sitios óptimos para el establecimiento, constituyen aportes concretos para la gestión forestal sostenible de *J. neotropica*.

A pesar de las limitaciones metodológicas enfrentadas, como la prohibición de muestreo destructivo, el uso de datos interpolados y la escasa disponibilidad de estudios previos, las estrategias alternativas han resultado satisfactorias para el estudio de *J. neotropica* en los Andes tropicales del sur de Ecuador. La instalación de sensores microclimáticos, el desarrollo de estudios ecofisiológicos, el uso de marcadores genéticos y el diseño de ensayos silviculturales contrastantes son líneas de investigación prioritarias que permitirán profundizar en el conocimiento de la especie y fortalecer su manejo adaptativo.

En síntesis, esta Tesis Doctoral aporta evidencia científica sólida y contextualizada sobre *J. neotropica*, posicionándola como una especie clave para la restauración de bosques montanos tropicales, la conservación de la biodiversidad andina y el desarrollo de estrategias silviculturales resilientes frente al cambio climático. La articulación entre ecología, genética, fenología y silvicultura, lograda a través del enfoque por compendio de publicaciones, constituye una contribución significativa al conocimiento forestal en Ecuador y en la región andina.

6. CONCLUSIONES

Los resultados de la Tesis Doctoral permiten establecer una diferenciación clara entre los niveles de análisis aplicados a *Juglans neotropica* Diels en el sur de Ecuador. La fenología aporta información sobre la adaptación temporal de la especie, evidenciando cómo los eventos de brotación, floración, fructificación y senescencia se sincronizan o divergen en respuesta a gradientes ambientales y estructurales.

El fenotipo, entendido como la expresión morfológica y funcional del genotipo en interacción con el ambiente, refleja la adaptación estructural y fisiológica de los individuos, manifestada en atributos como vigor, forma del fuste y capacidad de supervivencia. Los rasgos fenotípicos, medidos de manera cuantitativa (altura, diámetro basal, número de hojas, germinación y supervivencia), permiten objetivar y comparar la variabilidad adaptativa entre procedencias y ambientes de plantación, constituyendo indicadores clave para programas de restauración y mejoramiento genético.

Esta distinción conceptual refuerza la pertinencia de un enfoque multiescalar y ecosistémico, en el que la integración de la dinámica poblacional, la sincronía fenológica y la plasticidad fenotípica ofrece criterios técnicos aplicables a la conservación in situ, la planificación de reforestaciones y el diseño de estrategias de manejo forestal sostenible frente a escenarios de cambio climático y fragmentación del paisaje.

Las conclusiones globales de esta Tesis Doctoral por compendio de publicaciones sintetizan los principales aportes científicos, técnicos y territoriales derivados de los tres artículos publicados, articulados en torno al estudio de *J. neotropica* en ecosistemas montanos del sur de Ecuador. A través de un enfoque multietapa que integra caracterización ecológica, evaluación fenológica y análisis fenotípico, se ha logrado construir una propuesta metodológica y aplicada para la conservación, restauración y manejo forestal sostenible de esta especie nativa, actualmente clasificada como amenazada por la UICN.

La caracterización ecológica y estructural en seis localidades de la Región Sur (Zona 7) permitió identificar patrones de distribución agregada, alta densidad en sitios naturalizados y variabilidad significativa en parámetros dasométricos. Estos hallazgos aportan evidencia territorial clave para la planificación de estrategias de conservación in situ y el diseño de corredores ecológicos.

El monitoreo fenológico en poblaciones nativas y reforestadas reveló que los eventos estacionales están modulados por gradientes edáficos y orográficos, así como por la edad de los individuos. Esta información permite construir calendarios fenológicos representativos y adaptar las prácticas de manejo forestal a las condiciones locales.

La evaluación fenotípica en vivero y campo demostró que la procedencia y los tratamientos pregerminativos influyen significativamente en la germinación, supervivencia y crecimiento de *J. neotropica*. La aplicación de urea y el tratamiento de agua y sol mejoraron los indicadores de desempeño, mientras que los ambientes de plantación (bosque secundario, ripario y pastizal) condicionaron el desarrollo morfológico de los individuos.

La integración de los tres estudios confirma la plasticidad adaptativa de *J. neotropica,* su capacidad de responder a condiciones ambientales contrastantes y su potencial como especie estratégica para la restauración ecológica en zonas de alta fragilidad. Esta plasticidad debe ser considerada en los programas de reforestación, selección de genotipos y diseño de viveros.

Desde una perspectiva metodológica, la Tesis Doctoral valida el uso de diseños bifactoriales, análisis multivariados, georreferenciación ecológica y monitoreo fenológico longitudinal como herramientas eficaces para el estudio de especies forestales nativas. Esta aproximación puede ser replicada en otras regiones andinas con especies de interés ecológico y económico.

Los resultados obtenidos aportan evidencia técnica para la formulación de políticas públicas, la gestión de viveros comunitarios, la planificación territorial y el fortalecimiento de capacidades locales en conservación forestal. Asimismo, contribuyen al conocimiento científico sobre especies nativas poco estudiadas y promueven su valorización en contextos de desarrollo sostenible.

Finalmente, esta Tesis Doctoral reafirma la importancia de integrar enfoques ecológicos, fenotípicos y territoriales en el estudio de especies forestales amenazadas, y propone una ruta metodológica para su conservación activa, restauración asistida y aprovechamiento responsable. Aunque no se realizó una evaluación genética directa, la variabilidad fenotípica observada se considera una expresión indirecta de la diversidad genética intraespecífica. *J. neotropica* emerge, así, como un símbolo de resiliencia ecológica y de compromiso territorial con la biodiversidad andina.

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8. APÉNDICES

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Artículo	Revista	Año	DOI
Natural and Artificial Occurrence, Structure, and Abundance of Juglans neotropica Diels in Southern Ecuador	Agronomy	2023	https://doi.org/10.3390/agronomy13102531
Phenological Variation of Native and Reforested Juglans neotropica Diels in Response to Edaphic and Orographic Gradients in Southern Ecuador	Diversity	2025	https://doi.org/10.3390/d17090627
Phenotypic Variability of Juglans neotropica Diels from Different Provenances During Nursery and Plantation Stages in Southern Ecuador	Forests	2025	https://doi.org/10.3390/f16071141

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Esta Tesis Doctoral compila tres estudios sobre "Juglans neotropica" Diels en ecosistemas montanos del sur de Ecuador. Se caracteriza la estructura forestal en bosques naturales, evidenciando variabilidad en crecimiento y distribución entre sitios. Asimismo, se analiza la influencia de gradientes climáticos, edáficos y topográficos sobre rasgos fenotípicos, destacando la plasticidad y adaptabilidad de la especie frente al cambio climático. Además, se evalúa la calidad de la semilla y el establecimiento en vivero y campo, evidenciando alta viabilidad, germinación y supervivencia en ambientes diversos. Se incorpora el análisis de diversidad genética entre poblaciones naturales y reforestadas, aportando criterios para la selección de material en programas de restauración y silvicultura tropical.